Search for dark sector at BESIII

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The 2025 European Physical Society Conference on High Energy Physics
6 - 11 July 2025, Marseille, France

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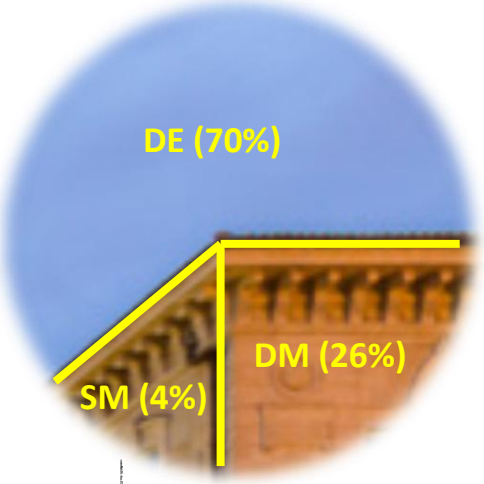
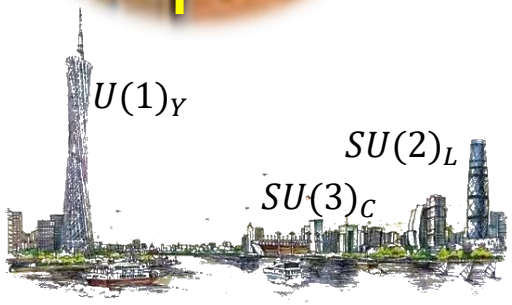
Standard model and Puzzles

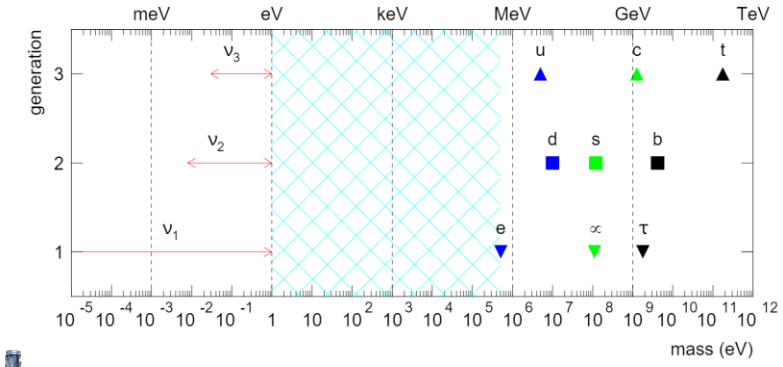
Dark Matter
Dark Energy

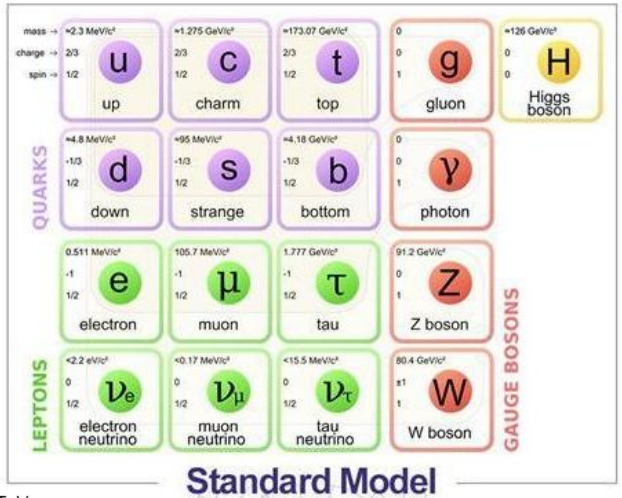
- SM explains most facts but not all
- More than two dark clouds

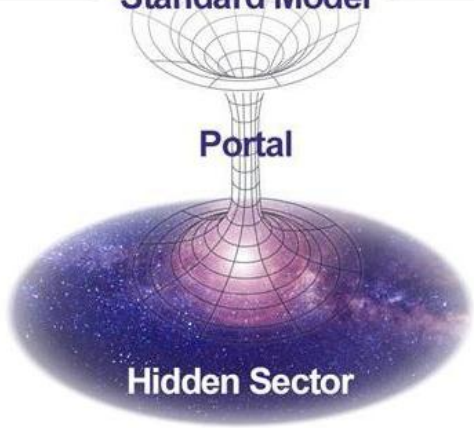




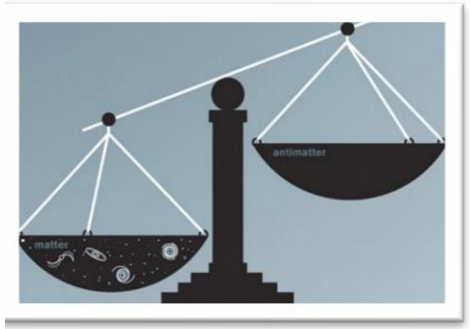
Fermion Mass Hierarchy



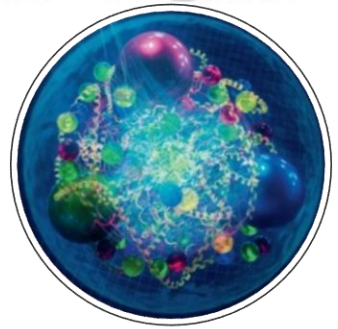




Matter Anti-matter Asymmetry



Strong CP Problem

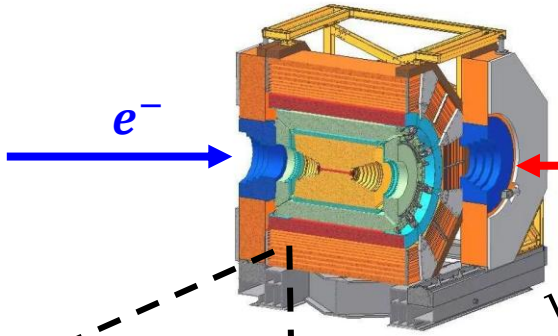


More . . .

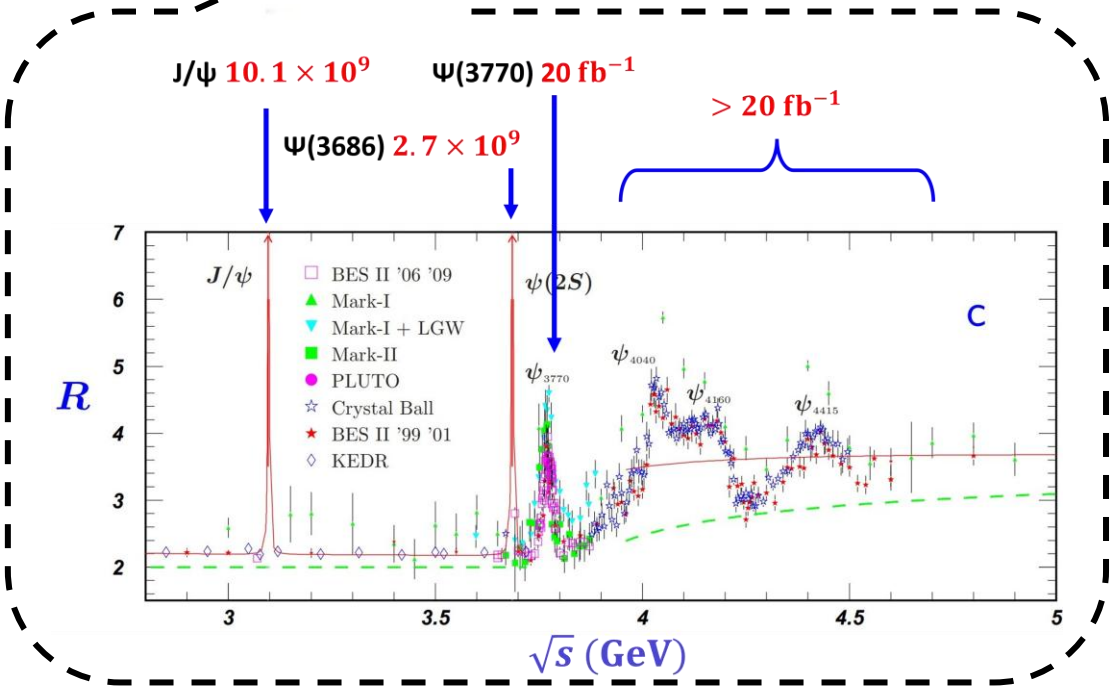
Potentials to find new physics

This talk: New dark sector results at BESIII

BESIII experiment



$\sqrt{s}$: 1.84~4.95 GeV



■ 10.1×10^9 J/ψ events

- Hyperon

Λ $\bar{\Lambda}$

$\Sigma^{0,+}$ $\bar{\Sigma}^{0,-}$ ~10^7

$\Xi^{0,-}$ $\bar{\Xi}^{0,+}$

- Light meson

η η'

ϕ ω ~10^7

K_S^0

■ 20 fb^{-1} $\psi(3770)$ ~10^7

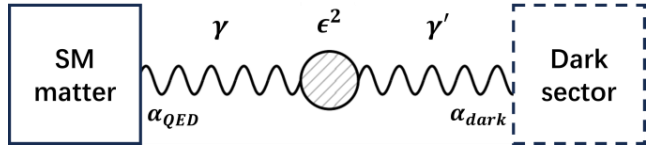
D^0 $\bar{D}^0$ D^+ D^-

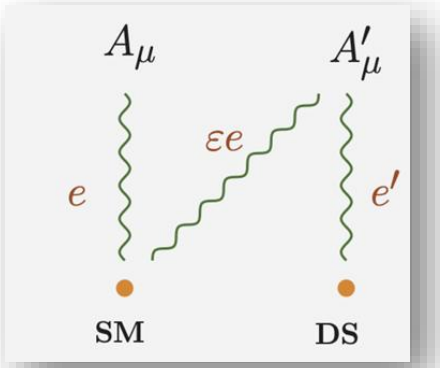
■ ……

➢ Rich physics with clean background

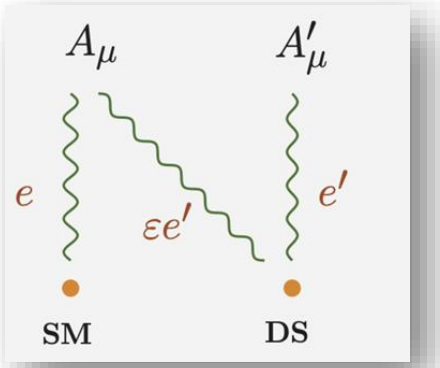
Massless dark photon

Simplest extension of the SM ⟹ An extra Abelian gauge group, $U(1)_D$ ⟹ dark photon





➢ **Massive dark photon**
- **Coupling with SM fermion**
- **Strong constraint**



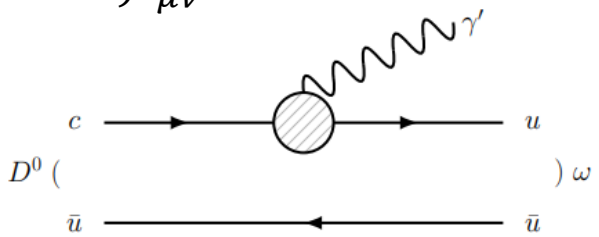
➢ **Massless dark photon**
- **No direct coupling with SM fermion**
- **Less constraint**
- **Also important role in dark sector**

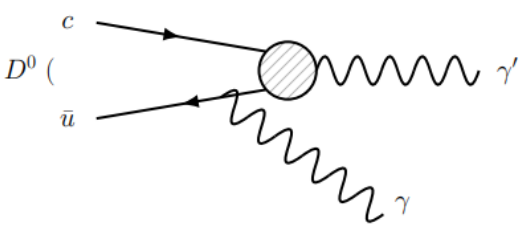
Searching for the massless case can only be in the higher dimension operator:

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

PRL 94, 151802 (2005)

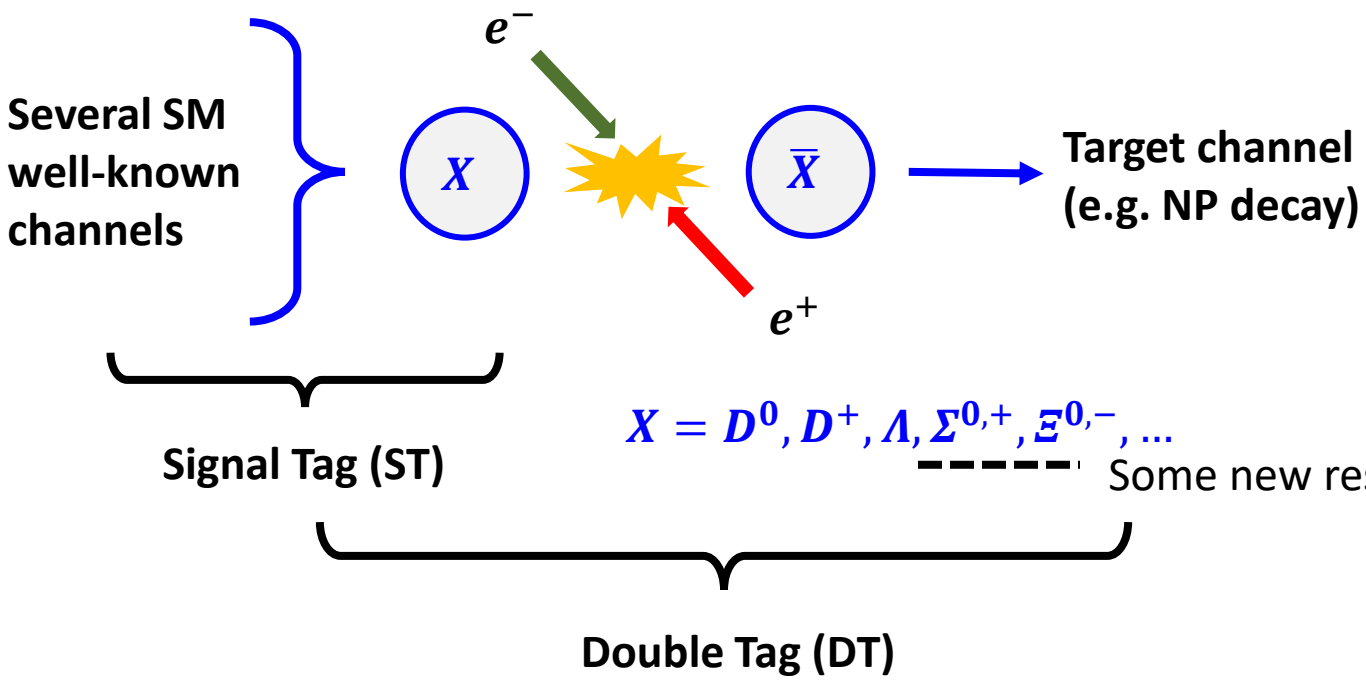
➢ **Naturally allow the FCNC coupling**
- **Less background and higher sensitivity**

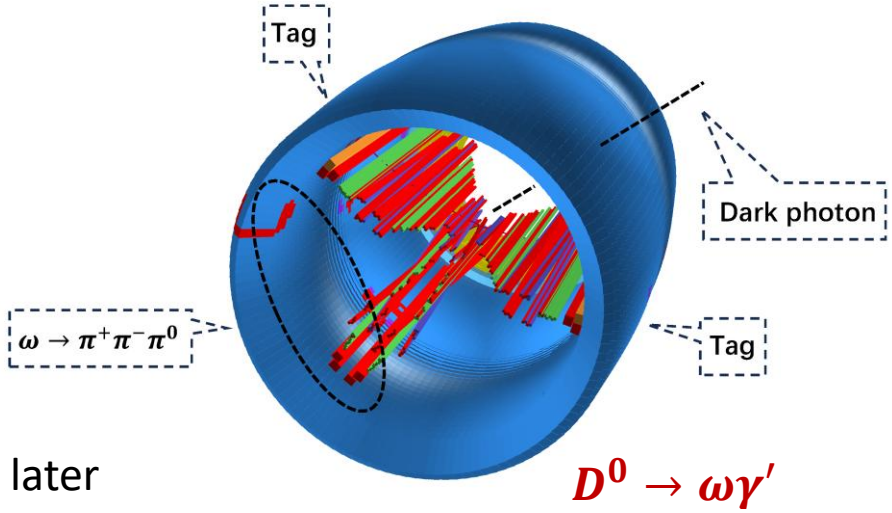


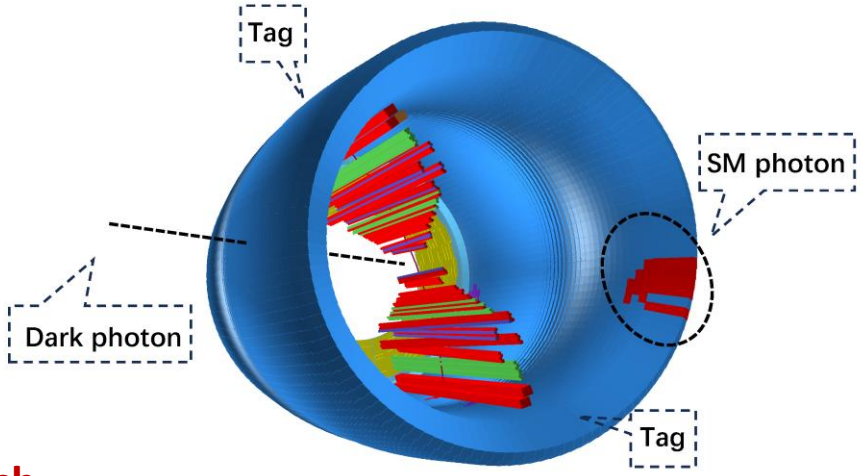


New searches at BESIII: through $cu\gamma'$ coupling in $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$

Double tag analysis at BESIII





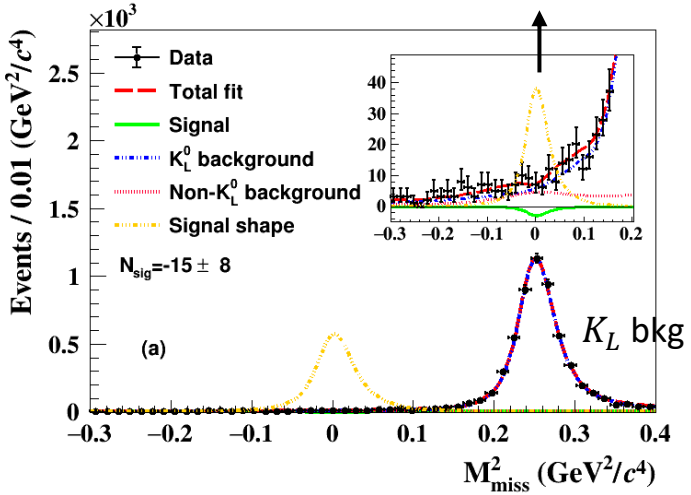


- Measure absolute branching fraction, $\mathcal{B} = \frac{N_{DT}/\epsilon_{DT}}{N_{ST}/\epsilon_{ST}}$
- Clean background
- Recoil missing particle, such as invisible particle
- Cancel systematic uncertainty

Active in dark sector search

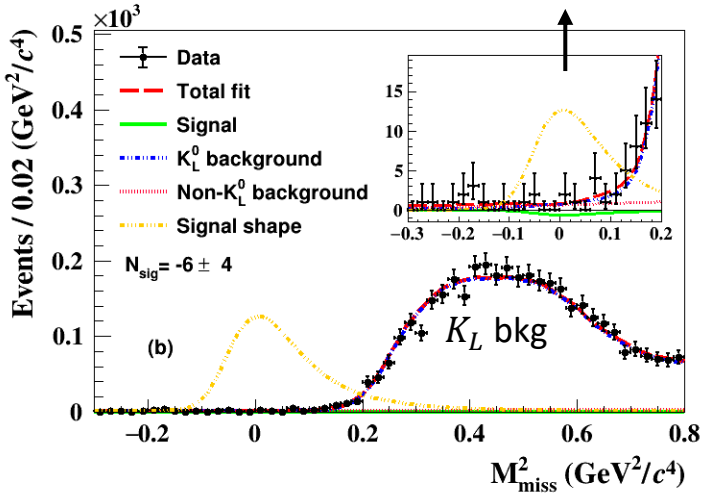
Search for $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$ at BESIII

Signal should peak at zero

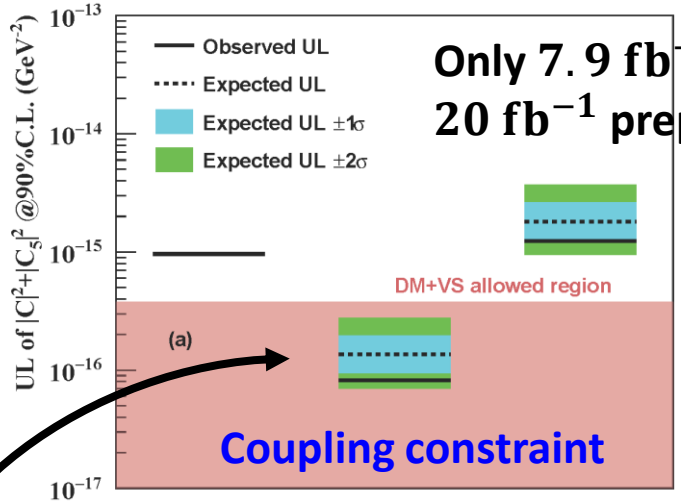


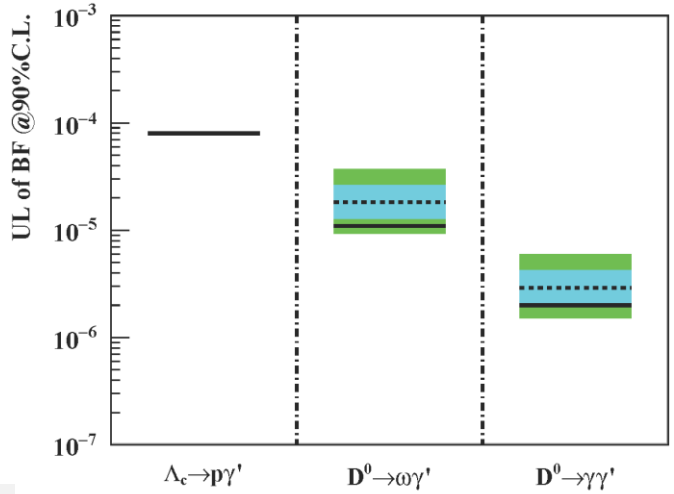
Signal extraction of $D^0 \to \omega\gamma'$

Signal should peak at zero



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





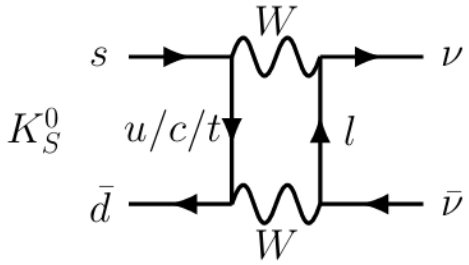
- **First search** for massless dark photon in D meson decay
- The constraint from $D^0 \to \omega\gamma'$ goes into the dark matter (DM) and vacuum stability (VS) allowed region for the first time, **improved by more than 1 order**

Phys.Rev.D 111 (2025) 1, L011103

K_S invisible decay

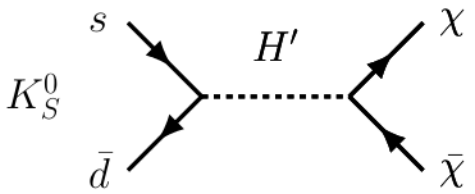
Invisible decay of K_S^0

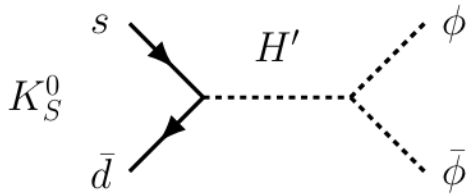
- **SM decay**



$BF < 10^{-16}$
FCNC && Helicity suppression
Phys.Rev.D 91 (2015) 1, 015004

- **Decay to DM**





2HDM model
$BF \sim \mathcal{O}(10^{-6})$
Natural Sci.Rev. 1 (2024) 5

- **Ordinary-mirror particle oscillations**

$K_S^0 \dashrightarrow K_S^{0\prime}$

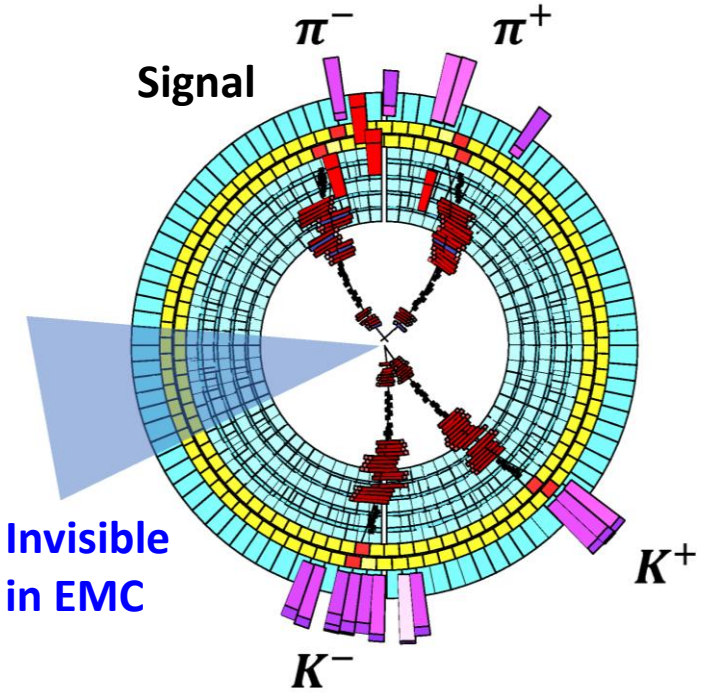
Mirror matter model
$BF \sim \mathcal{O}(10^{-6})$
arXiv: 2006.10746

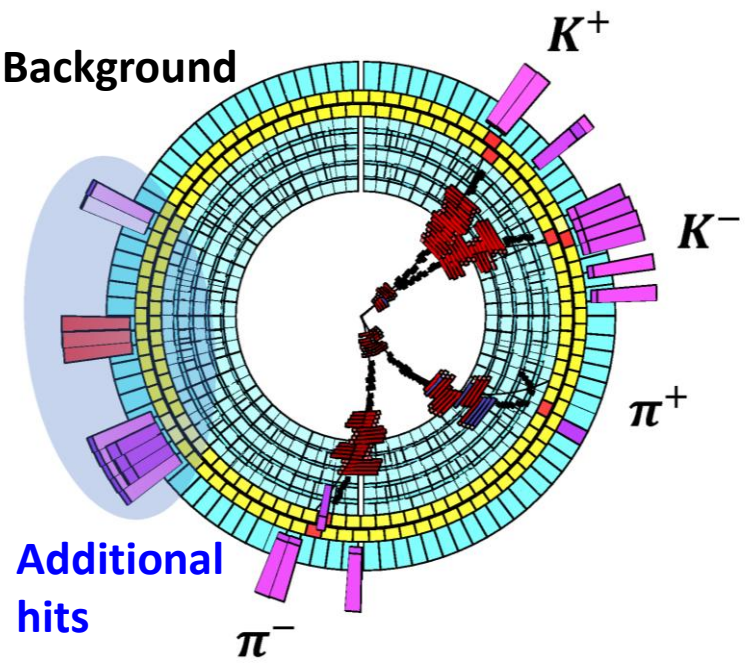
- **Input for CPT test**

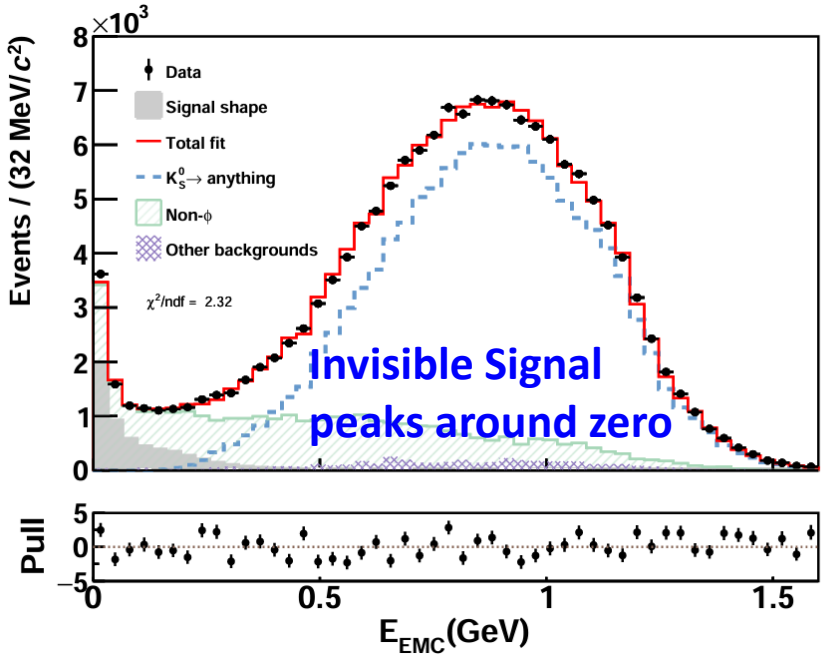
Bell-Steinberger relation **connects CPTV** to the amplitudes of all decay channels of neutral kaons.
BUT currently assumes no invisible modes

Phys.Rev.D 91 (2015) 1, 015004

Search for $K_S \to$ invisible at BESIII







- Using the deposited energy in EMC to identify the invisible signal
- An alternative method for invisible signal search at BESIIII

- $J/\psi \to \phi K_S^0 K_S^0$ from $\mathbf{10^{10}}$ J/ψ
- $N_{\rm sig} = 56 \pm 201$
- $\mathcal{B}(K_S^0 \to \text{invisible}) < 8.4 \times 10^{-4}$ @90% C.L.

First direct measurement of $K_S^0 \to$ invisible; the UL still lies above the NP prediction

JHEP 05 (2025) 092

Dark baryon

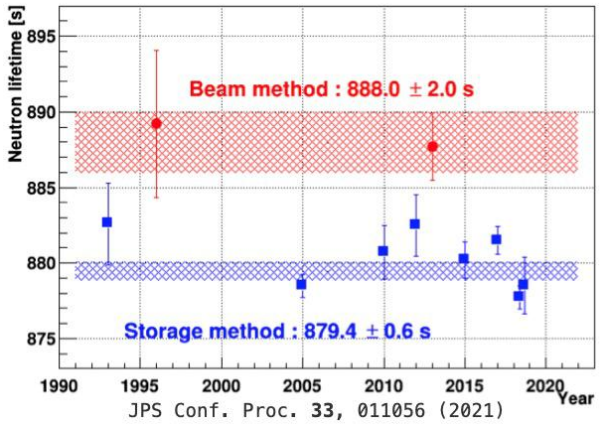
Coincidence problem

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 have non-zero baryon number**

Neutron lifetime puzzle



$$\tau_n^{\text{beam}} = \frac{\tau_n^{\text{bottle}}}{\text{Br}(n \to p + \text{ anything })}$$

$\mathcal{B}(n \to \text{dark}) \sim 1\%$

- **Motivates the existence of dark baryon**

B-Mesogenesis mechanism

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

- **Explain matter anti-matter asymmetry**
- **The origin of the dark matter**

Naturally, dark baryon interacts with all SM quark flavor

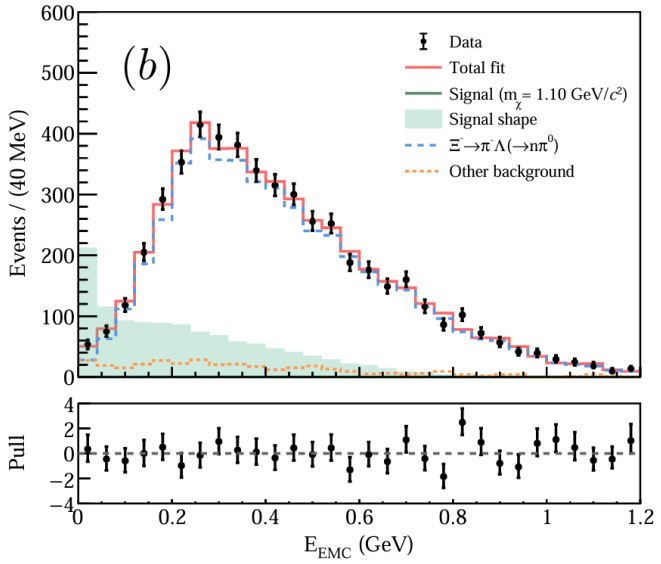
$\Longrightarrow$ **Search for dark baryon in hyperon decay at BESIII**

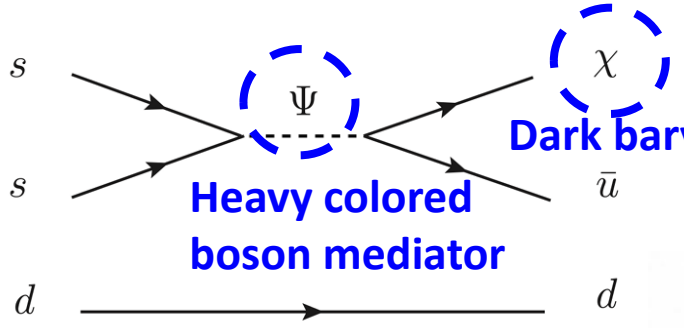
Search for $\Xi^- \to \pi^- \chi$ at BESIII

- $J/\psi \to \bar{\Xi}^+ \Xi^-$ from 10^{10} J/ψ

- Double tag method
- Dark baryon χ with mass hypothesis of 1.07, 1.10, m_Λ, 1.13, 1.16 GeV

- Deposited energy in EMC used to extract the invisible signal

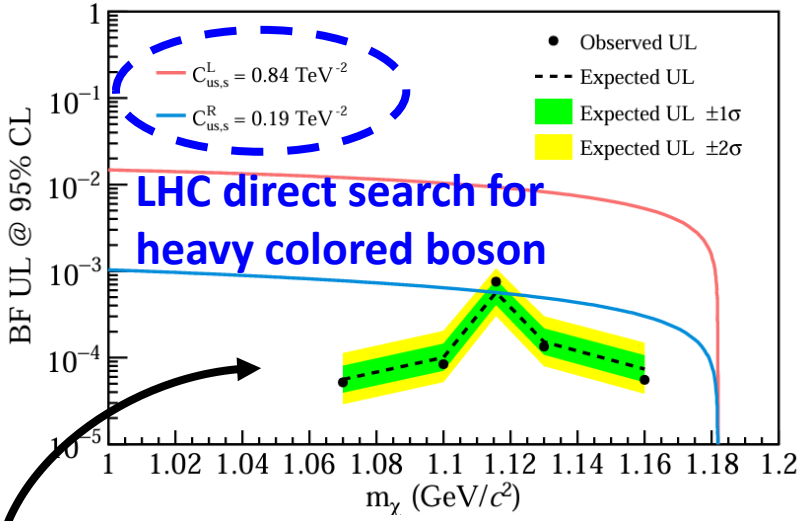


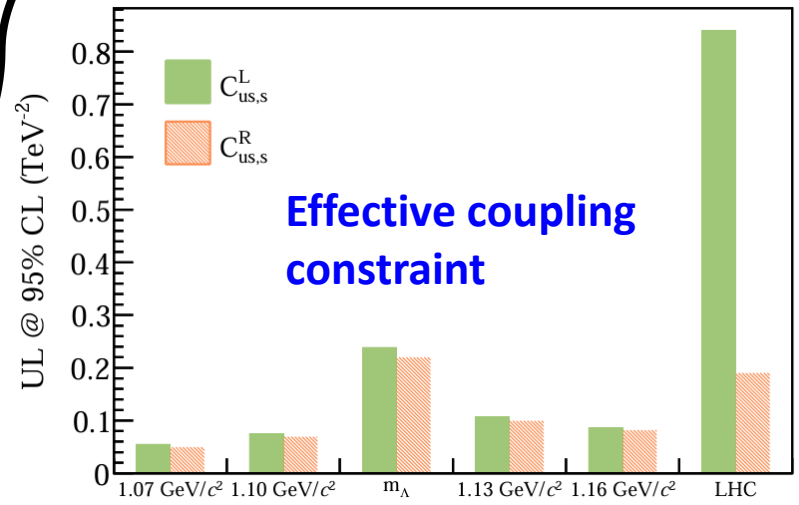


Heavy colored boson mediator

Dark baryon

- Better effective coupling constraints

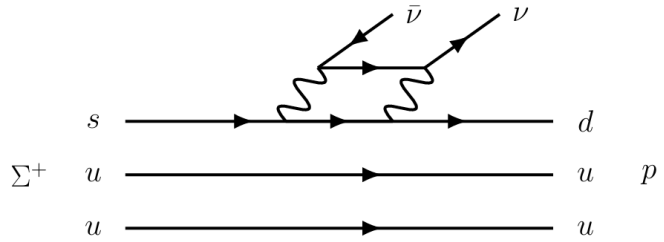




arXiv: 2505.22140

$\Sigma^+ \to p +$ invisible and QCD axion

SM decay



- $s \to d\nu\bar{\nu}$, **FCNC && GIM suppression**
- **BF** $< 10^{-11}$

Phys.Rev.D 94 (2016) 11, 115013

Decay to BSM particles

- **Solution to strong CP problem**
- An excellent **dark matter**
- $m_a \sim g \sim \frac{1}{F_a} \Longrightarrow m_a \ll 1$ **eV**;

g: coupling strength;
F_a: decay constant

➢ Naturally allow the FCNC coupling

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

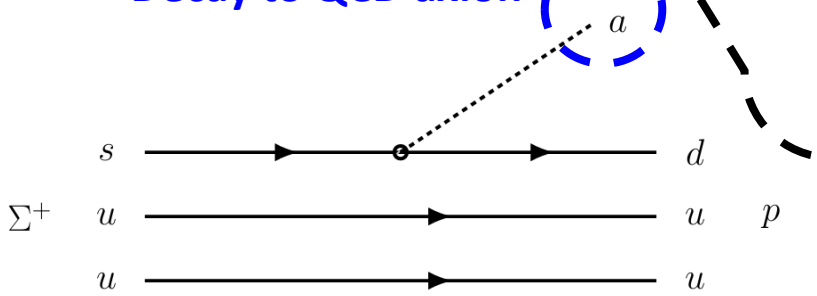
Vector coupling **Axial coupling**

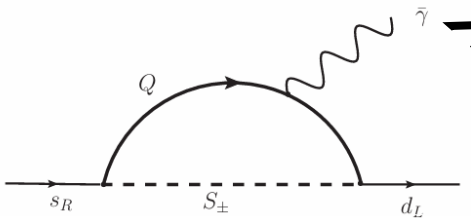
sensitive $K^+ \to \pi^+ a$

Both sensitive

Hyperon decay

Decay to QCD axion





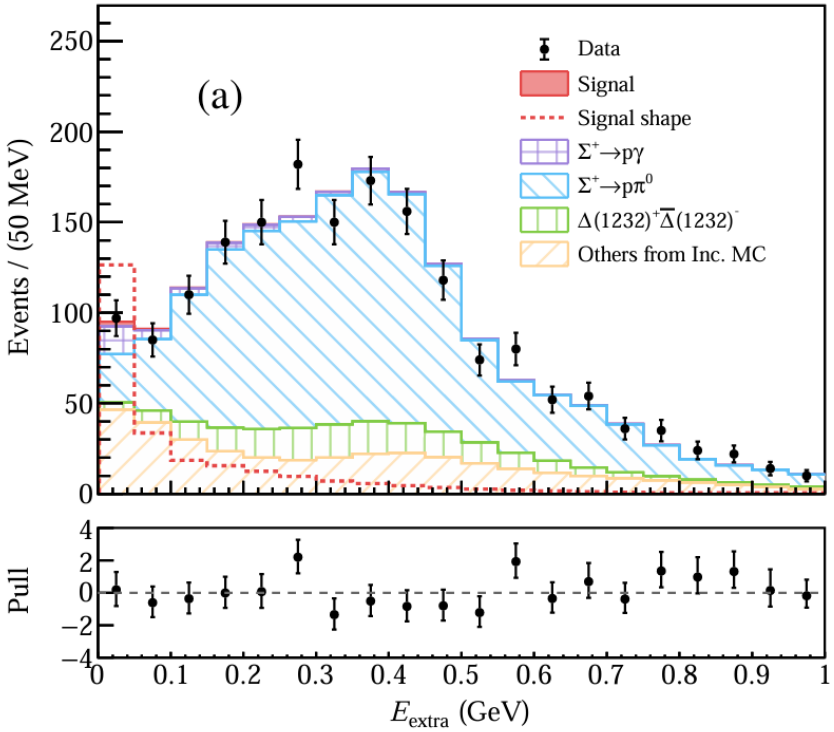
- Can also **Decay to massless dark photon**
- Maximum allowed BF $\sim 3.8 \times 10^{-5}$

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

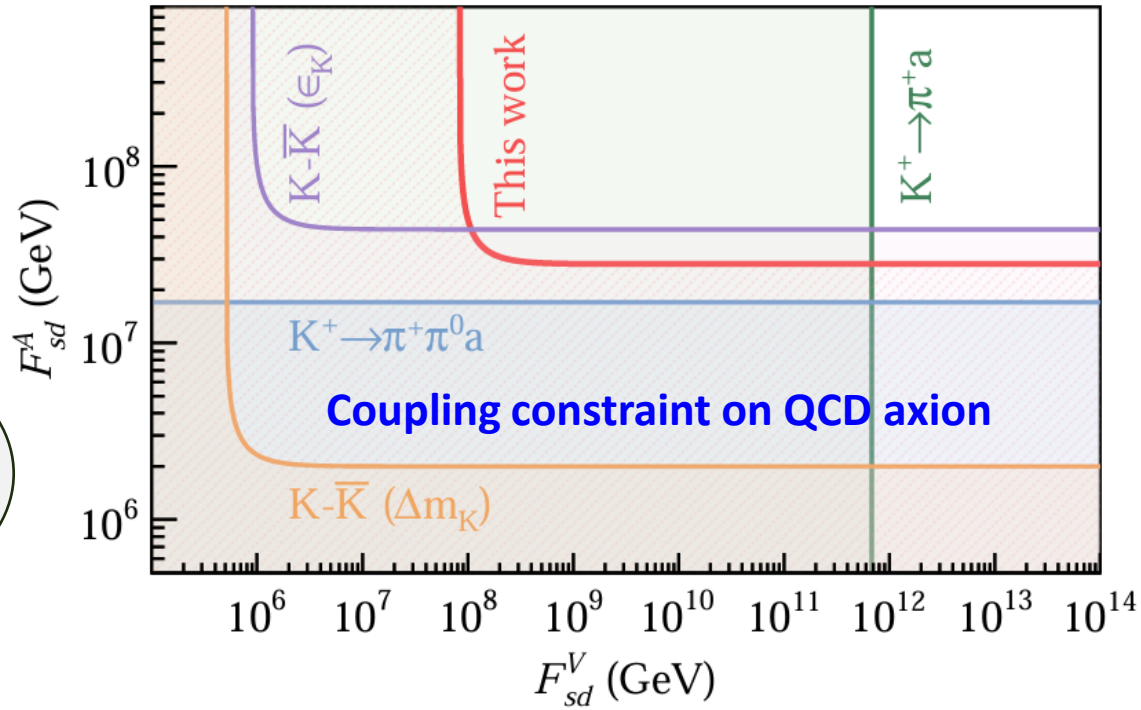
Search for $\Sigma^+ \to p +$ invisible at BESIII

- $J/\psi \to \Sigma^+\bar{\Sigma}^-$ from 10^{10} J/ψ
- Double tag method

- Invisible particle with mass hypothesis of zero
- Deposited energy in EMC used to extract the signal



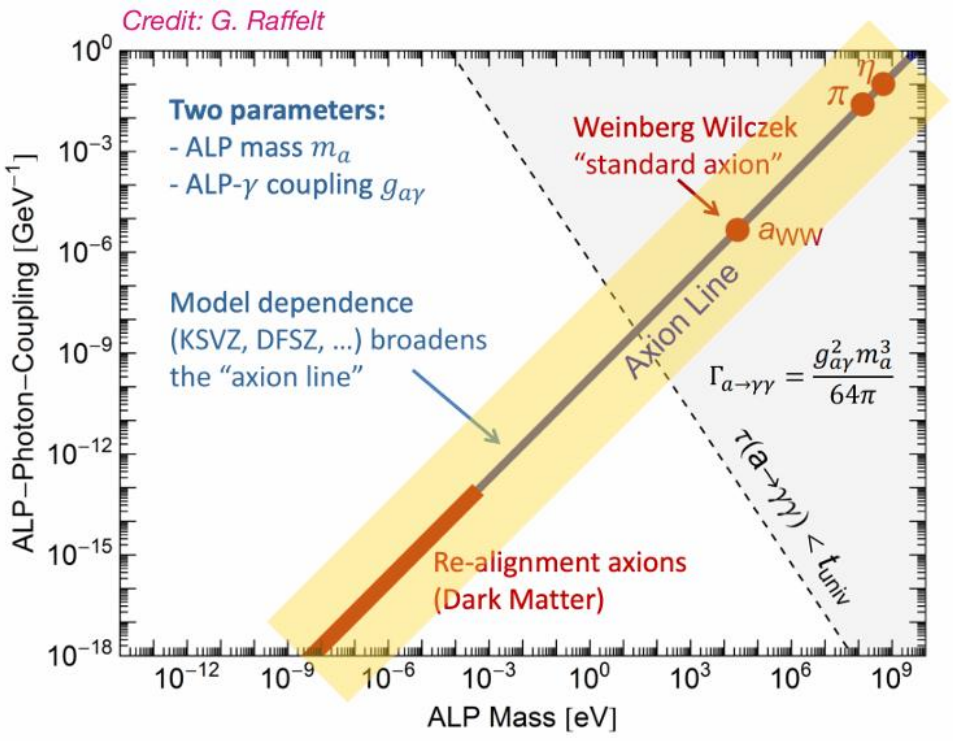
$\mathcal{B}(\Sigma^+ \to pa) < 3.2 \times 10^{-5}$ @90% C.L.



- Competitive constraint on the axial coupling temp F^A_{sd} of QCD axion
- The BF UL lies below the maximum allowed BF of massless dark photon decay (3.8×10^{-5})

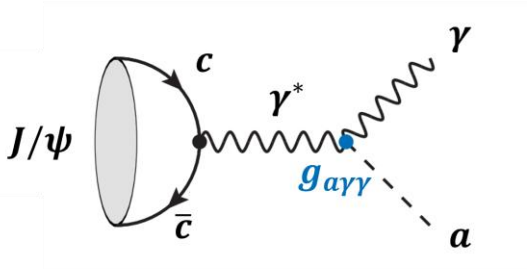
Phys.Lett.B 852 (2024) 138614

Axion-like particle



➢ **Axion-like particle (ALP)**
- Similar to QCD axion
- **arbitrary masses and couplings**

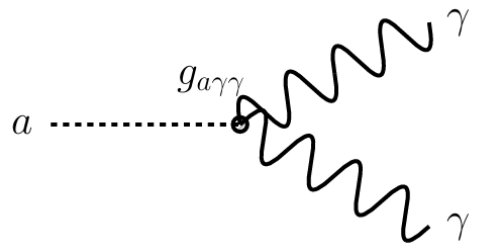
➢ **Considering the ALP-photon interaction**
- $\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$ JHEP 06 (2019) 091



- **Produced from heavy photon**

$$\frac{\mathcal{B}(J/\psi\to\gamma a)}{\mathcal{B}(J/\psi\to e^+e^-)} = \frac{m_{J/\psi}^2}{32\pi\alpha} g_{a\gamma\gamma}^2 \left(1-\frac{m_a^2}{m_{J/\psi}^2}\right)^3$$

$$\Longrightarrow \mathbf{BF}\sim g_{a\gamma\gamma}^2$$



- **Decay to di-photons**

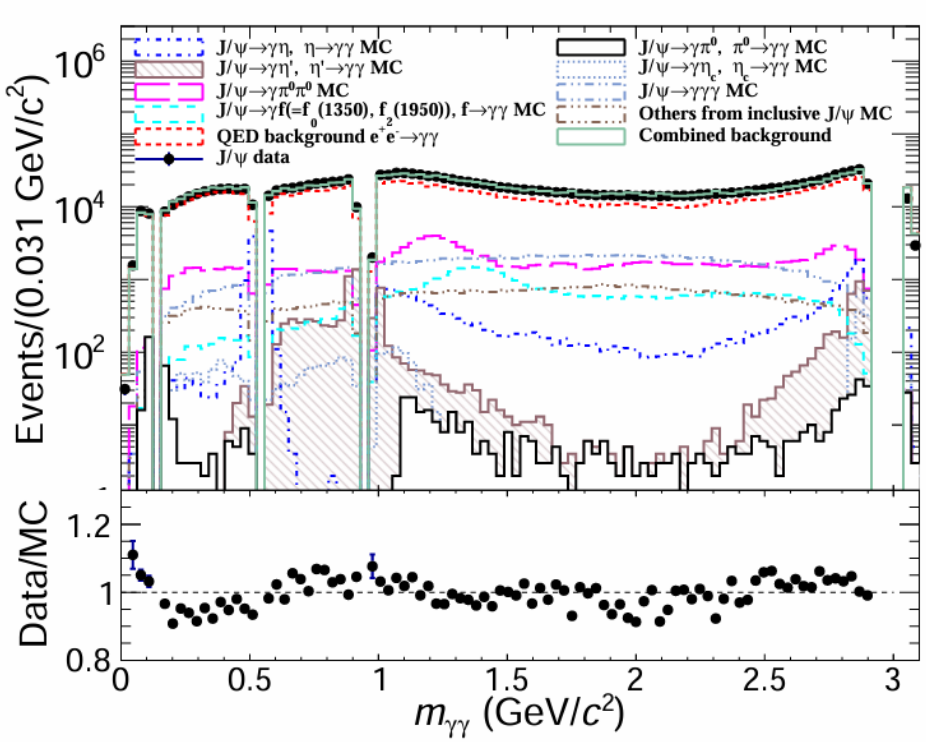
$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

$g_{a\gamma\gamma}\sim 10^{-4}$ GeV^{-1}, $m_a\sim$GeV

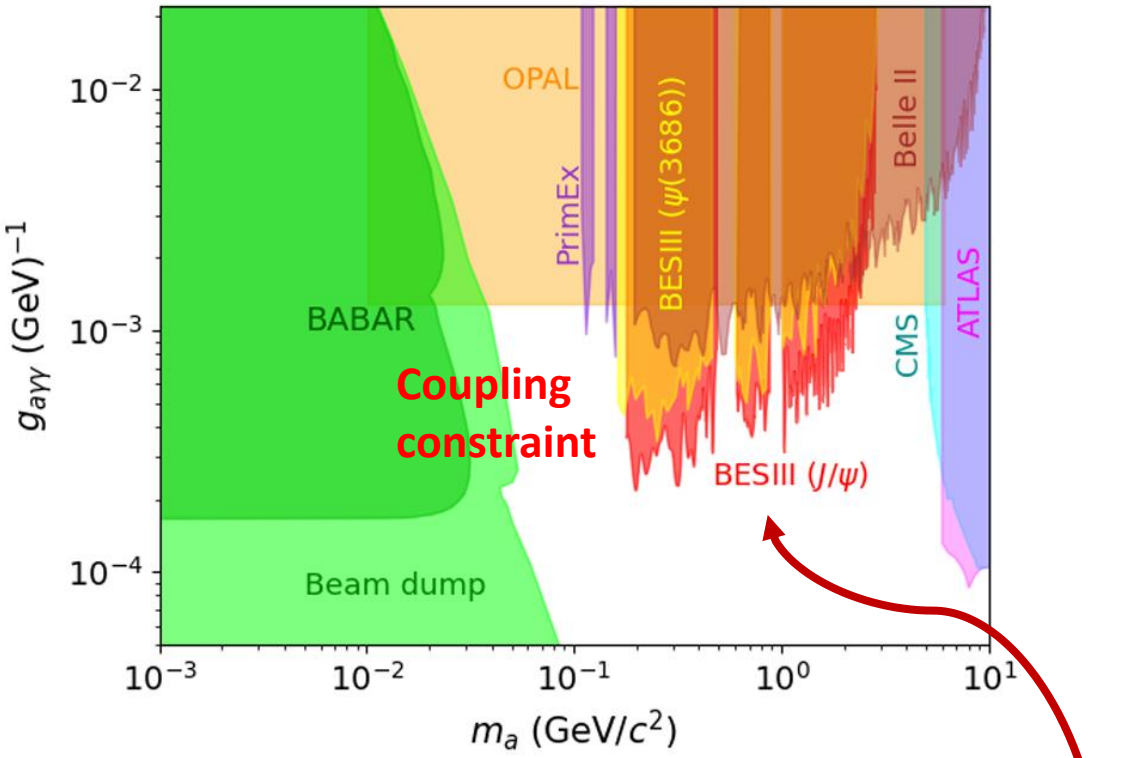
$\Longrightarrow$ **short-lived**

New searches for ALP at BESIII: $J/\psi \to \gamma a, a \to \gamma\gamma$

Search for $J/\psi \to \gamma a_{\gamma\gamma}$ at BESIII



- 10^{10} J/ψ events
- Extract signal from $M_{\gamma\gamma}$ distribution
- Maximum signal significance: $< 3\sigma$

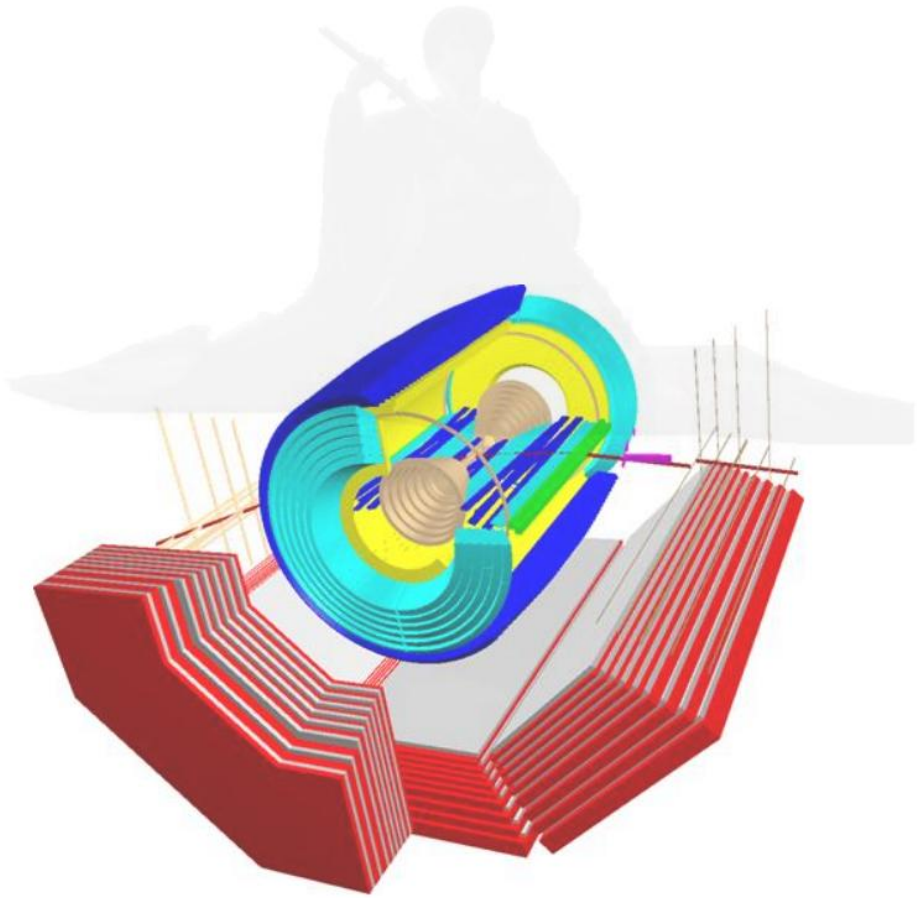


- UL on the BF of $\mathcal{B}(J/\psi \to \gamma a) \times \mathcal{B}(a \to \gamma\gamma)$ $(3.6 \sim 53.1) \times 10^{-8}$ @ 90% C.L.
- New stringent constraints on ALP-photon coupling for $0.18 \leq m_a \leq 2.85$ GeV

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

Summary

- New results of dark photon, dark baryon, axion and K_S^0 invisible decay at BESIII
- No evidence and New stringent constraint on NP
- 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

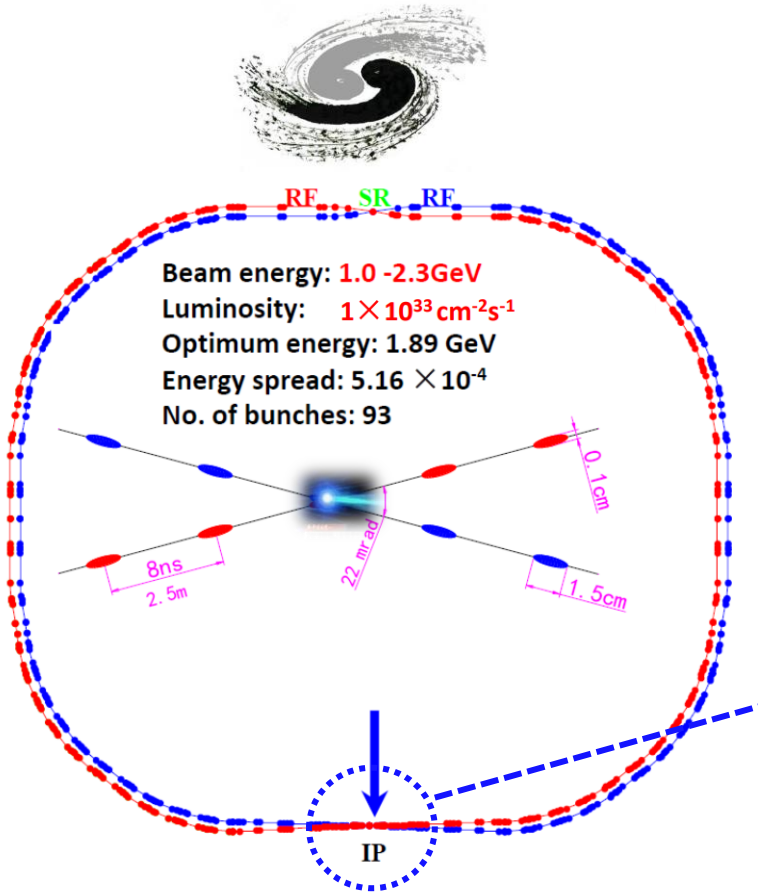


The future of Dark Sector is Bright !

THANK YOU

Appendix

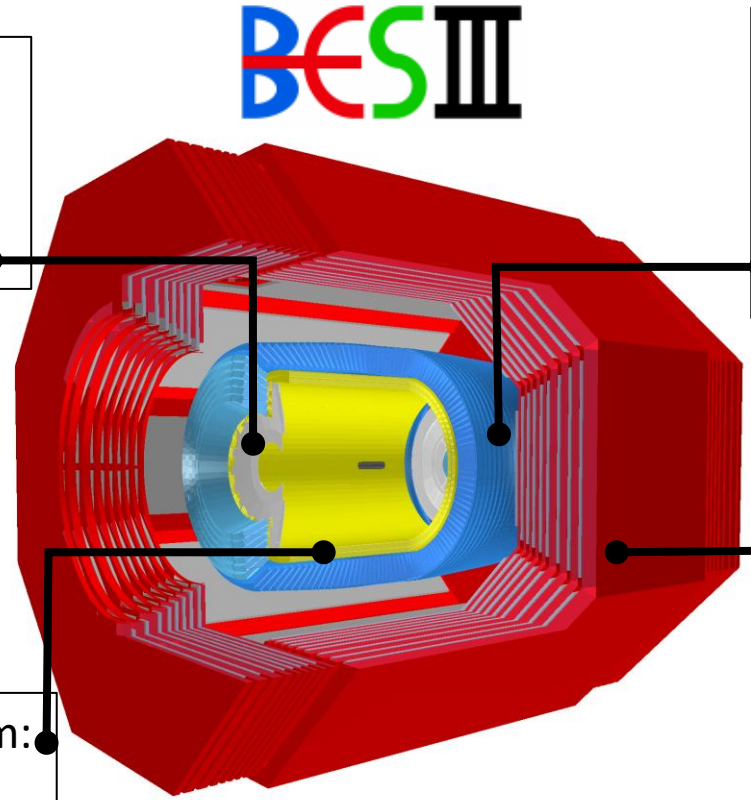
BEPCII and BESIII



✓ **B**eijing **E**lectron **P**ositron **C**ollider **II**

Multilayer **D**rift **C**hamber:
Δp/p=0.5% @ 1GeV
dE/dx: ~6%

Electro**M**agnetic **C**alorimeter:
CsI(Tl) 2.5%(5.0%)
Barrel(endcap)
@ 1GeV



e^+

e^-

Time-**O**f-**F**light system:
σT=68(60)ps
barrel(endcap)

MUon **C**hamber:
RPC 9(8) layers
barrel(endcap)

✓ **BE**ijing **S**pectrometer **III**

BESIII has collected large data samples in $\tau - c$ energy region which can benefit the search for the hidden dark sector

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

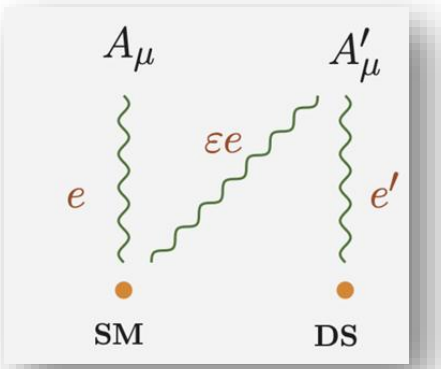
PRL 94, 151802 (2005)

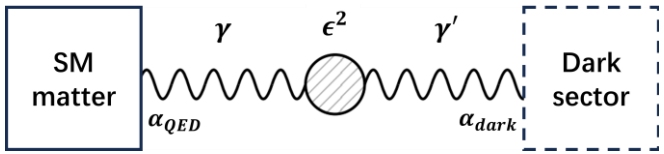
$$A^\mu \to A^\mu + \epsilon A'^\mu$$
$$\mathcal{L} = eJ_\mu A^\mu + e\epsilon J_\mu A'^\mu + e' J'_\mu A'^\mu$$

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

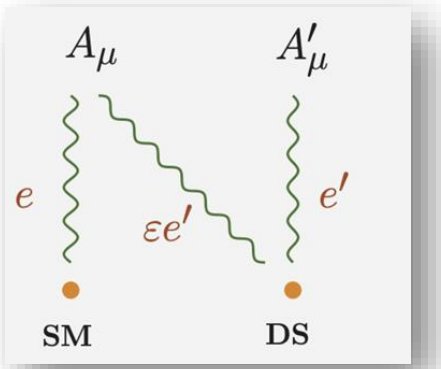
$$A'^\mu \to A'^\mu + \epsilon A^\mu$$
$$\mathcal{L} = eJ_\mu A^\mu + e'\epsilon J'_\mu A^\mu + e' J'_\mu A'^\mu$$

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





A portal to connect the SM matter and the dark sector

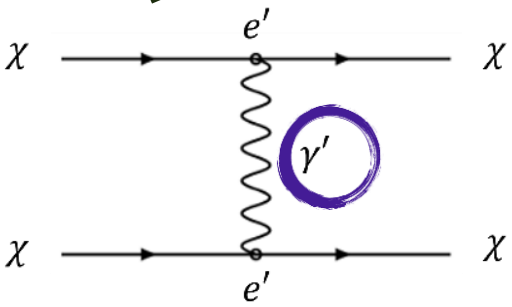


Massless dark photon has no interaction with the SM matter in the dimension-4 operator

arXiv:2005.01515

Role of the massless dark photon

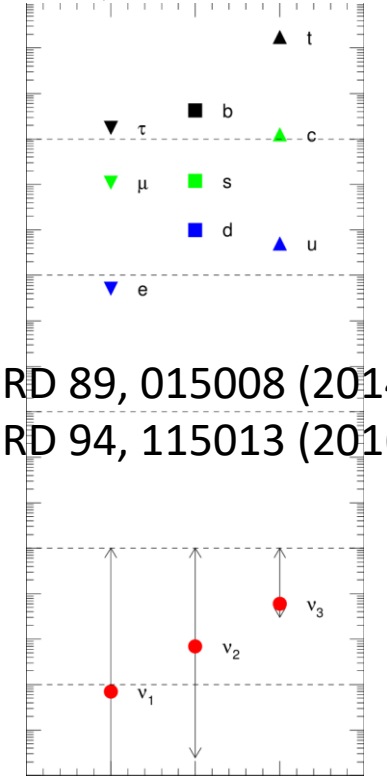
Provide a new long-range force of the DM



⟼ Explain the galaxy formation and dynamics

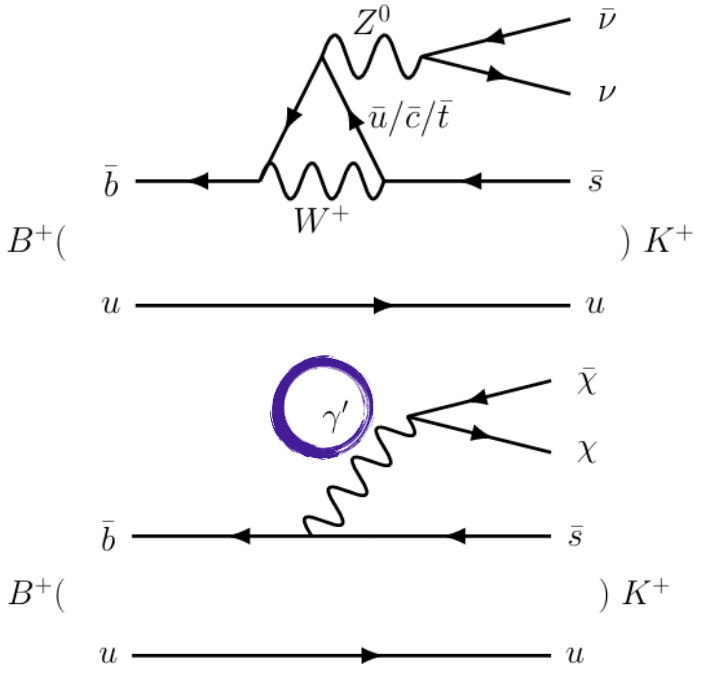
Phys.Rev.D 79 (2009) 023519
Phys.Rev.D 91 (2015) 023512
Phys.Lett.B 749 (2015) 236-241
JCAP 05, 022 (2017)
Phys.Rev.D 102 (2020) 8, 083009

Solution to the Fermion mass hierarchy



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

Explain excess 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 γ'

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

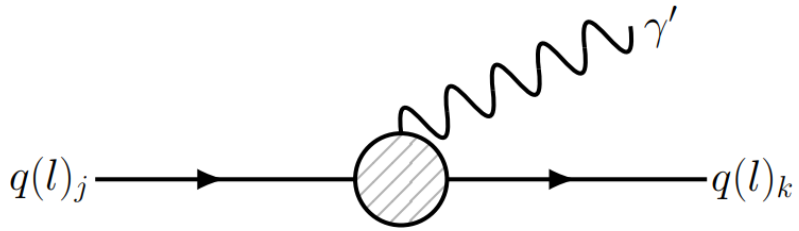
Down type quarks coupling

Charged leptons coupling

Massless dark photon

Λ_{NP}: New physics energy scale

C_{jk}^{i}: Dimensionless coefficient



Experimental search:

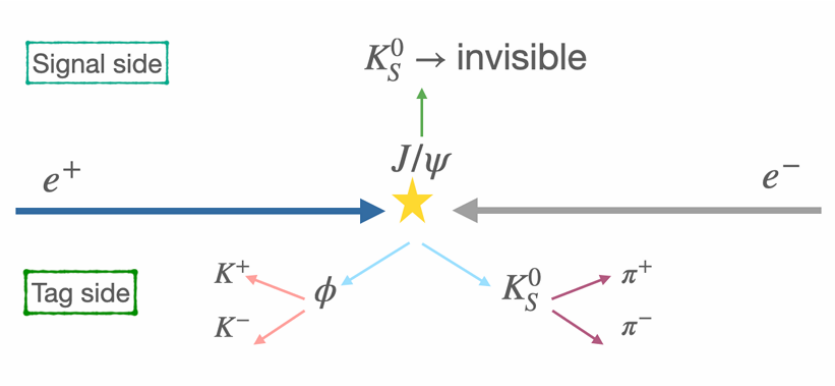
- $H \to \gamma\gamma'$
- $\mu \to e\gamma'$
- $\Lambda_c^+ \to p\gamma'$

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

Analysis strategy

K_S^0 source

$J/\psi \to \phi K_S^0 K_S^0$ from $(10087 \pm 44) \times 10^6$ J/ψ

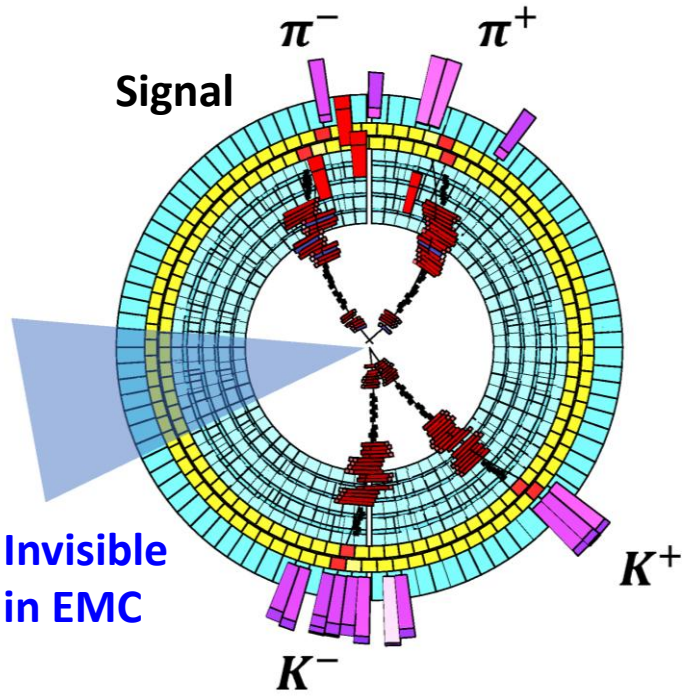


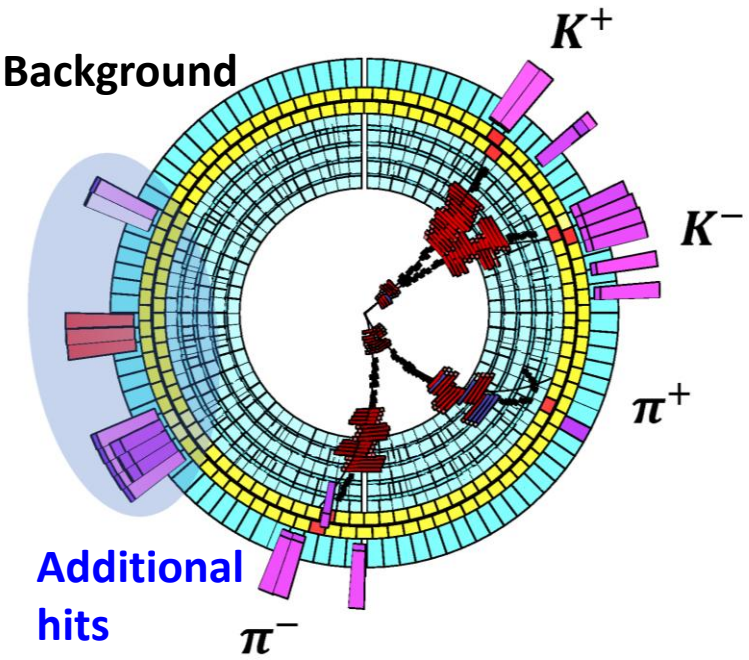
Why this channel?

- $J/\psi \to \phi K_S^0 K_L^0$ is forbidden with C Parity conservation, **lower background**
- But still have $J/\psi \to K^+K^-K_S^0K_L^0$

JHEP 05 (2025) 092

Signal feature

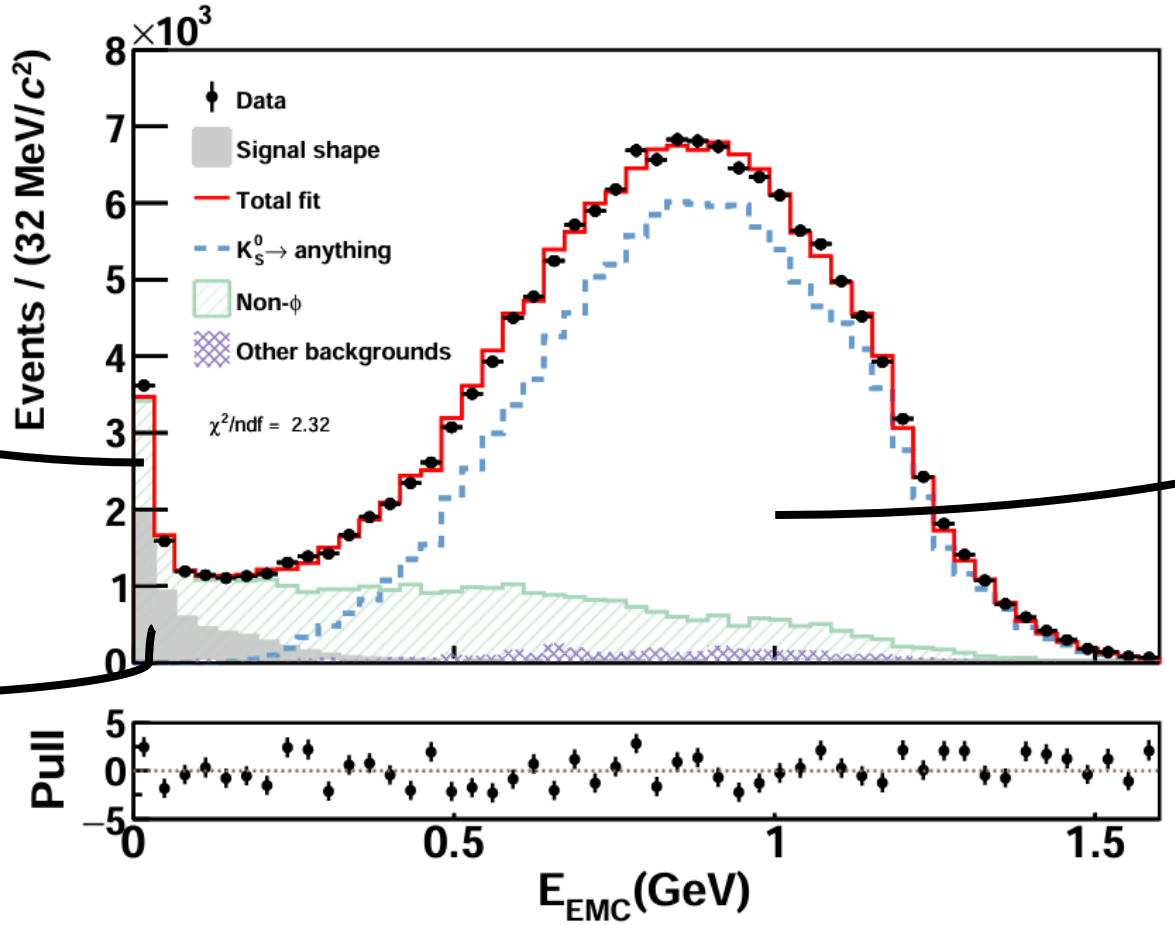




Using the deposited energy in EMC to identify the invisible signal

Signal extraction

$J/\psi \to K^+K^-K_S^0K_L^0$ peaking background shape from ϕ sideband



Other background modeled with MC simulation, such as $K_S^0 \to \pi^0\pi^0$

Invisible Signal peaks around zero

$N_{sig} = 56 \pm 201$

$\mathcal{B}(K_S^0 \to \text{invisible}) < 8.4 \times 10^{-4}$ (90% C.L.)

JHEP 05 (2025) 092

First direct measurement of $K_S^0 \to$ invisible; the UL still lies above the NP prediction