

BESIII



Search for dark sector and rare decays at BESIII

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On behalf of the BESIII Collaboration

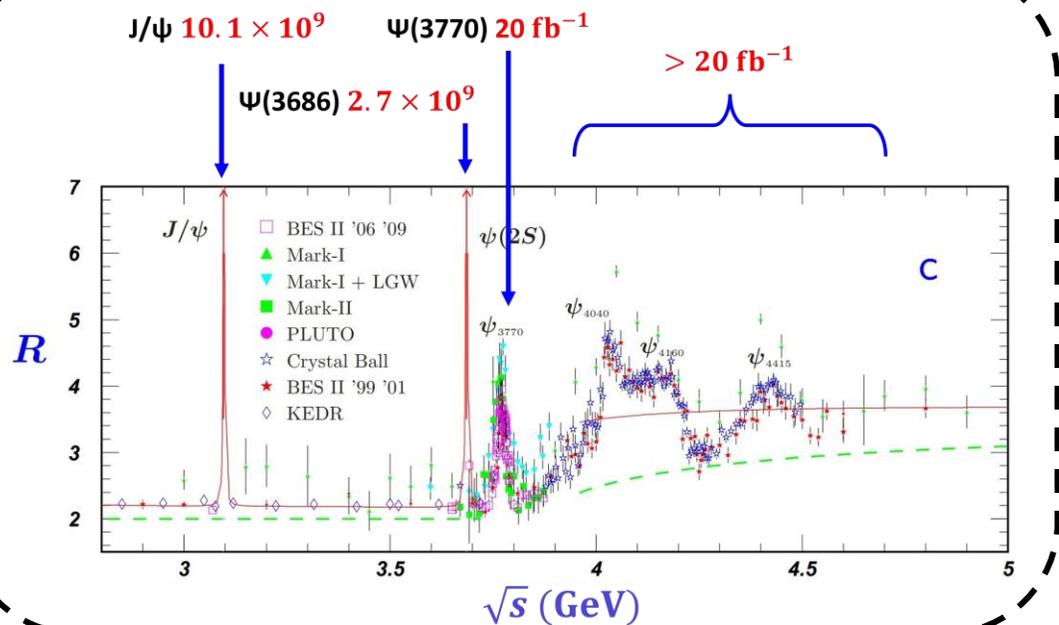
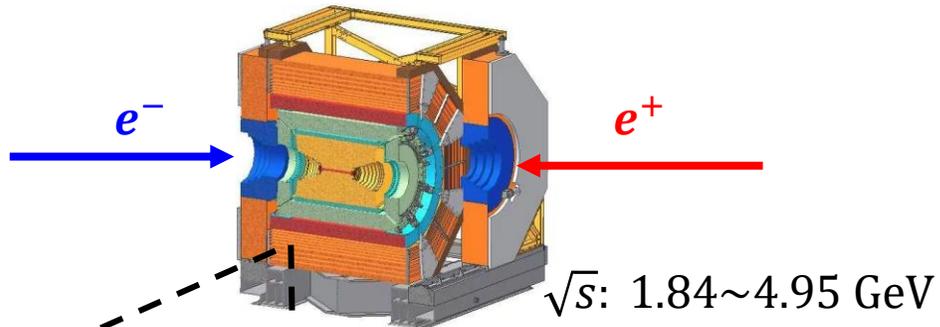
60th Rencontres de Moriond EW, 15 - 22 March 2026, La Thuile, Italy

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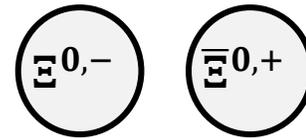
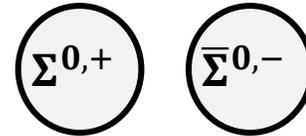
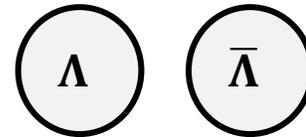
BESIII experiment



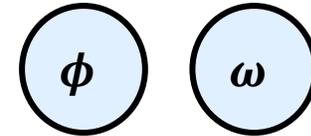
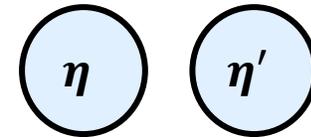
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■ $10.1 \times 10^9 J/\psi$ events

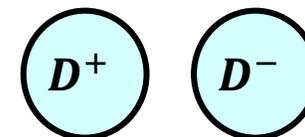
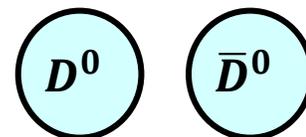
• Hyperon



• Light meson



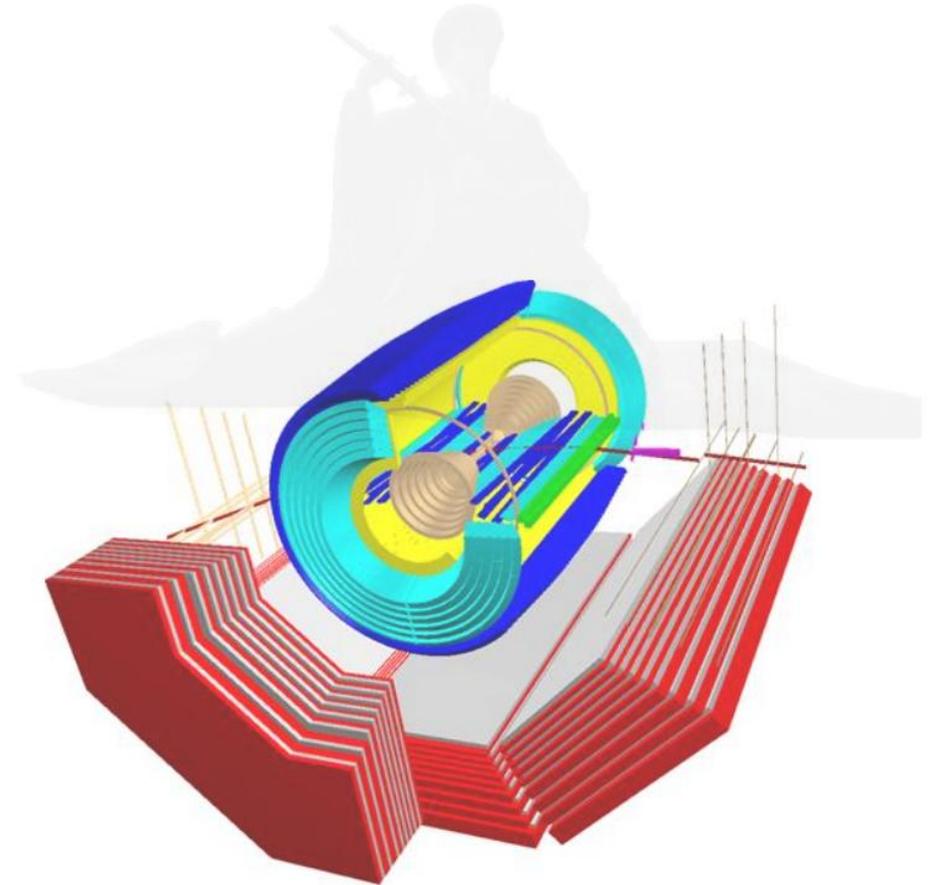
■ $20 \text{ fb}^{-1} \psi(3770)$



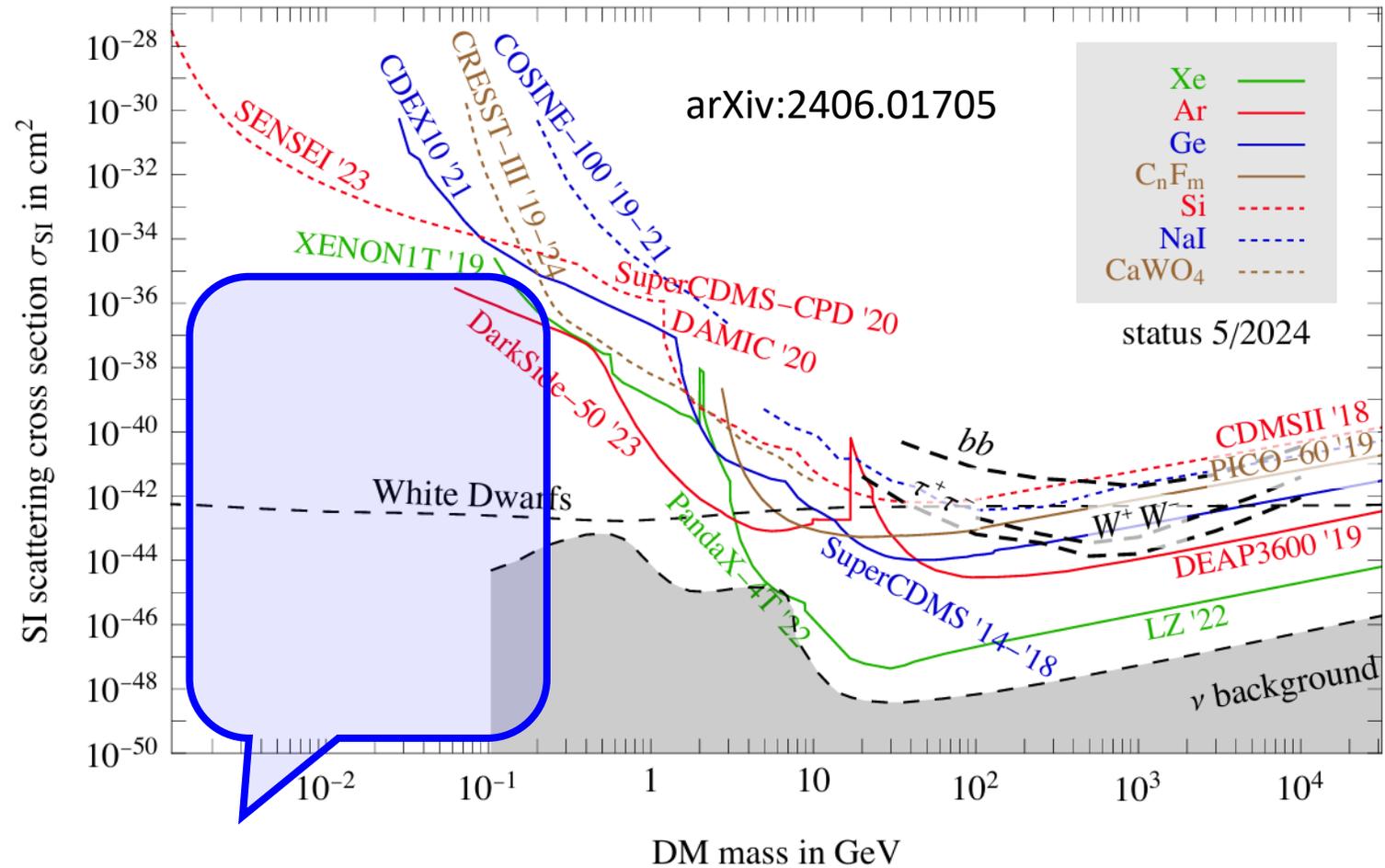
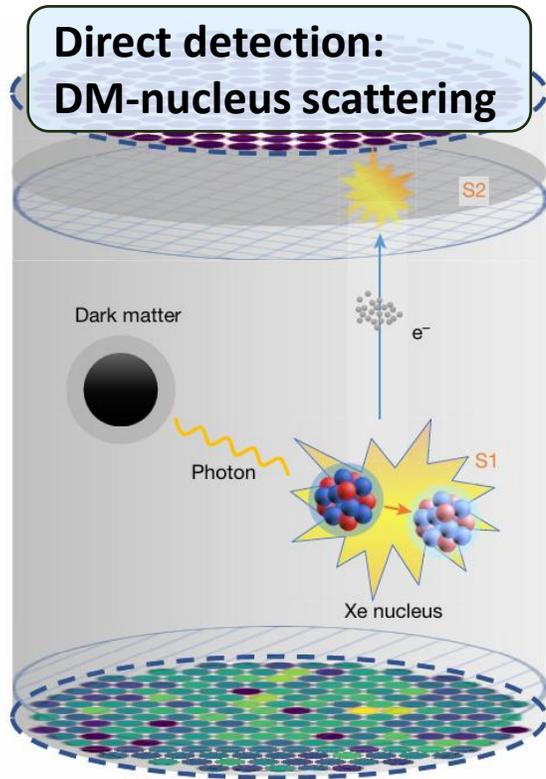
- Wide range of physics with clean background
- Beneficial to search for dark sector and rare decays

OUTLINE

- **Sub-GeV DM search in $\eta \rightarrow \pi^0 + \text{invisible}$**
- Other new dark sector searches at BESIII
- CLFV, LNV, BNV rare decays
- Charmonium weak decays



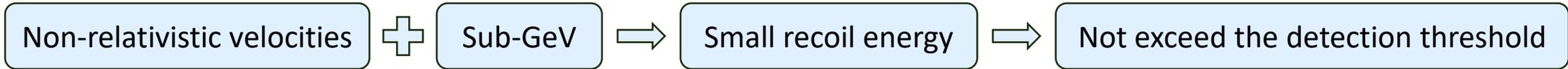
Dark matter (DM) search status



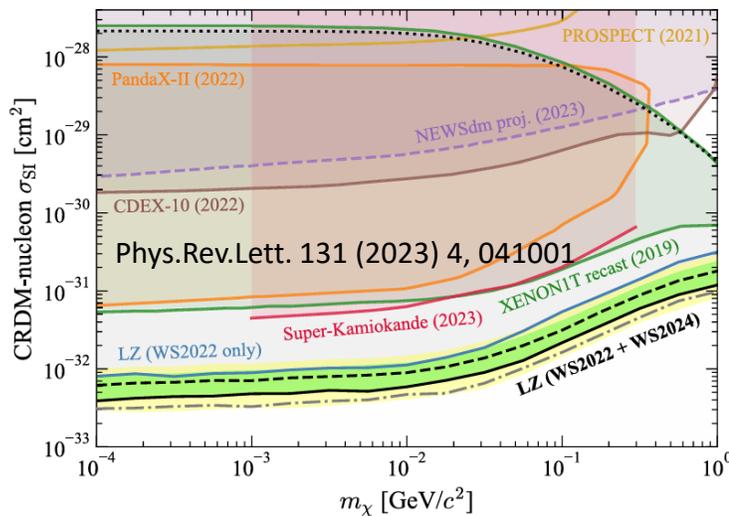
- GeV to TeV scale: strong constraint, not found any WIMP signal
- Sub-GeV: insufficient nuclear recoil energy to be detected, less exploration

Sub-GeV DM search status

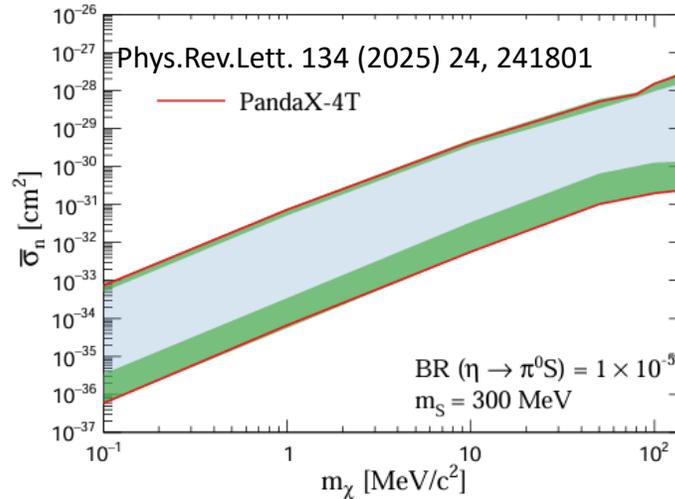
➤ The challenge of the sub-GeV DM detection



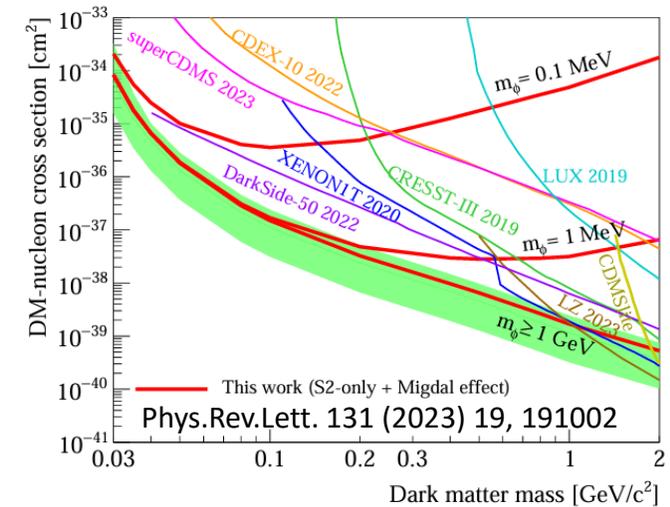
➤ Solutions of the sub-GeV DM detection: **1. boosted DM** **2. low threshold detection**



Cosmic-ray boosted DM



Atmospheric-meson-decay boosted DM

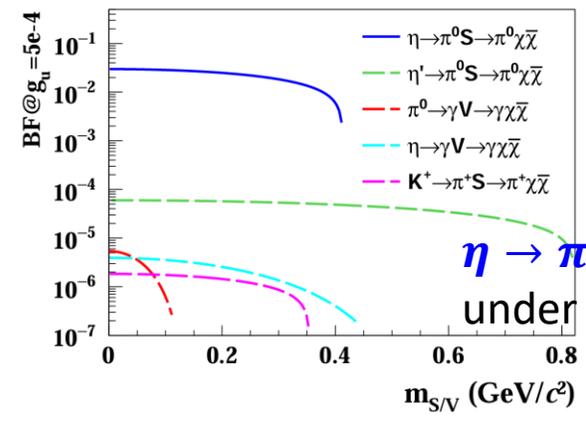
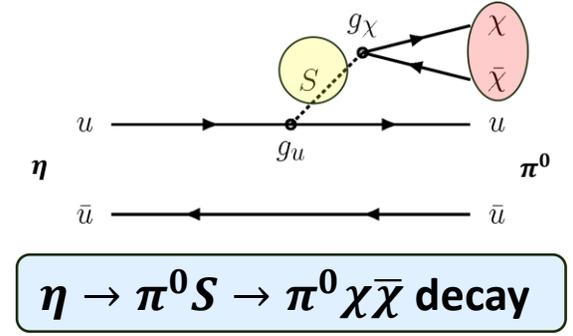
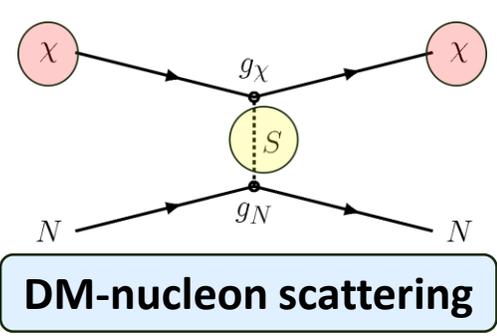


Migdal effect to lower the threshold

- Hard work but **sensitivity remains limited** due to the reduced DM Flux or reduced detection probability
- **BESIII operates in $\sim \text{GeV}$ region, can offer a unique opportunity to probe sub-GeV DM from the collider**



Search for $\eta \rightarrow \pi^0 + \text{invisible}$ at BESIII



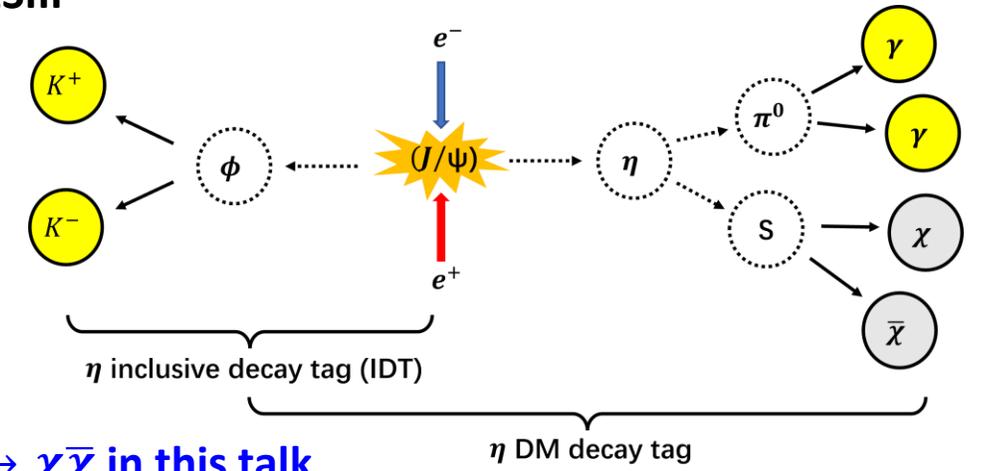
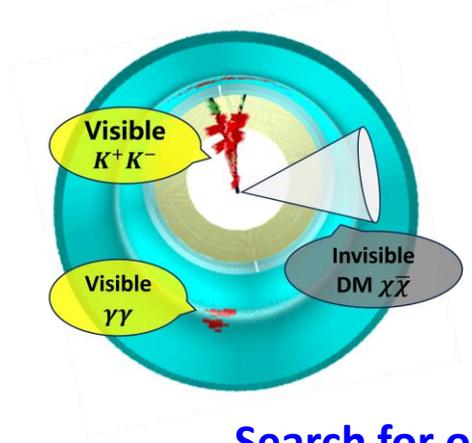
Flavor Conservation DM decays

$\eta \rightarrow \pi^0 S \rightarrow \pi^0 \chi \bar{\chi}$ has the largest BF under the equal coupling strength

- The two processes involve the same new physics
- S is a dark scalar boson, and χ is the DM

Search for sub-GeV dark particles with $\eta \rightarrow \pi^0 S \rightarrow \pi^0 \chi \bar{\chi}$ at BESIII

- Data set @ 3.097 GeV $(10087 \pm 44) \times 10^6 J/\psi$
- η source: $J/\psi \rightarrow K^+ K^- \eta$
- **Charged kaons help to tag η and DM**

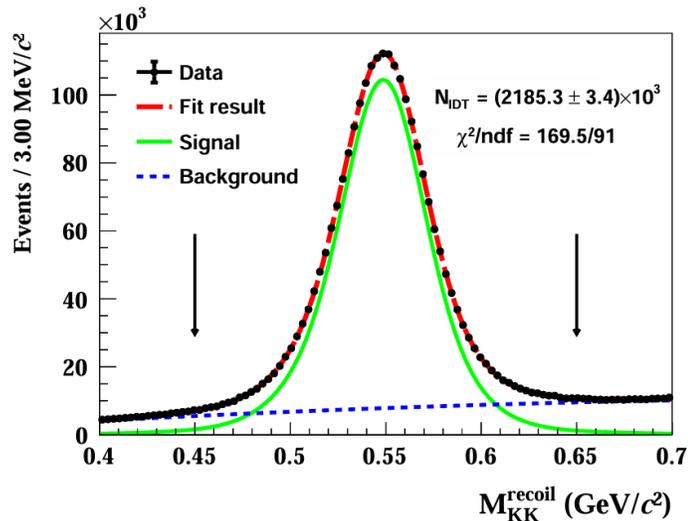


Search for on-shell $S \rightarrow \chi \bar{\chi}$ in this talk
 The off-shell $S \rightarrow \chi \bar{\chi}$ search is ongoing



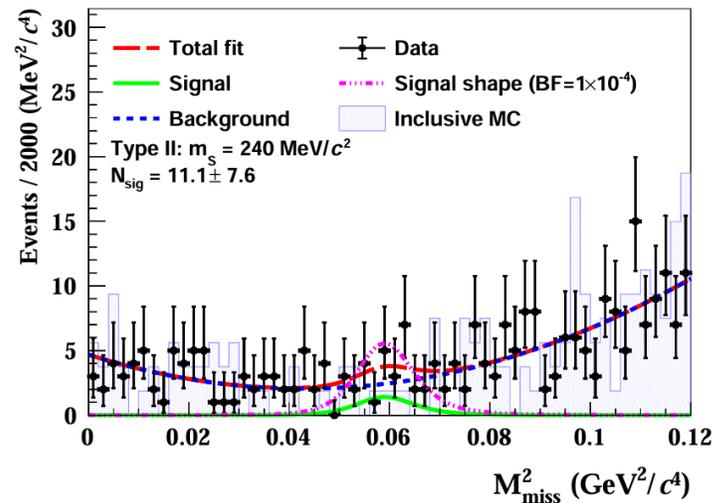
Search for $\eta \rightarrow \pi^0 + \text{invisible}$ at BESIII

Tag K^+K^- with $\eta \rightarrow \text{any}$



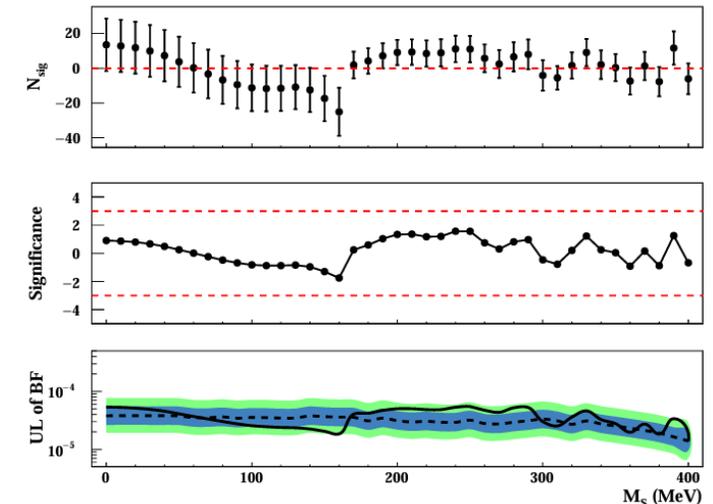
- The recoiling mass of K^+K^-
- $\sim 2 \times 10^6$ η events are tagged
- Not the world largest η data set, but may be the cleanest η data

Further tag $\eta \rightarrow \pi^0 + \text{inv}$



- The recoiling mass square of $K^+K^-\pi^0$
- On-shell $S \rightarrow \chi\bar{\chi}$

Scan signal with different m_S



- Signal yield and upper limit (UL)
- S mass from ~ 0 to 400 MeV
- **UL on $\mathcal{B}(\eta \rightarrow \pi^0 S)$ @90% C.L.:**
 $(1.8 \sim 5.5) \times 10^{-5}$

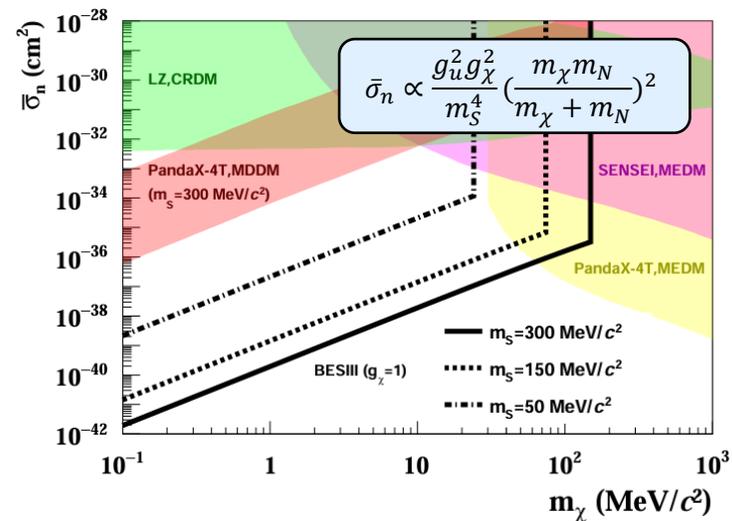
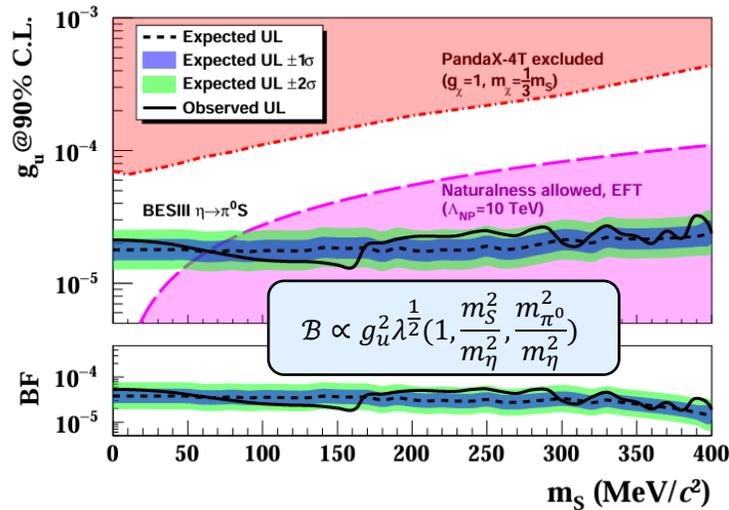
▣ Advantages of **DM study at BESIII**

- **Clean background, full reconstruction, high efficiency, absolute BF measurement...**

Discussion within the specific model

$$\mathcal{L} \supset -g_\chi S \bar{\chi}_L \chi_R - g_u S \bar{u}_L u_R + h.c., \quad g_u \equiv \frac{c_{SV}}{\sqrt{2}\Lambda_{NP}}$$

- The coupling strength g_u not necessarily proportional to the Higgs Yukawa couplings



$$\text{UL on } g_u \text{ @90\% C.L.: } (1.3 \sim 3.2) \times 10^{-5}$$

- Better than the result of atmospheric-boosted DM from PandaX-4T
- Constraint on $\bar{\sigma}_n$: **model-dependent** (scattering mediated by on-shell S)
 - Improved by approximately 5 orders** of magnitude over previous DM-nucleon scattering experiments



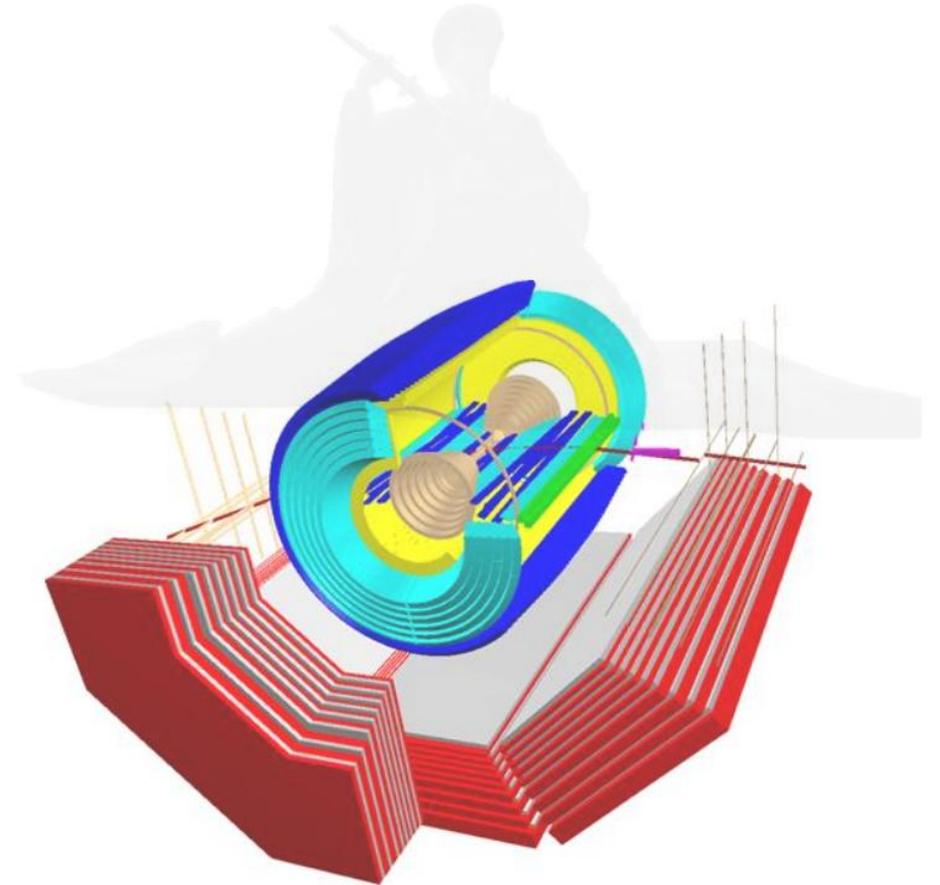
- The idea of this work was from the dinner in Moriond 2024

Ongoing and Future

- Off-shell S case in $\eta \rightarrow \pi^0 \chi \bar{\chi}$
- Pseudo-scalar case in $\eta \rightarrow \pi^+ \pi^- \chi \bar{\chi}$
- Vector case in $\pi^0 / \eta \rightarrow \gamma \chi \bar{\chi}$
-

OUTLINE

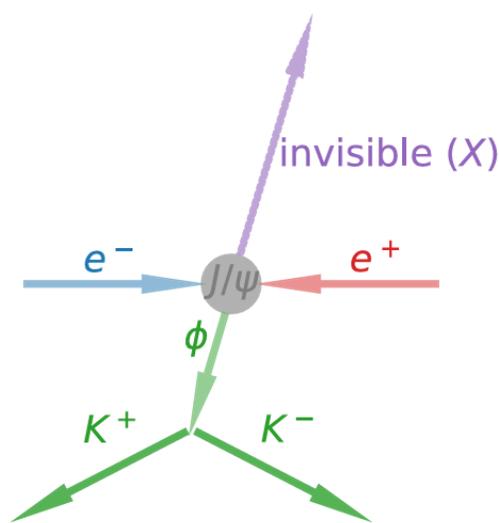
- Sub-GeV DM search in $\eta \rightarrow \pi^0 + \text{invisible}$
- **Other new dark sector searches at BESIII**
- CLFV, LNV, BNV rare decays
- Charmonium weak decays



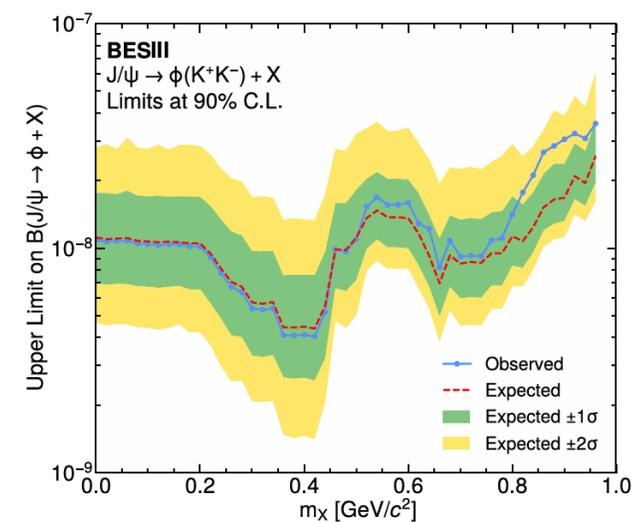
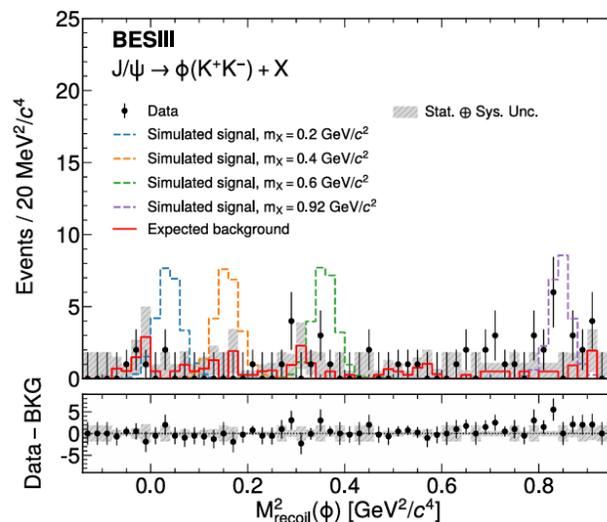


Search for $J/\psi \rightarrow \phi + \text{invisible}$ at BESIII

- Motivation **similar to the previous $\eta \rightarrow \pi^0 + \text{invisible}$**
- Using $(8774.0 \pm 39.4) \times 10^6$ J/ψ events to search for sub-GeV particles in $J/\psi \rightarrow \phi + \text{invisible}$



Reconstruct the invisible signal by the K^+K^- recoil



- **UL on $\mathcal{B}(J/\psi \rightarrow \phi X)$** with m_X ranging from 0 to 0.96 GeV @90% C.L.
 $4 \times 10^{-9} \sim 4 \times 10^{-8}$
- UL on the inclusive invisible BF of $J/\psi \rightarrow \phi X$: 7.0×10^{-8} @90% C.L.
- Taking $X = \eta$, **UL on $\mathcal{B}(\eta \rightarrow \text{invisible})$** : 2.4×10^{-5} @90% C.L., improved by more than 4 times

Lacking the theoretical connection to the physical coupling (and DM XS)
More theoretically complex in charm decay, still wait for a calculation...

Dark baryon

Coincidence problem

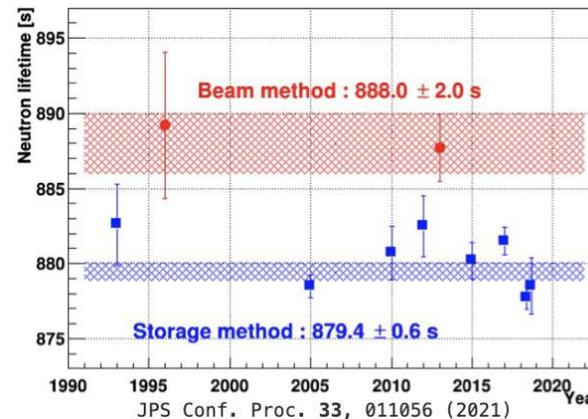


The baryon and dark matter energy densities are fairly similar
 $\Omega_{DM}/\Omega_b \cong 5.36 \pm 0.06$

- Potential connection between their origins
- **DM may carry non-zero baryon number**



Neutron lifetime puzzle



$$\tau_n^{\text{beam}} = \frac{\tau_n^{\text{bottle}}}{\text{Br}(n \rightarrow p + \text{anything})} \quad \mathcal{B}(n \rightarrow \text{dark}) \sim 1\%$$

- **Motivates the existence of dark baryon**

B-Mesogenesis mechanism



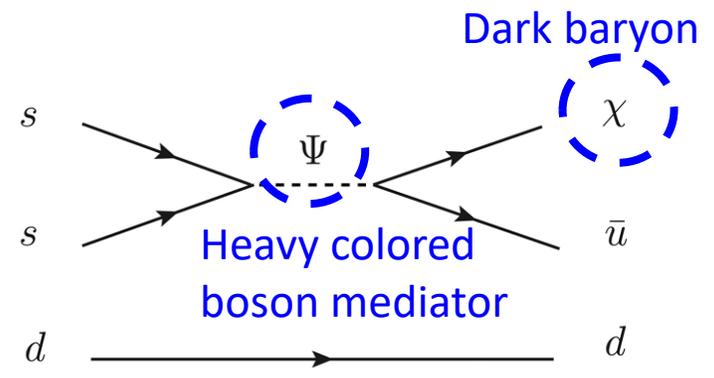
CP asymmetry in $B \rightarrow \text{baryon} + \text{dark baryon}$

1. Explain matter anti-matter asymmetry
2. The origin of the dark matter

Naturally, dark baryon interacts with all SM quark flavor
 \Rightarrow **Search for dark baryon in hyperon decay at BESIII**

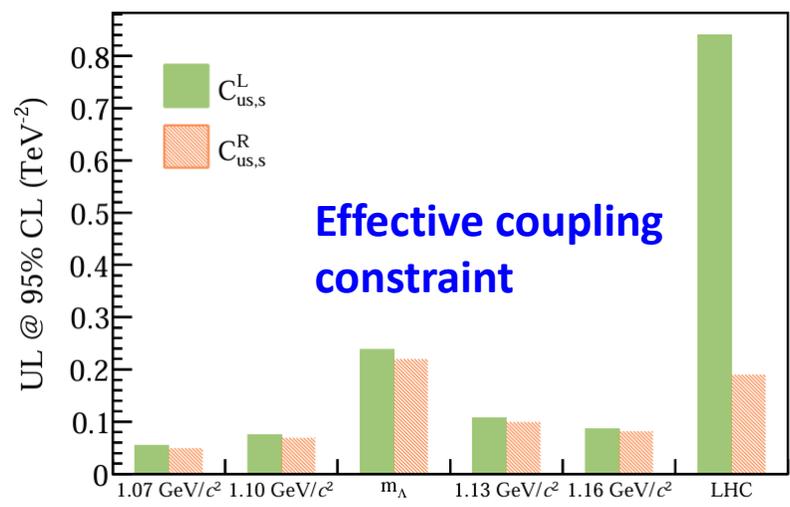
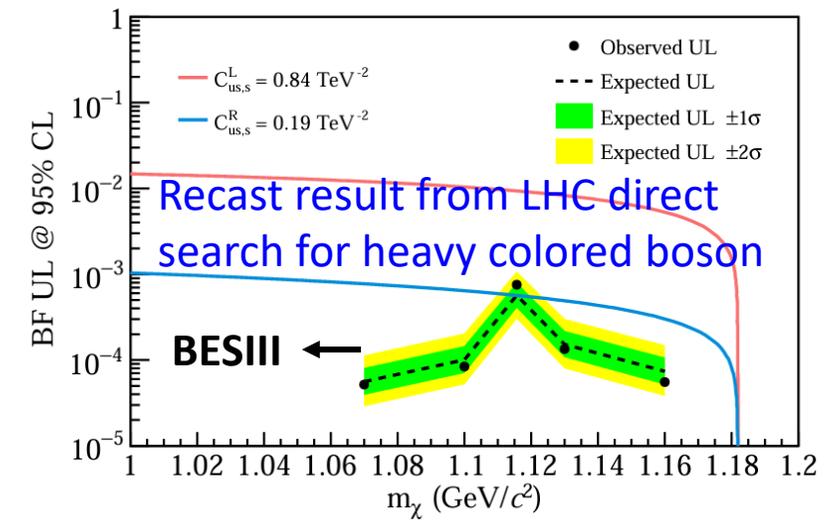
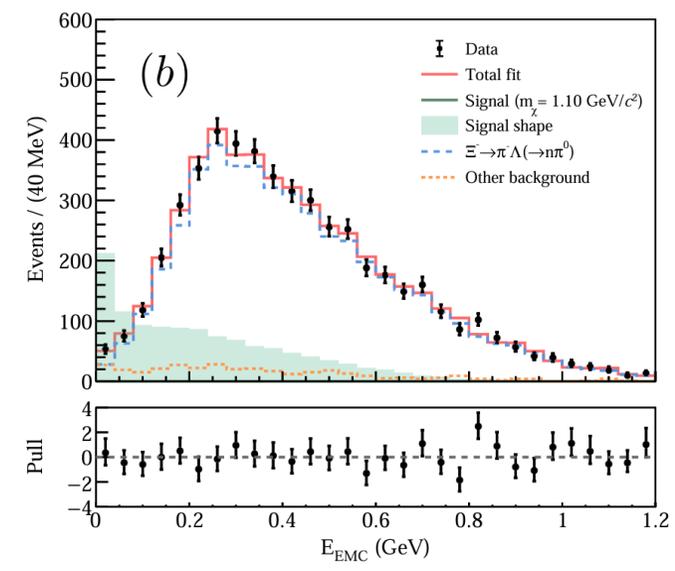


Search for $\Xi^- \rightarrow \pi^- + \text{invisible}$ at BESIII



➤ $J/\psi \rightarrow \Xi^+ \Xi^-$ from $10^{10} J/\psi$

- $\Xi^+ \rightarrow \text{SM}, \Xi^- \rightarrow \pi^- \chi$
- Dark baryon χ with mass hypothesis of 1.07, 1.10, m_Λ , 1.13, 1.16 GeV
- Deposited energy in EMC used to identify the invisible signal



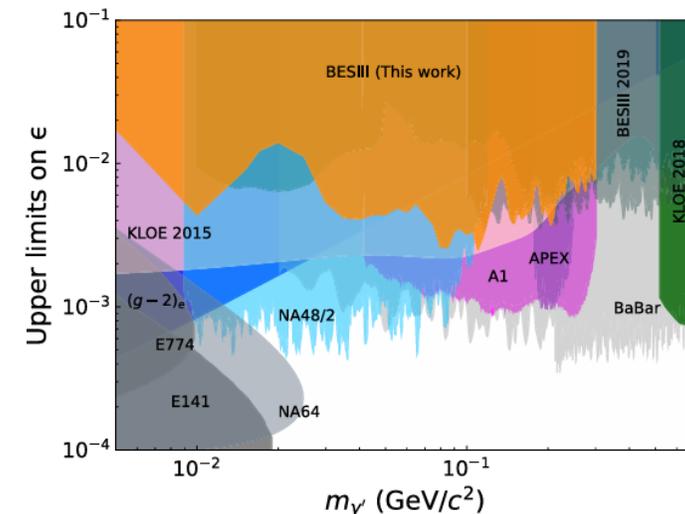
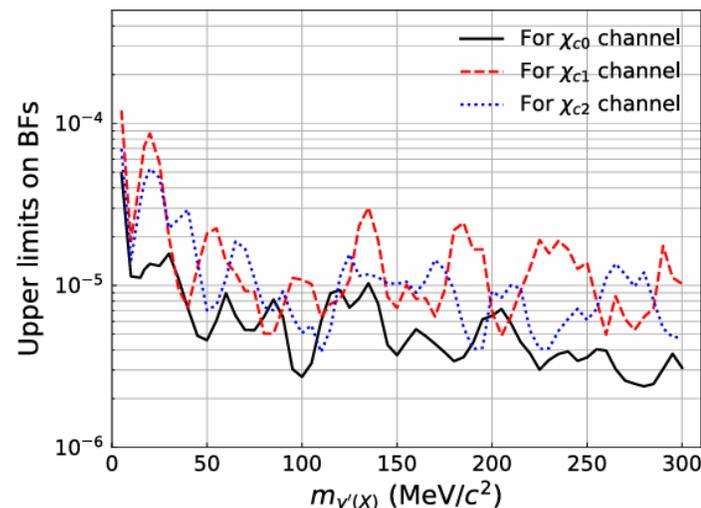
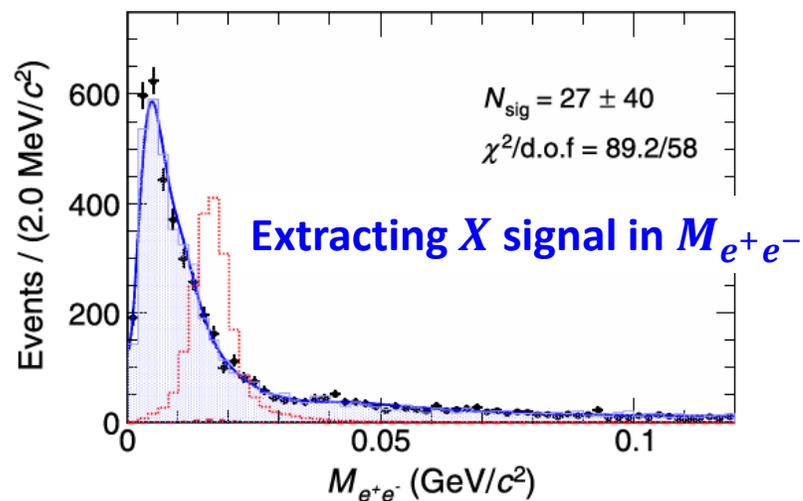
Better effective coupling constraints





Search for $\chi_{cJ} \rightarrow J/\psi X, X \rightarrow e^+ e^-$ at BESIII

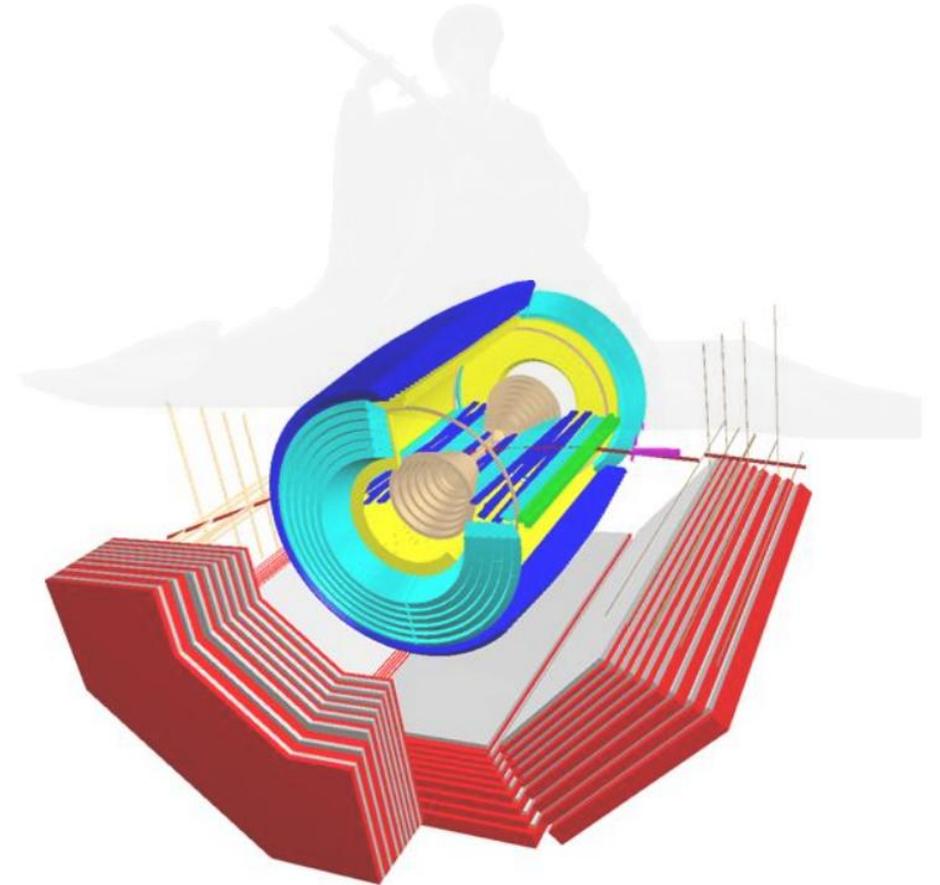
- Search for a **light vector boson X** : $\mathcal{L} \supset \sum_f eq_f \epsilon_f X^\mu \bar{\psi}_f \gamma_\mu \psi_f$
 - If there is no dark sector lighter than X , can only $X \rightarrow f\bar{f}$
- Data set: $2.7 \times 10^9 \psi(2S)$
 - χ_{cJ} from $\psi(2S) \rightarrow \gamma \chi_{cJ}$



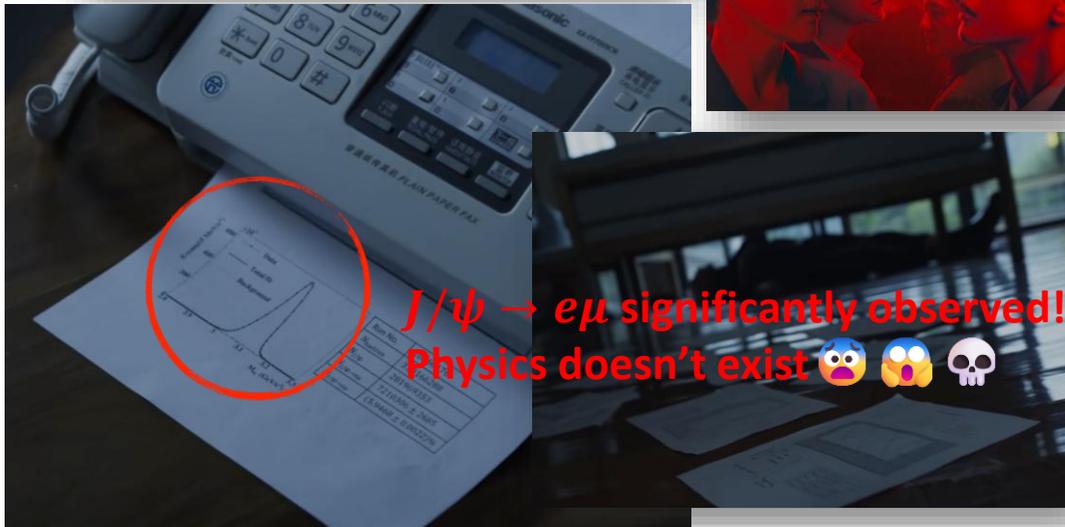
- UL on $\mathcal{B}(\chi_{cJ} \rightarrow J/\psi X) \times \mathcal{B}(X \rightarrow e^+ e^-)$ @90% C.L.: $2 \times 10^{-6} \sim 10^{-4}$ for X mass ranging from 5 to 300 MeV
- **Coupling strength with charm quark** @90% C.L.: $(2.5 \sim 17.5) \times 10^{-3}$ (in unit of eq_c)
- In dark photon model, X shares a universal ϵ_f for different fermion
 - This work has no advantage in dark photon model, but provides **unique probe on coupling with charm** in some un-universal coupling models

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- **CLFV, LNV, BNV rare decays**
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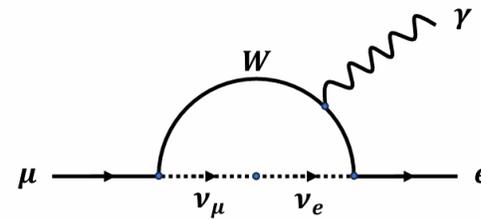
Charged lepton flavor violation (CLFV)



NOTE: three-body is a scientific fiction written by Cixin Liu, In 2023, it was adapted for television

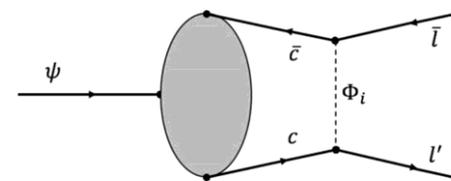
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- In 2023, the search for $J/\psi \rightarrow e\mu$ has been reported by BESIII: $\mathcal{B} < 4.5 \times 10^{-9}$
- Physics still exist... Sci.China Phys.Mech.Astron. 66 (2023) 2, 221011



- In the (extended) **SM**
- allowed by the neutrino oscillation
- **Highly suppressed** by the tiny mass of neutrino

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



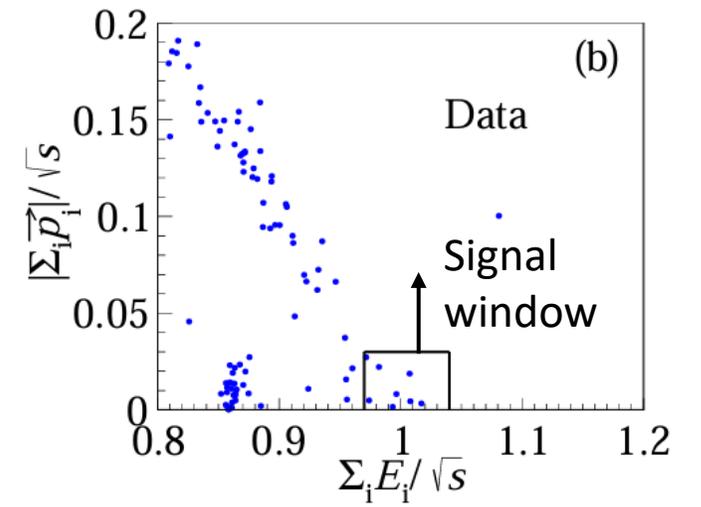
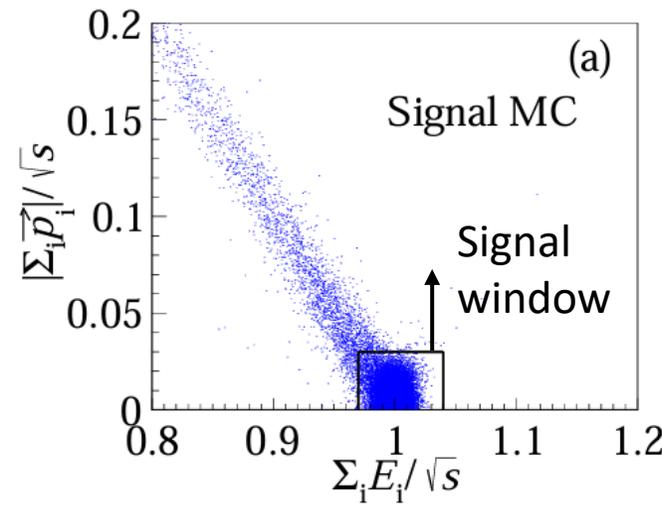
- Many **new physics allows** the CLFV
- RPV SUSY
- Z' model
- Lepton-quark
- ...

New CLFV result from BESIII: search for $\psi(2S) \rightarrow e\mu$

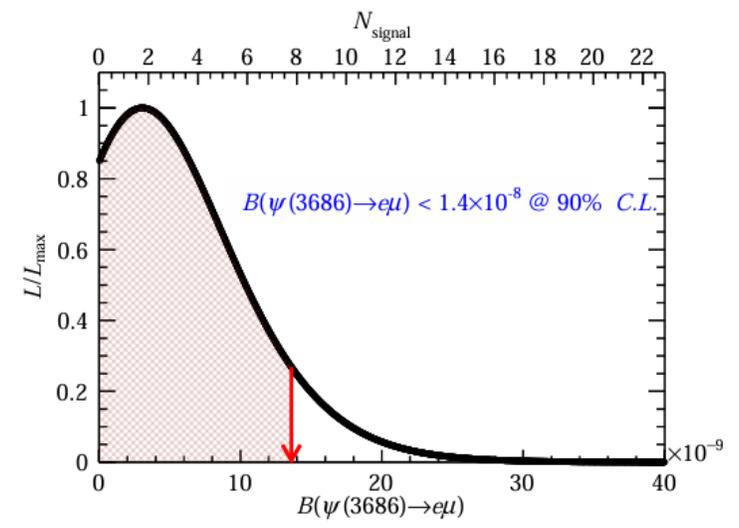
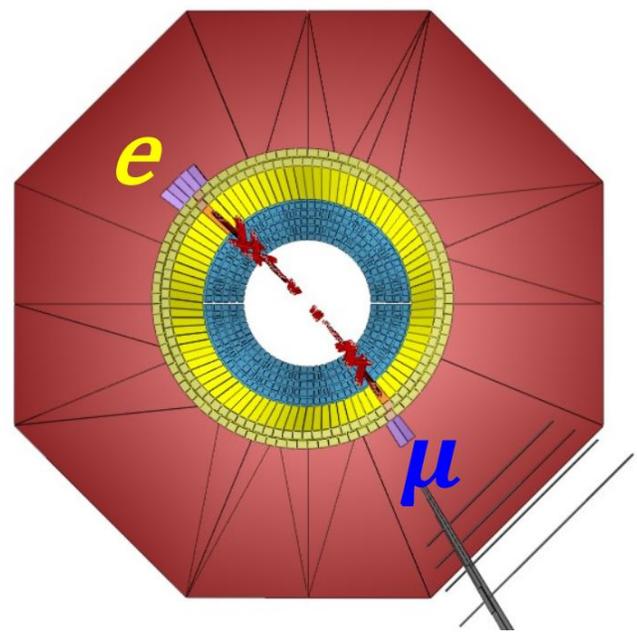


Search for $\psi(2S) \rightarrow e\mu$ at BESIII

- Data set: $(2367.0 \pm 11.1) \times 10^6 \psi(2S)$ events
- **8 candidate events** are observed in data
- Estimated background: 6.2 ± 1.4



First search



- $\mathcal{B}[\psi(2S) \rightarrow e\mu] < 1.4 \times 10^{-8}$ @90% C. L.
- $\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_{\text{NP}}^2} \sum_i C_i^{(6)} \mathcal{O}_i^{D=6} + \dots$ PRD 94,074023(2016)
- Combined the result of $J/\psi \rightarrow e\mu$,

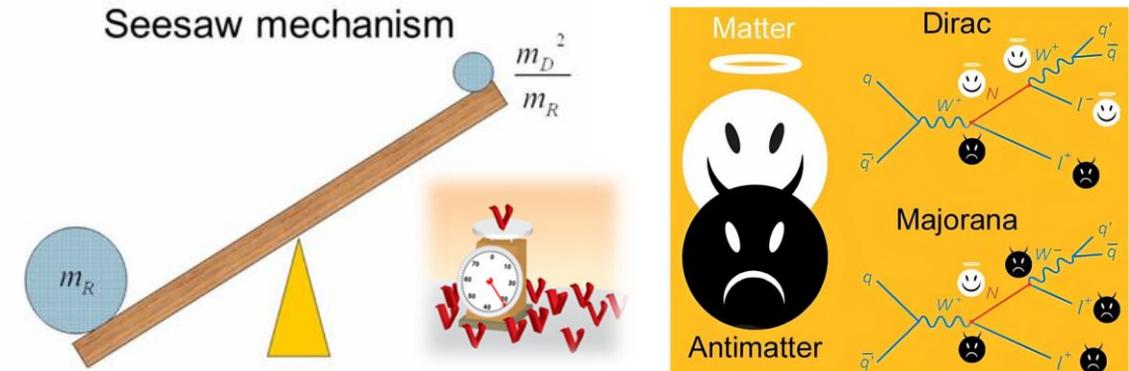
Constraint on Wilson coefficients of $C_i^{(6)}$

$C_{DL/R}^{e\mu} / \Lambda^2$	$< 1.77 \times 10^{-4} \text{ GeV}^{-2}$
$C_{VL/R}^{ce\mu} / \Lambda^2$	$< 1.72 \times 10^{-6} \text{ GeV}^{-2}$
$C_{TL/R}^{ce\mu} / \Lambda^2$	$< 7.75 \times 10^{-1} \text{ GeV}^{-2}$

Lepton/baryon(L/B) number(N) violation(V)

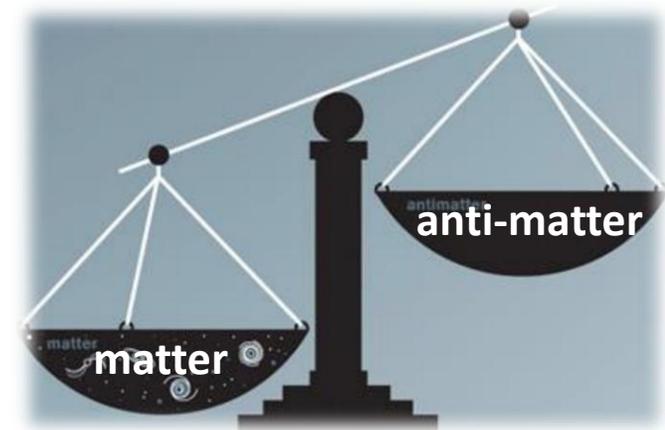
Open question: Dirac or Majorana?

- Neutrino oscillations → neutrinos have small mass
- See-saw: small mass of observed light neutrino arises from heavy Majorana neutrino
- Neutrinos are Dirac or Majorana is still an open question
- **Majorana neutrino can be revealed through LNV decay by $\Delta L = 2$**



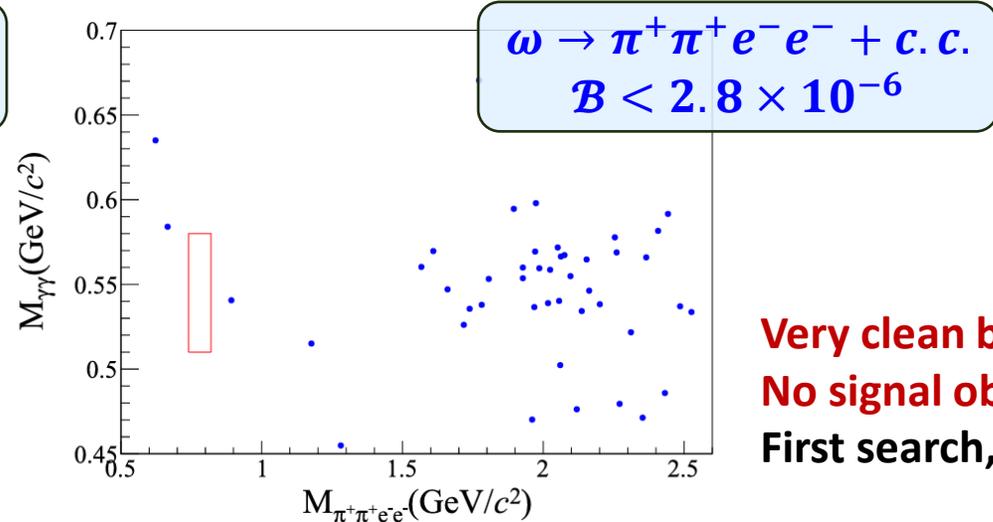
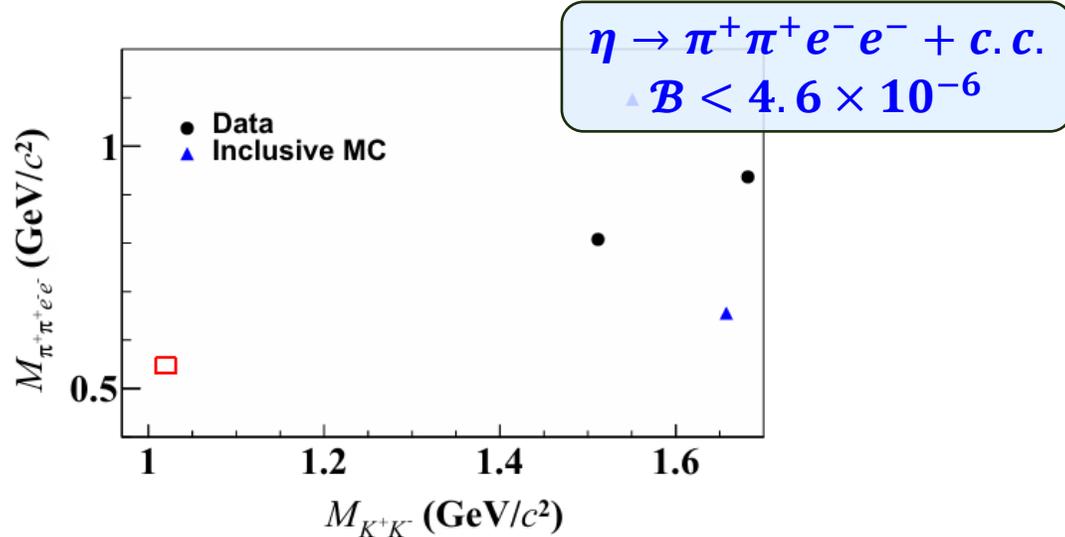
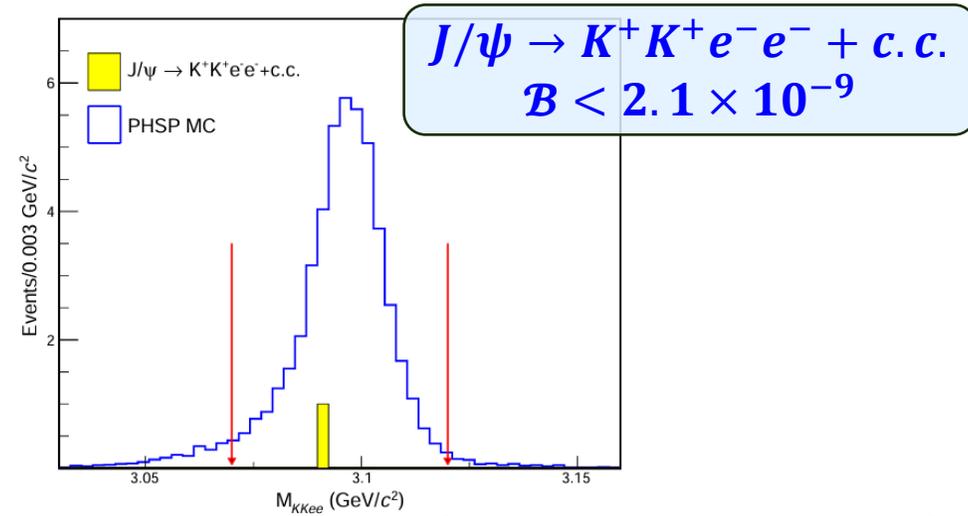
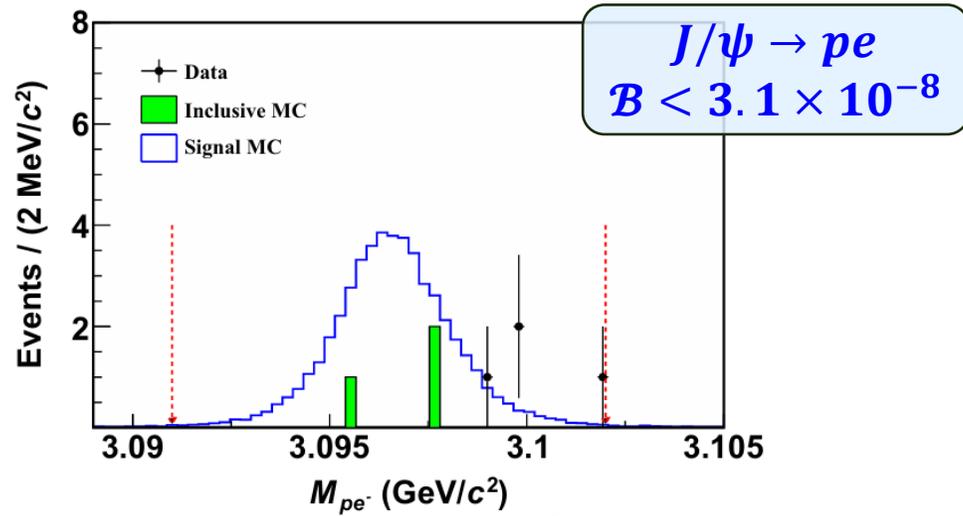
Frontier issue: matter-antimatter asymmetry

- One of the Sakharov conditions: violation of baryon number conservation
- In the SM, baryon number is always conserved.
- BNV is allowed in grand unified theories (GUT) and SM extensions with $\Delta(B - L) = 0$
- Some dimension seven operators also allow $\Delta(B - L) = 2$





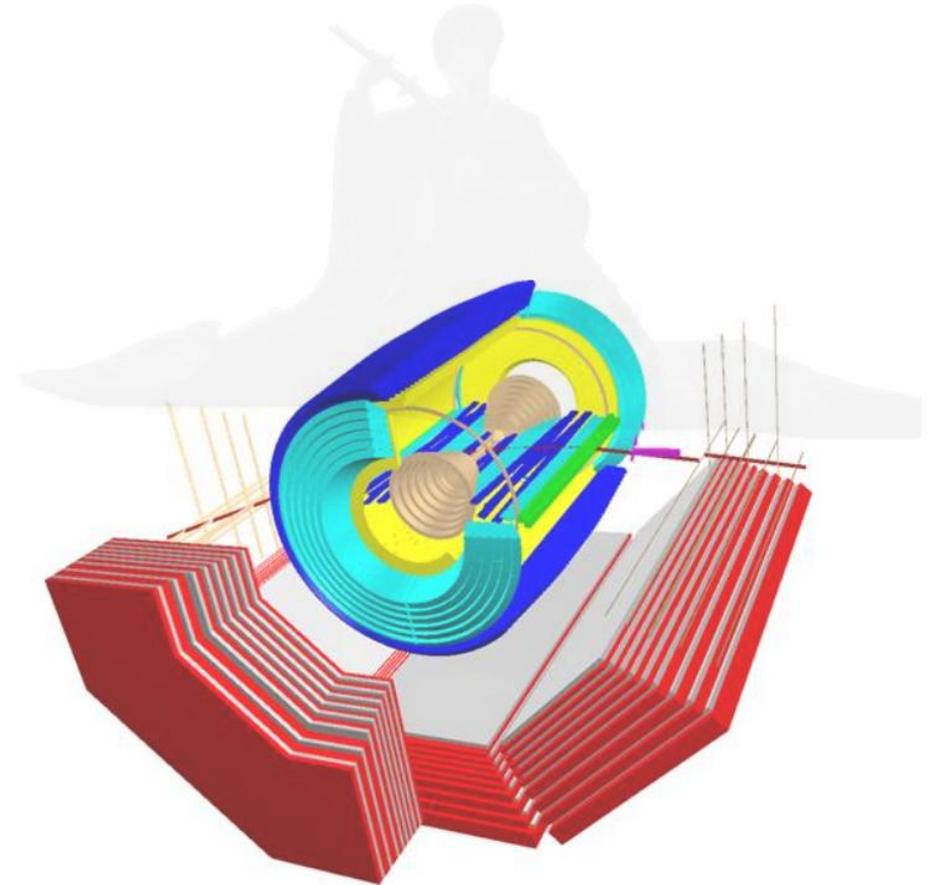
Some new results of BNV/LNV at BESIII



Very clean background
No signal observed
First search, UL set @90% C.L.

OUTLINE

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Charmonium weak decay

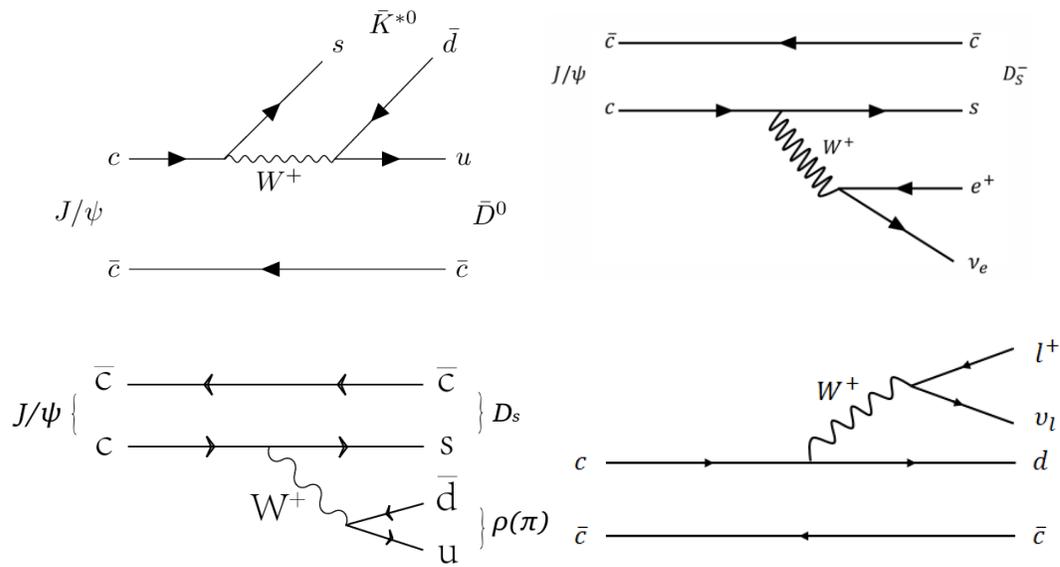
➤ Charmonium weak decays are **allowed in SM**, but with small BF squeezed by the strong and EM decays

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

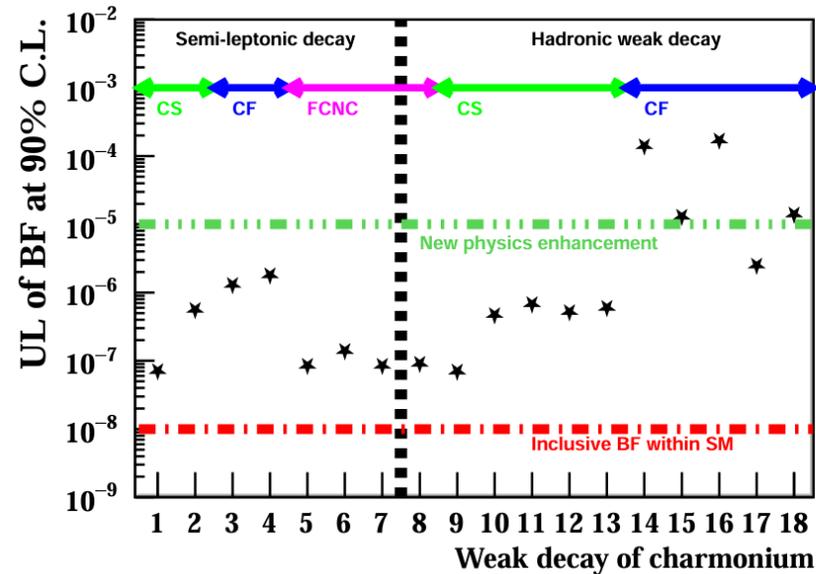
Z. Phys. C 62 271 (1994)

• 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) PRD 15, 1958 (1977)
 PLB 119, 136 (1982) PRD, 60, 014011 (1999)



Hadronic or semi-leptonic



- | | |
|--|--|
| 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: $\psi(2S) \rightarrow \Lambda_c^+ \Sigma_c^- + c.c.$ |

➤ **Current experiment status of the charmonium weak decay**



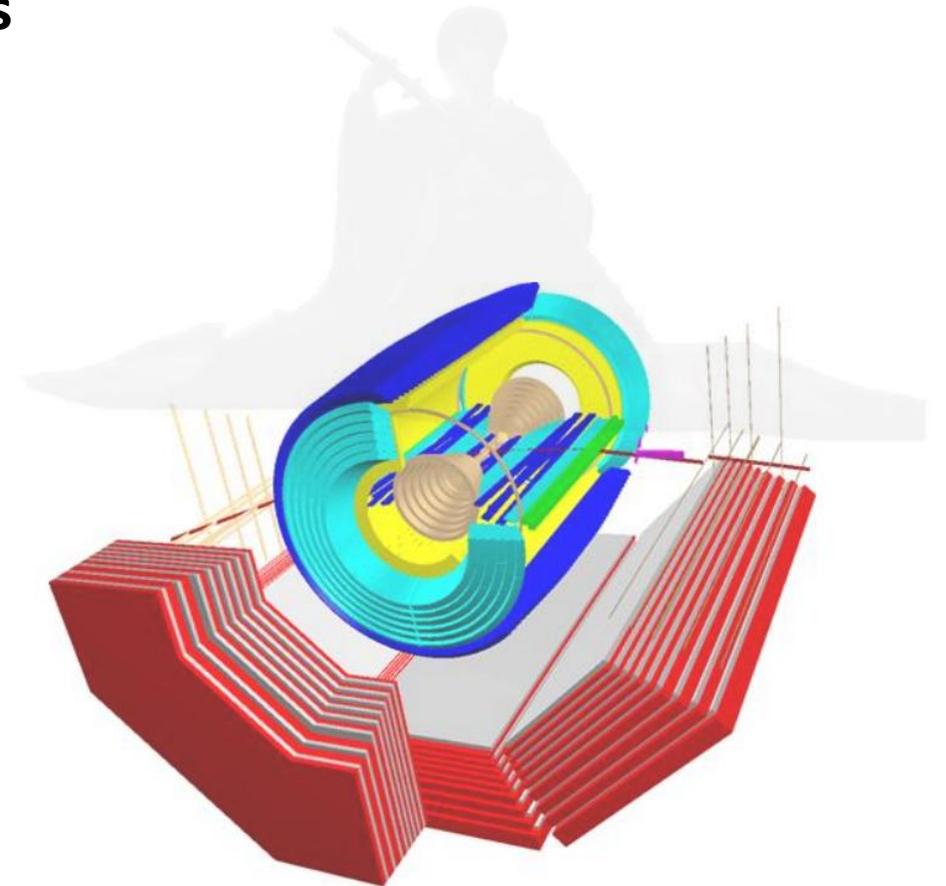
New charmonium weak decay results at BESIII

	$J/\psi \rightarrow D_s^- e^+ \nu_e$	$J/\psi \rightarrow D_s^- \rho^+$	$J/\psi \rightarrow D_s^- \pi^+$	$J/\psi \rightarrow D^0 K^{*0}$	$\psi(2S) \rightarrow D_s^- \rho^+$	$\psi(2S) \rightarrow D_s^- \pi^+$
	Experimental result (BF @90% C.L.)					
D tag (accounting BF)	$D_s^- \rightarrow \text{hads}$ (13%)	$D_s^- \rightarrow \phi e \nu$ (2.4%)	$D_s^- \rightarrow \phi e \nu$ (2.4%)	$D^0 \rightarrow K e \nu$ (3.5%)	$D_s^- \rightarrow \phi e \nu$ (2.4%)	$D_s^- \rightarrow \phi e \nu$ (2.4%)
Previous result	$< 1.3 \times 10^{-6}$	$< 1.3 \times 10^{-5}$	$< 1.3 \times 10^{-4}$	$< 2.5 \times 10^{-6}$	—	—
New result	$< 1.0 \times 10^{-7}$	$< 8.0 \times 10^{-7}$	$< 4.1 \times 10^{-7}$	$< 1.9 \times 10^{-7}$	$< 7.0 \times 10^{-6}$	$< 1.4 \times 10^{-6}$
	Theoretical BF in the SM ($\times 10^{-10}$)					
CLFQ(2024)	$10.21^{+0.89}_{-1.55}$	$29.5^{+2.0}_{-2.5}$	$3.64^{+0.86}_{-1.04}$	—	$12.2^{+4.2}_{-2.2}$	$1.23^{+0.60}_{-0.55}$
QCDSR	$1.8^{+0.7}_{-0.5}$	$12.6^{+3.0}_{-1.2}$	$2.0^{+0.4}_{-0.2}$	$1.54^{+0.68}_{-0.38}$	—	—
BSW	$10.4^{+0.90}_{-0.75}$	$51.1^{+7.6}_{-6.0}$	$7.41^{+0.13}_{-0.23}$	$7.61^{+1.6}_{-1.2}$	—	—
BSM	$3.67^{+0.52}_{-0.44}$	$26.2^{+3.7}_{-3.2}$	$4.75^{+0.67}_{-0.59}$	$4.75^{+0.68}_{-0.58}$	—	—
CLFQ(2008)	5.3 – 5.8	28^{+0}_{-9}	$2.5^{+0.0}_{-0.1}$			
LQCD	1.9 ± 0.08	—	—			
CCQM	3.3	—	—			

SM BF of the Cabibbo-favor decays: $10^{-9} \sim 10^{-10}$
Current experimental sensitivity: $10^{-6} \sim 10^{-7}$
Future: Larger data? New tag method?

Summary

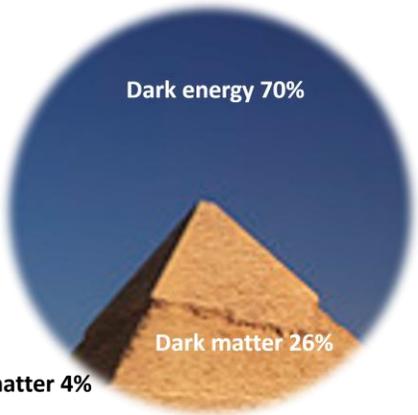
- New results of sub-GeV dark sector and rare decays
 - **Unique stringent constraints on the sub-GeV DM**
 - **First or improved UL on rare processes** of CLFV, BNV, LNV, and charmonium weak decays
- BESIII has collected $10^{10} J/\psi$, $2.7 \times 10^9 \psi'$, 20 fb^{-1} @ 3.77 GeV data ($D\bar{D}$) and more...
- **More & better** results are coming soon



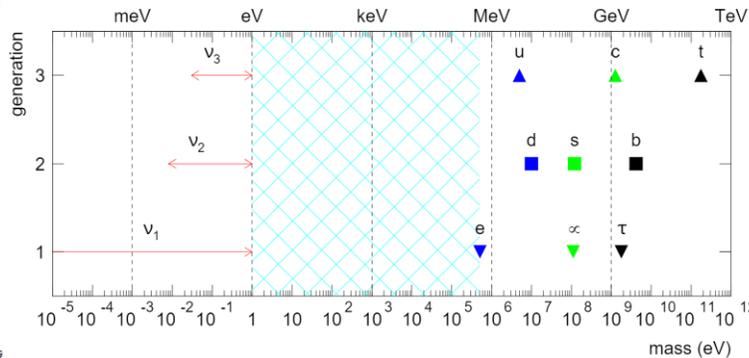
Standard model and Puzzles

Dark Matter
Dark Energy

- SM explains most facts but not all
- More than two dark clouds

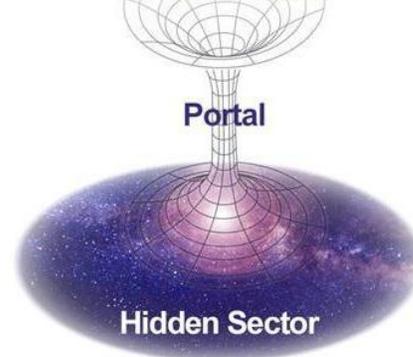


Fermion Mass Hierarchy

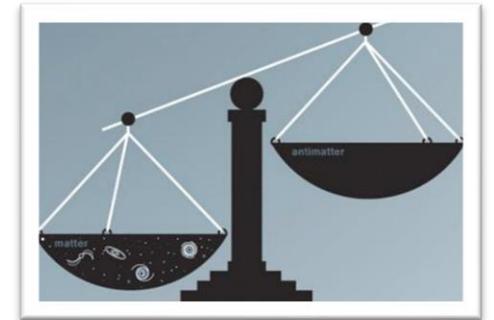


mass →	~2.3 MeV/c ²	~1.275 GeV/c ²	~173.07 GeV/c ²	0	~126 GeV/c ²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u	c	t	g	H
	up	charm	top	gluon	Higgs boson
QUARKS					
	~4.8 MeV/c ²	~95 MeV/c ²	~4.18 GeV/c ²	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d	s	b	γ	
	down	strange	bottom	photon	
LEPTONS					
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	91.2 GeV/c ²	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e	μ	τ	Z	
	electron	muon	tau	Z boson	
	~2.2 eV/c ²	~0.17 MeV/c ²	~15.5 MeV/c ²	80.4 GeV/c ²	
	0	0	0	1	
	1/2	1/2	1/2	1	
	ν_e	ν_μ	ν_τ	W	
	electron neutrino	muon neutrino	tau neutrino	W boson	
					GAUGE BOSONS

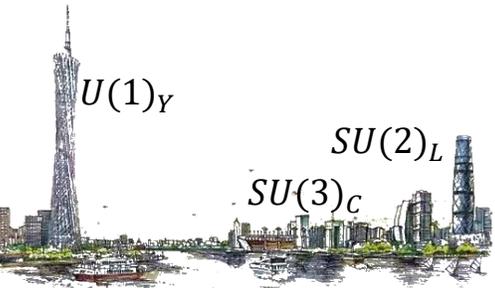
Standard Model



Matter Anti-matter Asymmetry



Strong CP Problem

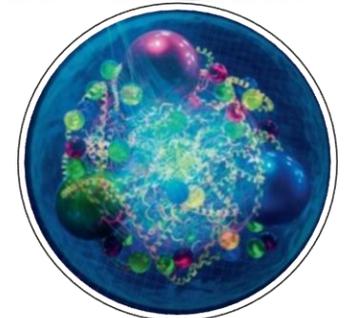


2026/3/18

More ...

Potentials to find new physics

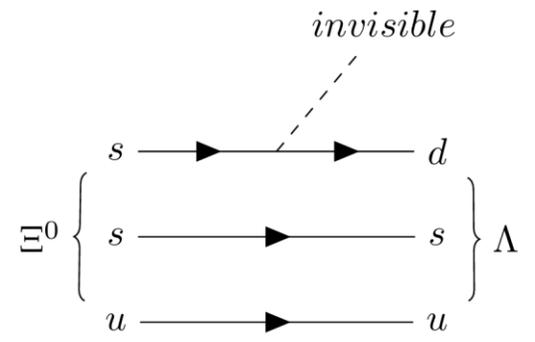
This talk: New dark sector and rare decay results at BESIII





Search for $\Xi^0 \rightarrow \Lambda + \text{invisible}$ at BESIII

- SM decay: $s \rightarrow dv\bar{v}$, FCNC & GIM suppression; $\text{BF} < 10^{-11}$
- Decay to BSM particles (with FCNC coupling)



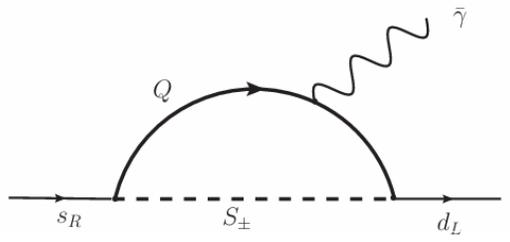
QCD axion a

$$\mathcal{L}_{a-f} = \partial_\mu a \bar{f}_i \gamma^\mu \left(\frac{1}{F_{ij}^V} + \frac{\gamma^5}{F_{ij}^A} \right) f_j$$

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$m_a \ll 1 \text{ eV}$ motivated by

$m_a \propto \frac{1}{F_a}$ with $F_a \gg \text{PeV}$



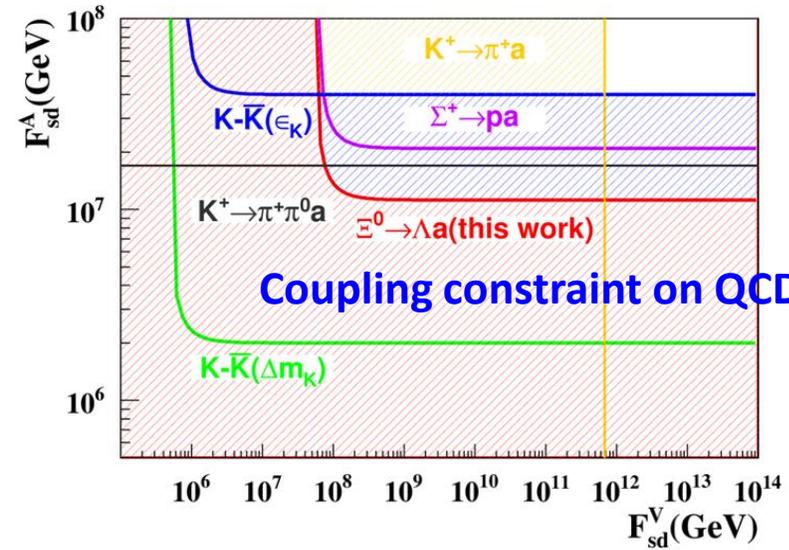
Massless dark photon γ'

$$\mathcal{L}_{\text{NP}} = \frac{1}{\Lambda_{\text{NP}}^2} C_{jk}^D \bar{q}_j \sigma^{\mu\nu} d_k H \bar{F}_{\mu\nu}$$

Allowed BF: 1.2×10^{-4}

Phys.Rev.D 102 (2020) 1, 015023

- $J/\psi \rightarrow \bar{\Xi}^0 \Xi^0$ from $10^{10} J/\psi$ events
 - $\bar{\Xi}^0 \rightarrow \text{SM}, \Xi^0 \rightarrow \Lambda a/\gamma'$
- Deposited energy in EMC used to extract the invisible signal
- $\mathcal{B}(\Xi^0 \rightarrow \Lambda a/\gamma') < 2.3 \times 10^{-4}$ @90% C.L.



Coupling constraint on QCD axion

Competitive constraint on the axial coupling temp F_{sd}^A