Dark matter study at BESIII

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2026年紫金山暗物质研讨会 新疆·乌鲁木齐

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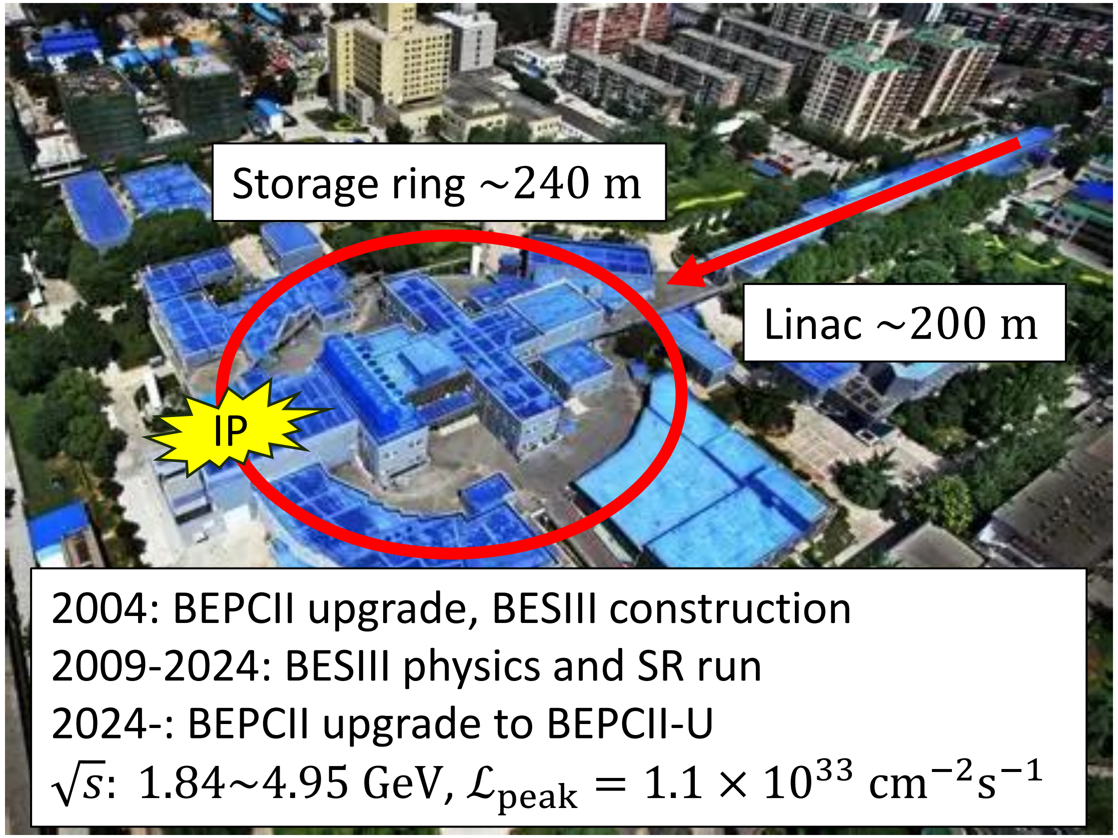
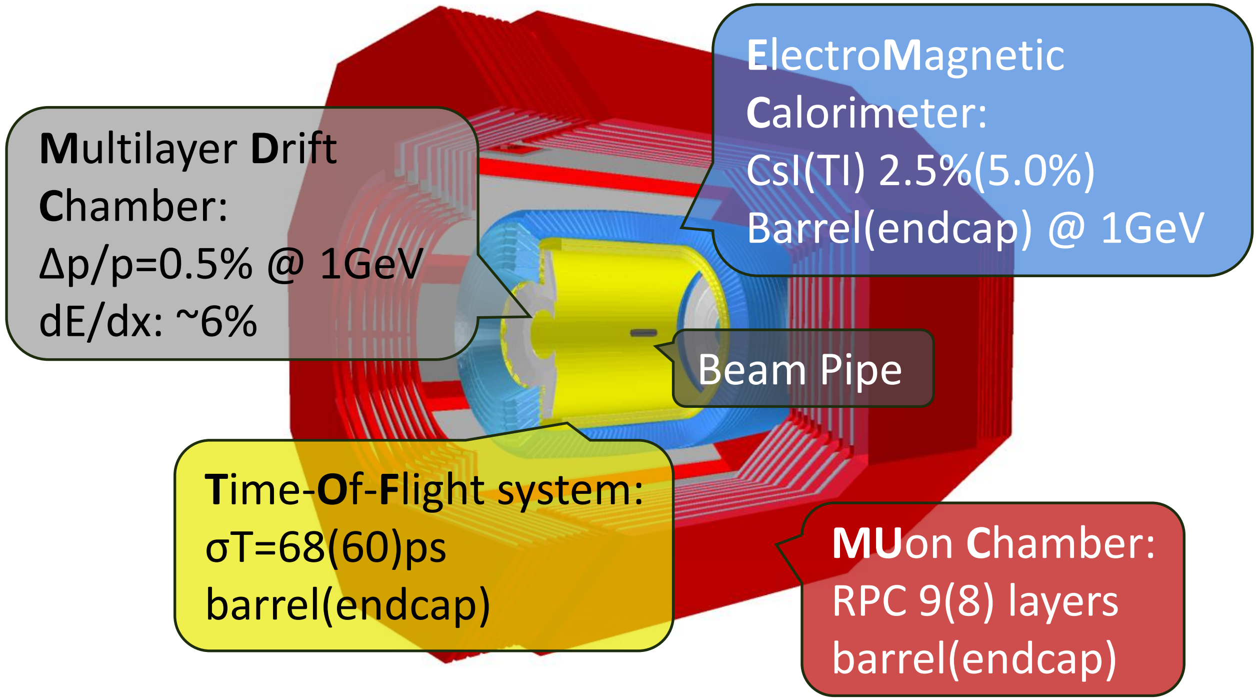
BEPCII and BESIII

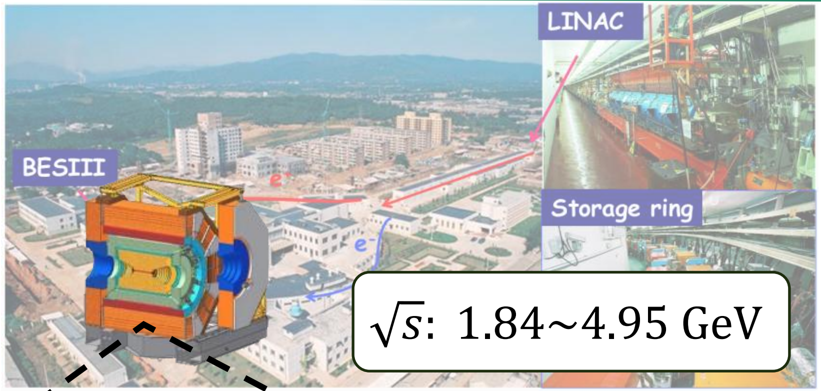


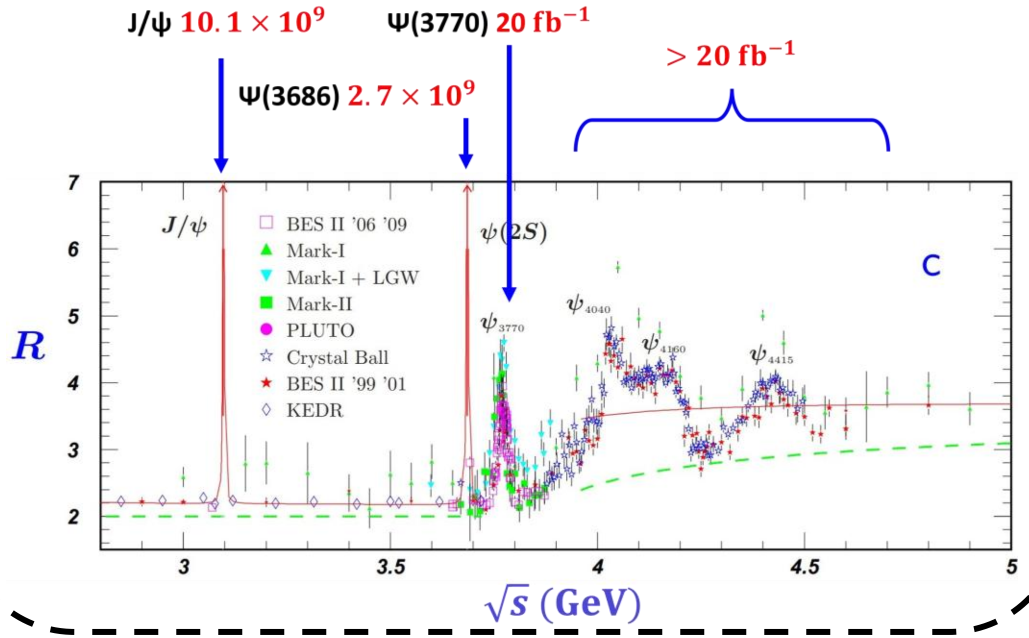
Beijing Electron Positron Collider II



BEijing Spectrometers III

Data set at BESIII





■ $10.1\times10^{9}\ J/\psi$ events

- Hyperon

Λ $\bar{\Lambda}$

$\Sigma^{0,+}$ $\bar{\Sigma}^{0,-}$ $\sim10^{7}$

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

- Light meson

η η'

ϕ ω $\sim10^{7}$

K_S^0

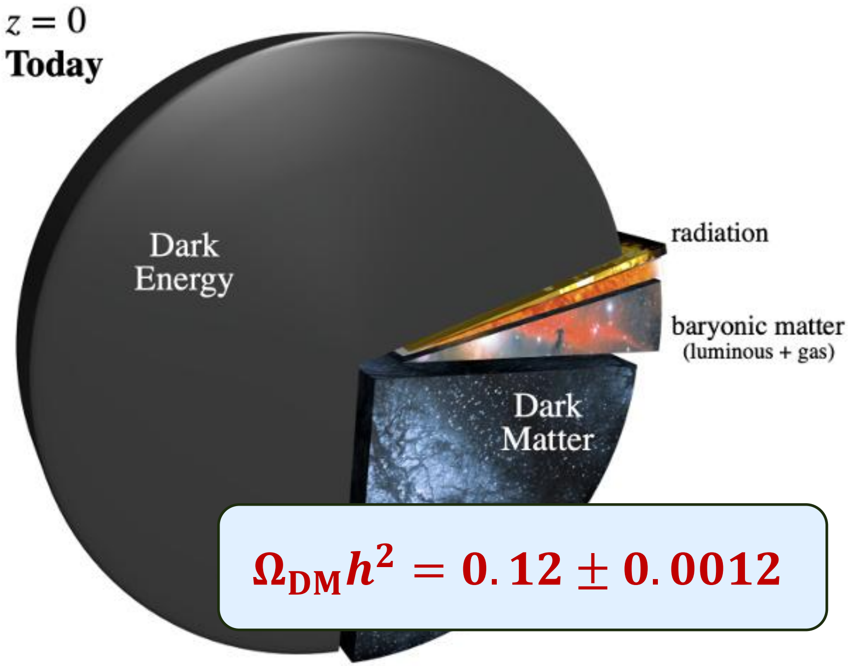
■ $20\ \mathrm{fb}^{-1}\ \psi(3770)$ ■ ……

D^0 $\bar{D}^0$ D^+ D^- $\sim10^{7}$

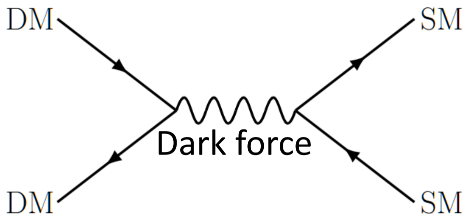
➢ **Wide range of physics with clean background**

➢ **Beneficial to search for dark sector**

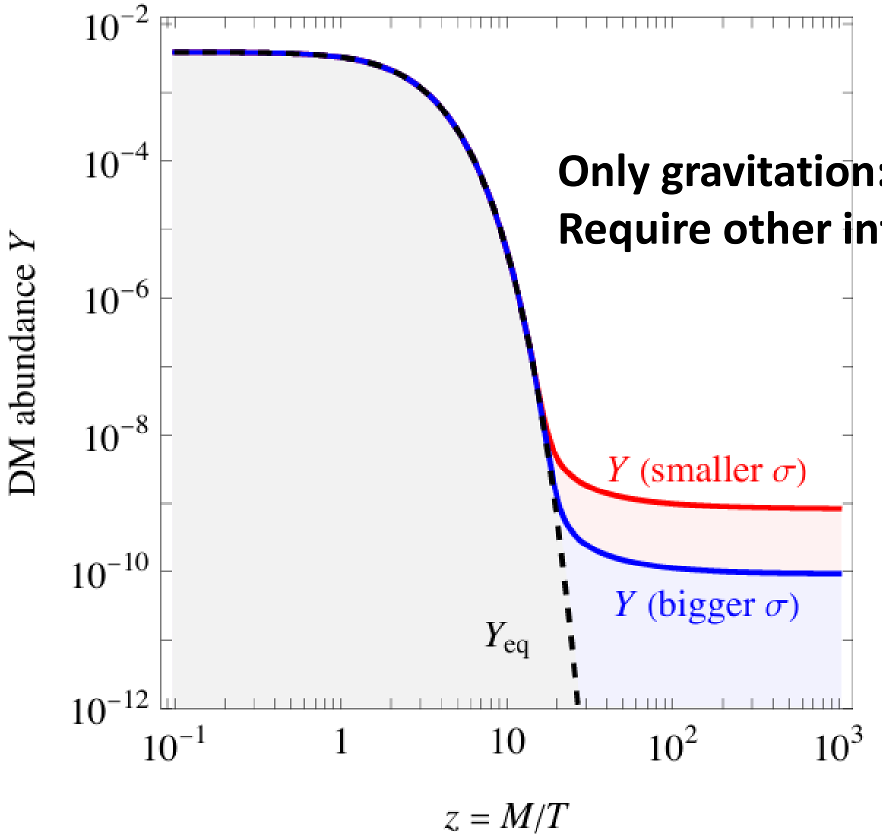
Dark matter (DM) in cosmology



$$\Omega_{\rm DM}h^2 = 0.12 \pm 0.0012$$



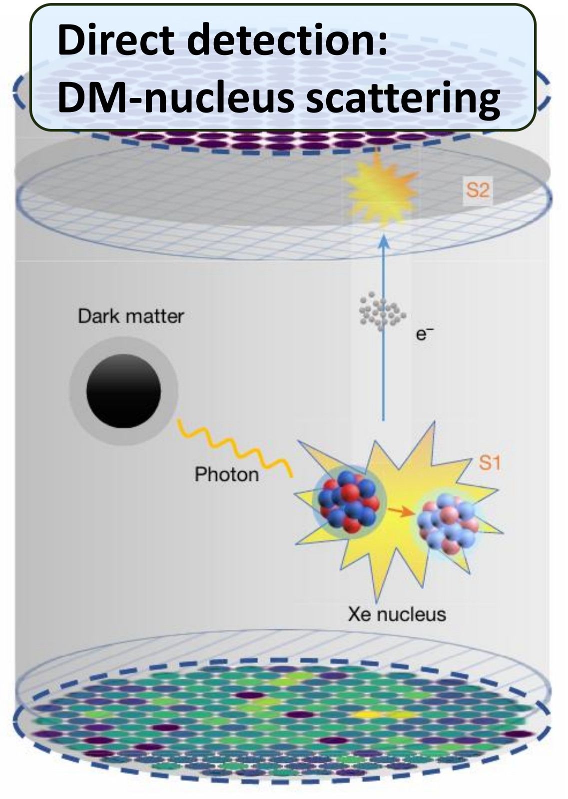
thermal relic by freeze-out

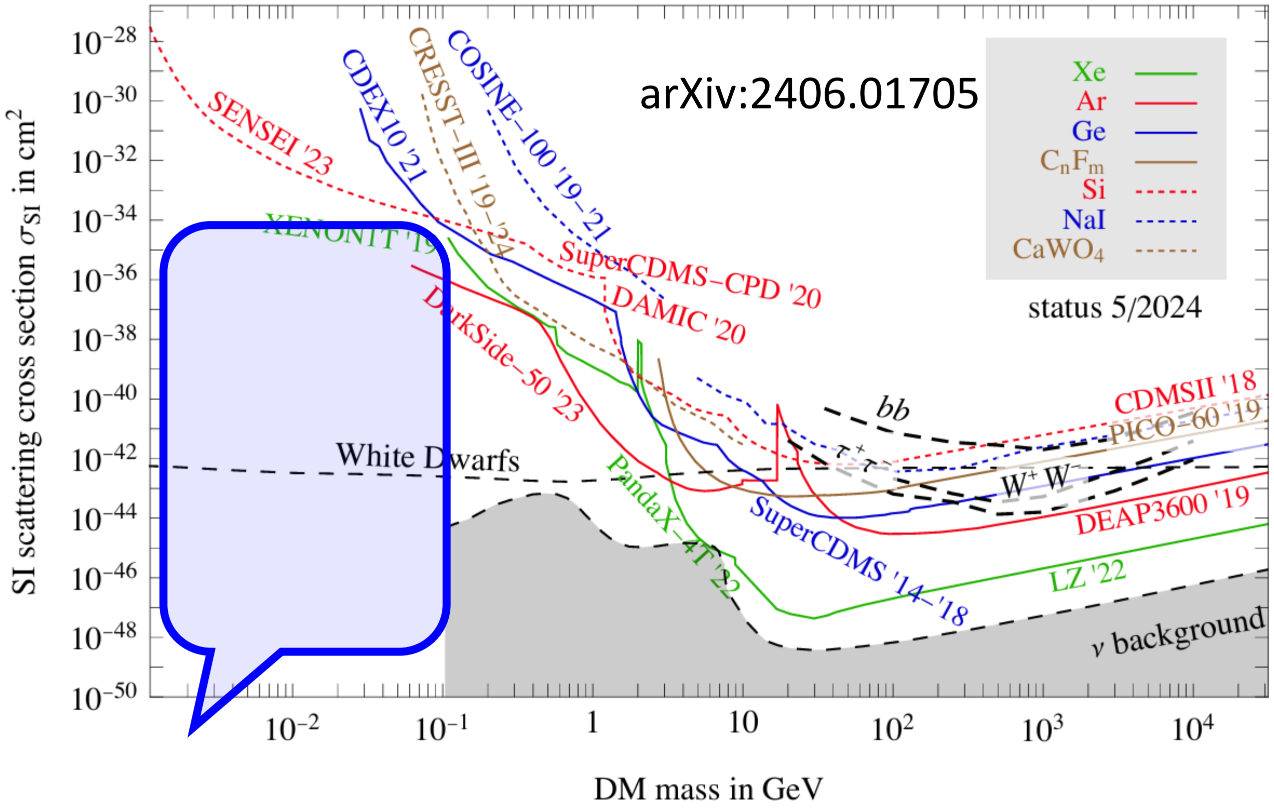


Only gravitation: too weak; Require other interactions

- For DM≫GeV, coupling~$\mathcal{O}(1)$, eg. WIMP
- **For DM≲GeV, coupling $\ll 1$**

DM search status

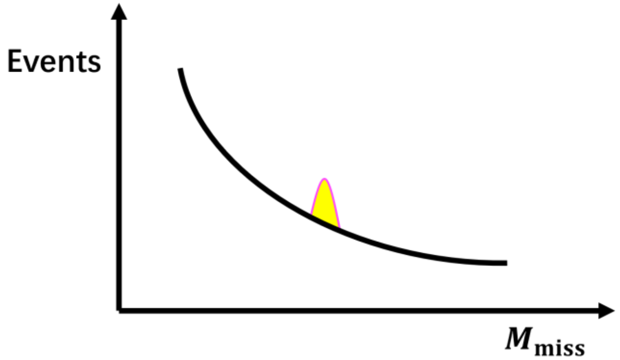


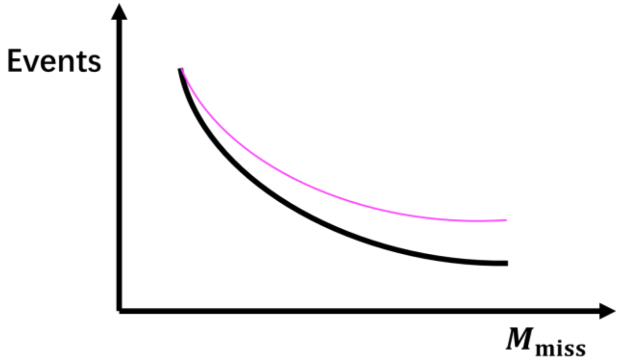


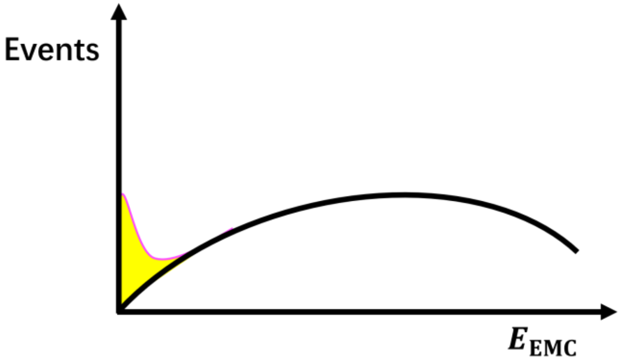
- GeV to TeV scale: strong constraint, not found any WIMP signal
- Sub-GeV: insufficient nuclear recoil energy to be detected, less exploration

- **BESIII operates in ∼GeV region, can offer a unique opportunity to probe sub-GeV DM from the collider**

DM search approach at BESIII

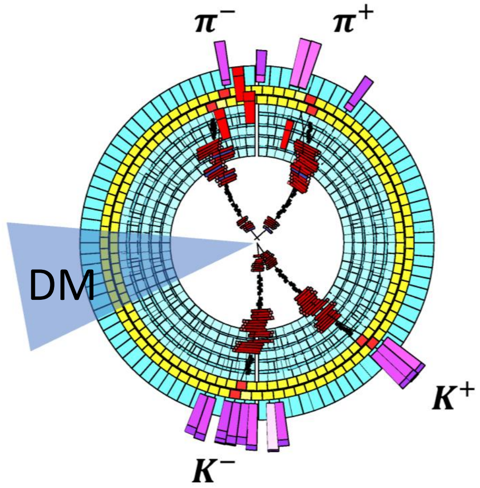






Missing Mass
Resonance dark matter

Missing Mass or Other features
Non-Resonance dark matter

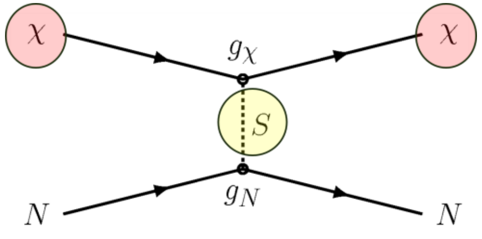


Missing Energy in EMC

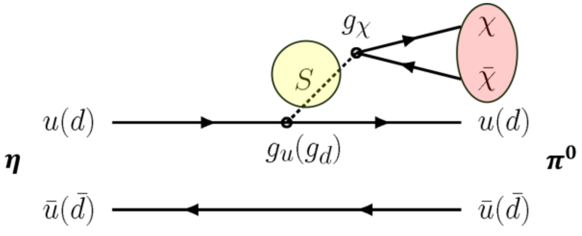
- Invisible signal at the detector
- “Visible” by the recoiling or zero energy deposited

Phys. Rev. Lett. 137, 031804 (2026), Editors' Suggestion

Search for $\eta \to \pi^0$ + invisible at BESIII

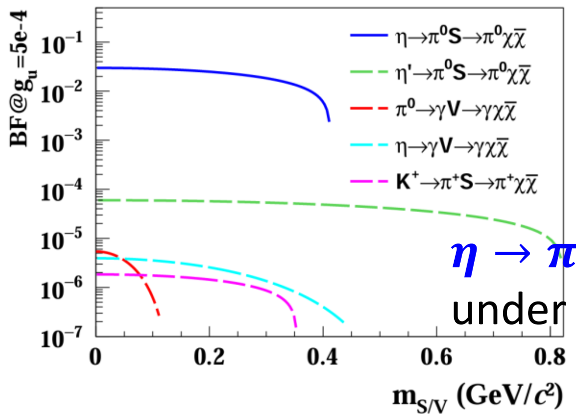


DM-nucleon scattering



$\eta \to \pi^0 S \to \pi^0 \chi\bar{\chi}$ decay

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

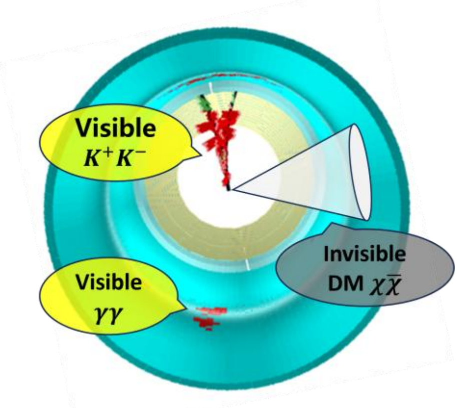


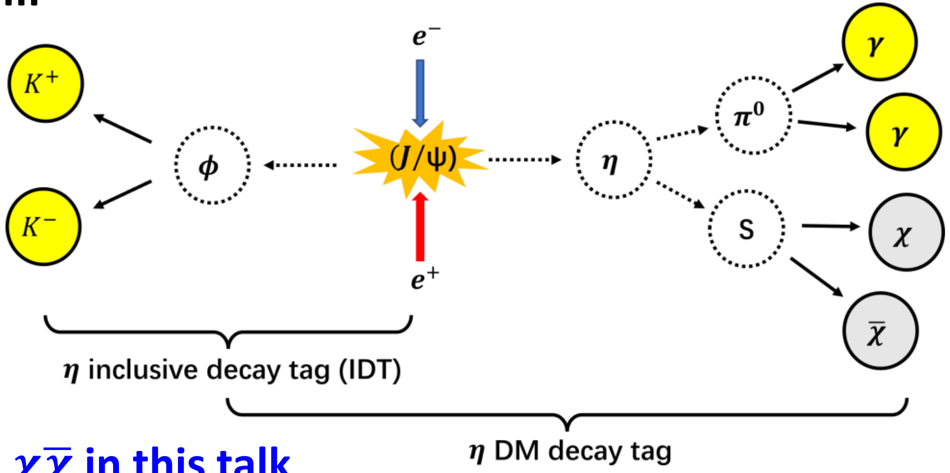
Flavor Conservation DM decays

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

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

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





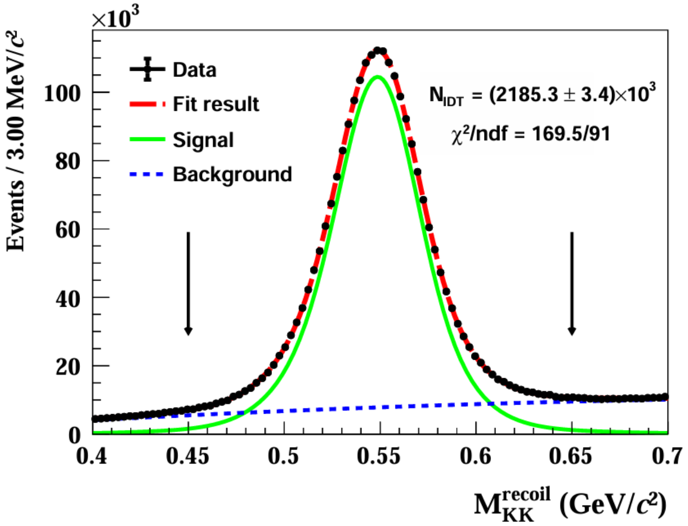
Search for on-shell $S \to \chi\bar{\chi}$ in this talk

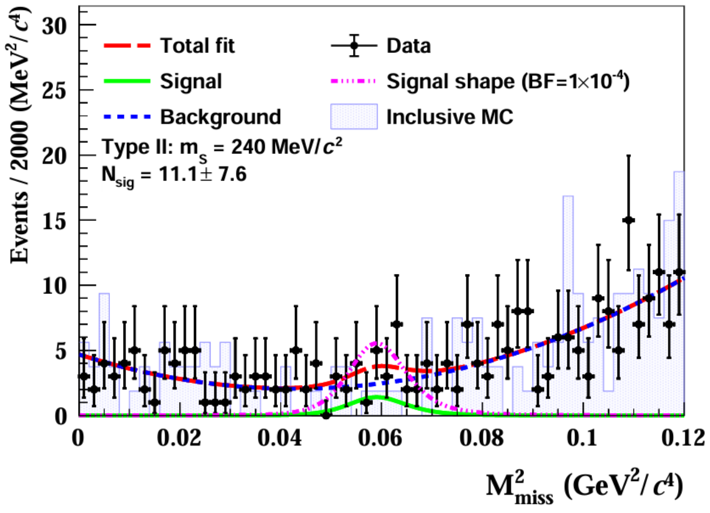
The off-shell $S \to \chi\bar{\chi}$ search is ongoing

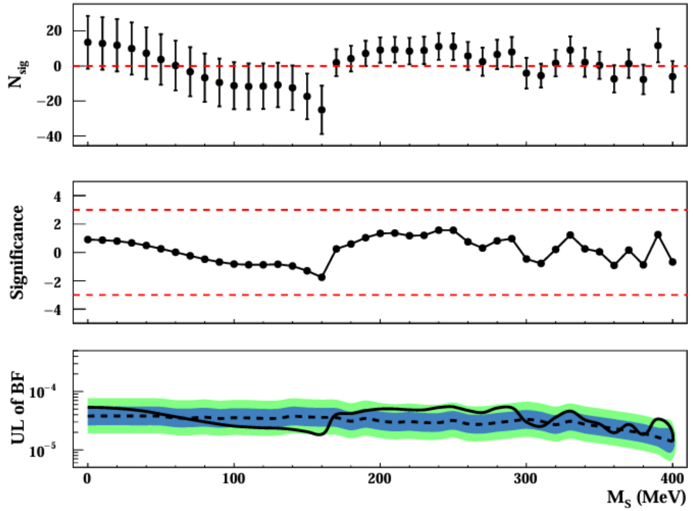
Phys. Rev. Lett. 137, 031804 (2026), Editors' Suggestion

Search for $\eta \to \pi^0$ + invisible at BESIII

Tag K^+K^- with $\eta \to$ any → **Further tag $\eta \to \pi^0 + \mathrm{inv}$** → **Scan signal with different m_S**







- ➢ 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

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

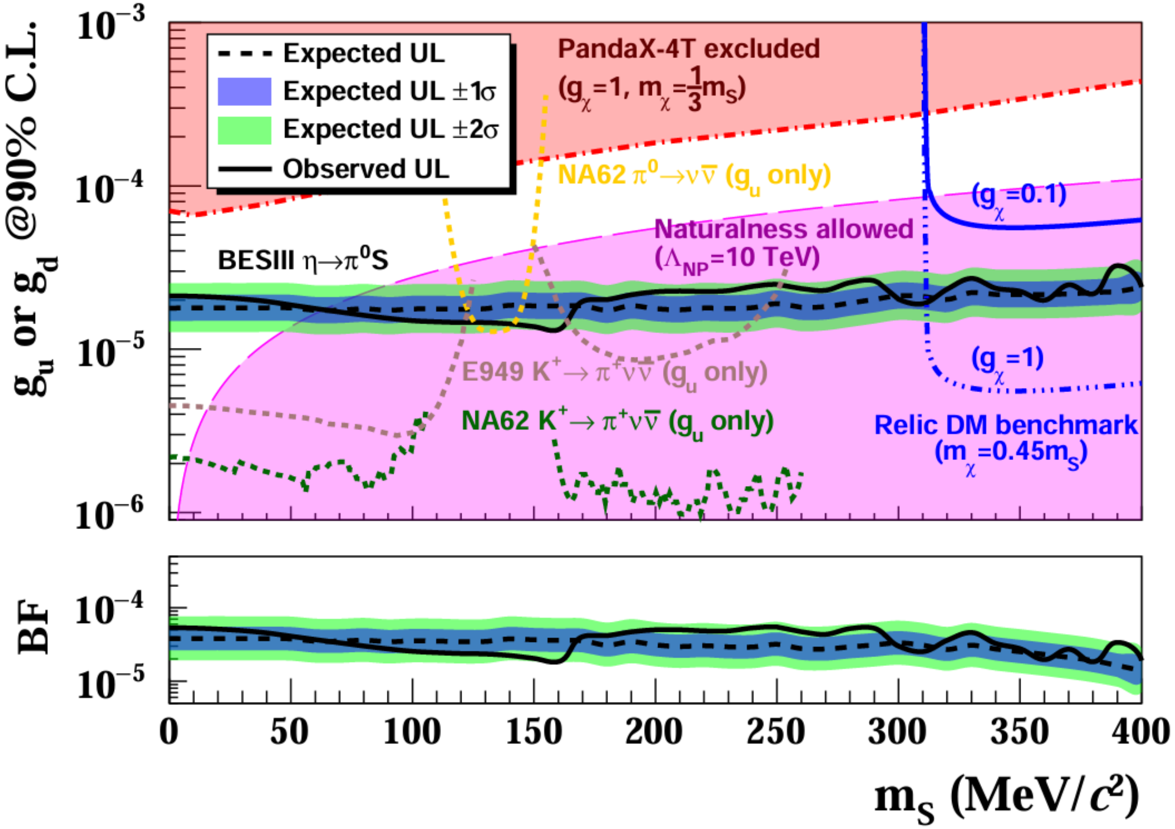
- ➢ Signal yield and upper limit (UL)
- S mass from ~ 0 to 400 MeV
- **UL on $\mathcal{B}(\eta \to \pi^0 S)$ @90% C.L.: $(1.8 \sim 5.5) \times 10^{-5}$**

❑ Advantages of **DM study at BESIII**
- **Clean background, full reconstruction, high efficiency, absolute BF measurement…**

Phys. Rev. Lett. 137, 031804 (2026), Editors' Suggestion

Search for $\eta \to \pi^0$ + invisible at BESIII

- $\mathcal{L} \supset -g_\chi S\bar{\chi}_L\chi_R - g_u S\bar{u}_L u_R + h.c.,\quad g_u \equiv \frac{c_S v}{\sqrt{2}\Lambda_{NP}}$
  - The coupling strength g_u not necessarily proportional to the Higgs Yukawa couplings



$$\mathcal{B} \propto g_u^2 \lambda^{\frac{1}{2}}\left(1, \frac{m_S^2}{m_\eta^2}, \frac{m_{\pi^0}^2}{m_\eta^2}\right)$$

- **UL on g_u or g_d @90% C.L.: $(1.3\sim3.2)\times10^{-5}$**
  - Better than the result of atmospheric-boosted DM from PandaX-4T
- Constraints from $K^+ \to \pi^+$ + invisible: only for g_u
- Naturalness bound in EFT, setting $\Lambda_{NP} = 10$ TeV
  - $g_u \leq \frac{16\pi^2}{\sqrt{2}} \frac{m_S v}{\Lambda_{NP}^2}$
- **Thermal Relic DM** benchmark: Freeze-out by $\chi\bar{\chi} \to \pi\pi$
  - **Excluded when $g_\chi = 0.1$**

Phys. Rev. Lett. 137, 031804 (2026), Editors' Suggestion

Search for $\eta \to \pi^0$ + invisible at BESIII

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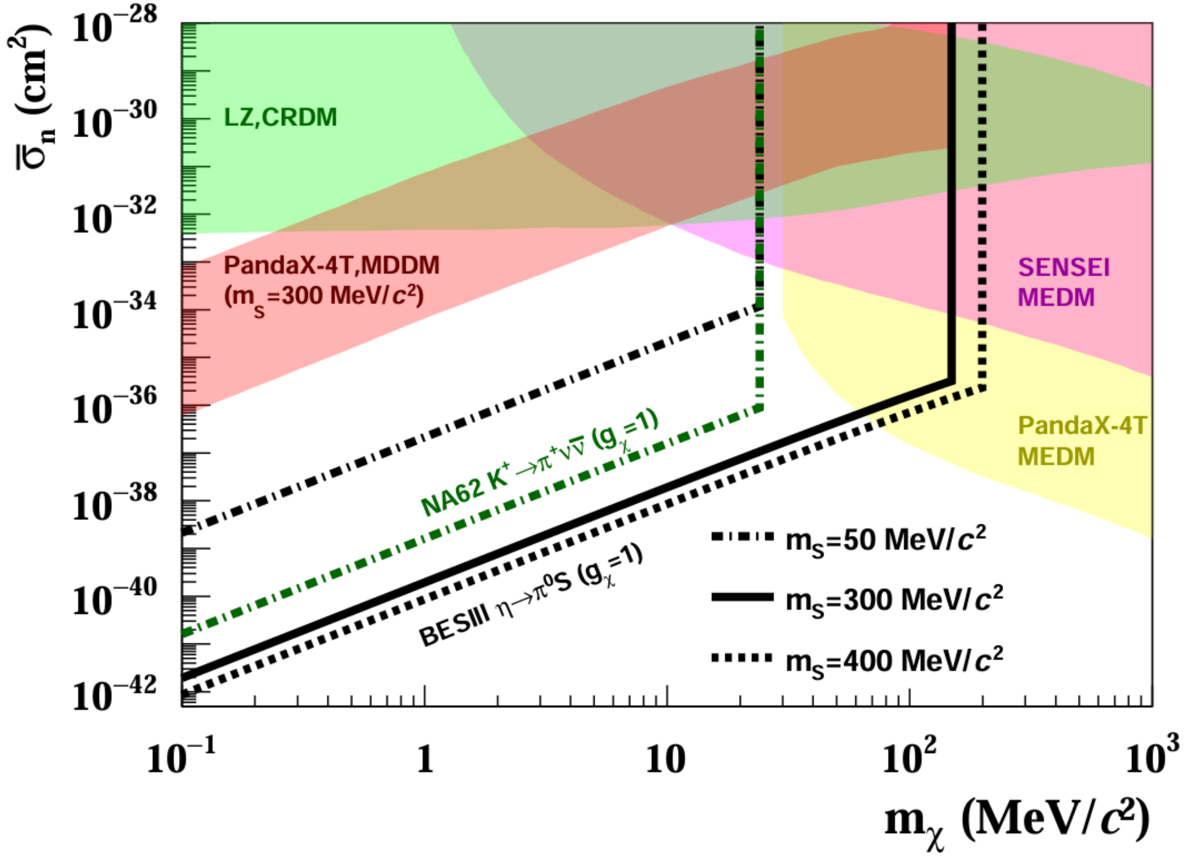


$$\bar{\sigma}_n \propto \frac{g_u^2 g_\chi^2}{m_S^4}\left(\frac{m_\chi m_N}{m_\chi + m_N}\right)^2$$

- Constraint on DM-nucleon cross section ($\bar{\sigma}_n$)
  - **Improved by approximately 5 orders** of magnitude over previous DM-nucleon scattering experiments

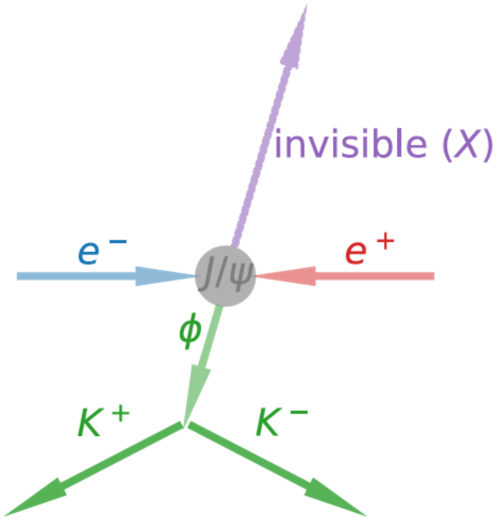
- **Model-dependent constraint**:
  - Scattering mediated by on-shell S

- **Ongoing and Future**
  - Off-shell S case in $\eta \to \pi^0\chi\bar{\chi}$
  - Larger S mass in $\eta' \to \pi^0\chi\bar{\chi}$
  - Pseudo-scalar case in $\eta \to \pi^+\pi^-\chi\bar{\chi}$
  - Vector case in $\pi^0/\eta \to \gamma\chi\bar{\chi}$
  - ……

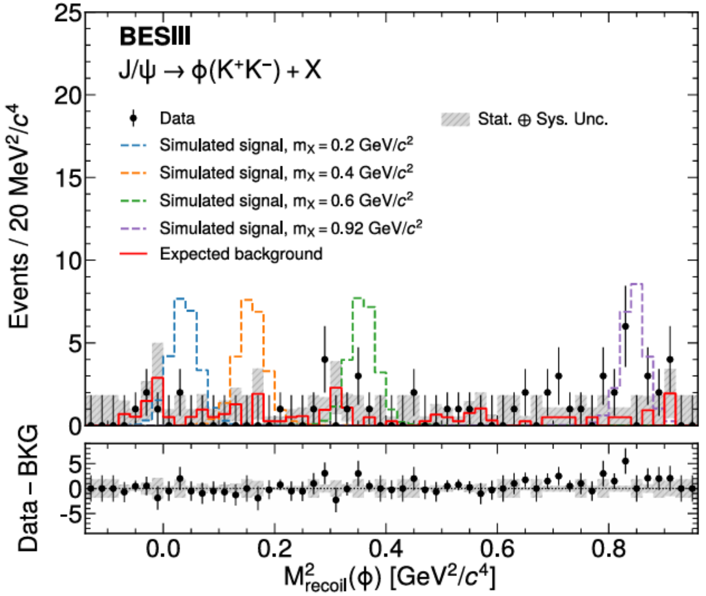
Phys.Rev.Lett. 135, 151804 (2025)

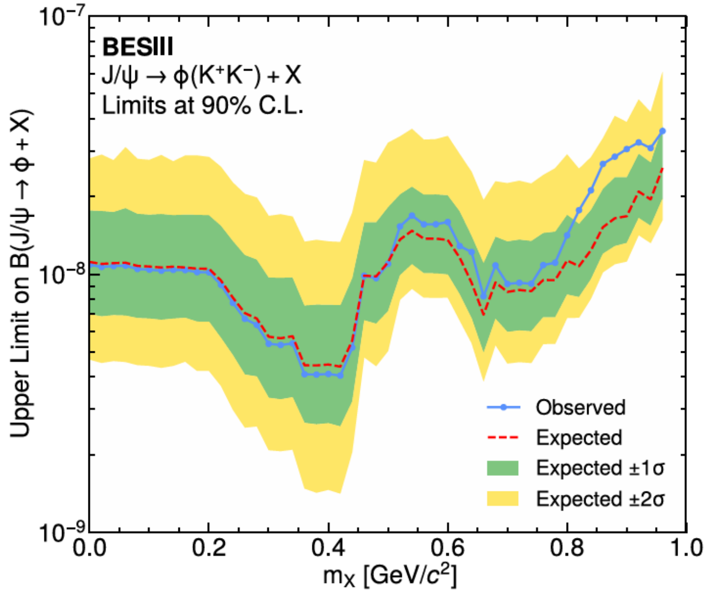
Search for $J/\psi \to \phi$ + invisible at BESIII

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



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



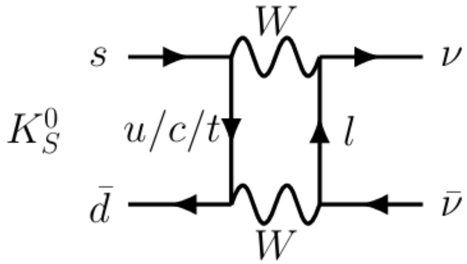


- **UL on $\mathcal{B}(J/\psi \to \phi X)$** with m_X ranging from 0 to 0.96 GeV @90% C.L.
  $\mathbf{4 \times 10^{-9} \sim 4 \times 10^{-8}}$
- UL on the inclusive invisible BF of $J/\psi \to \phi X$: 7.0×10^{-8} @90% C.L.
- Taking $X = \eta$, **UL on $\mathcal{B}(\eta \to \text{invisible})$: $\mathbf{2.4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

K_S invisible decay

Invisible decay of K_S^0

SM decay

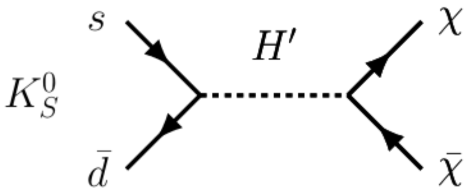


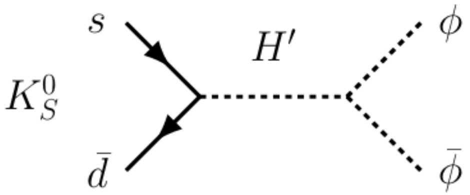
BF $< 10^{-16}$

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

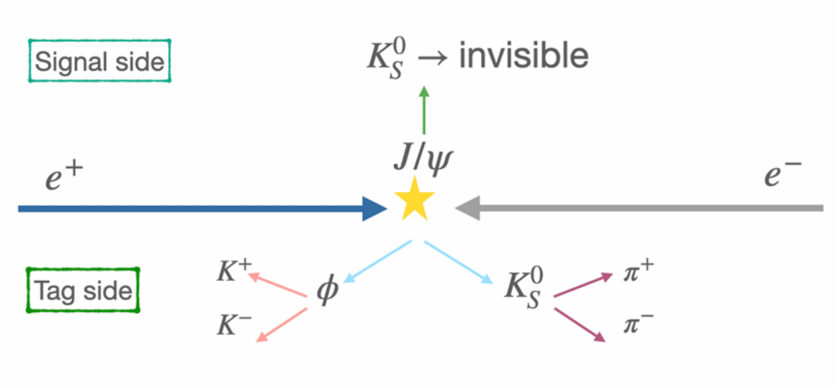
Phys.Rev.D 91 (2015) 1, 015004

JHEP 05 (2025) 092

Search for K_S^0 invisible decay at BESIII

K_S^0 source

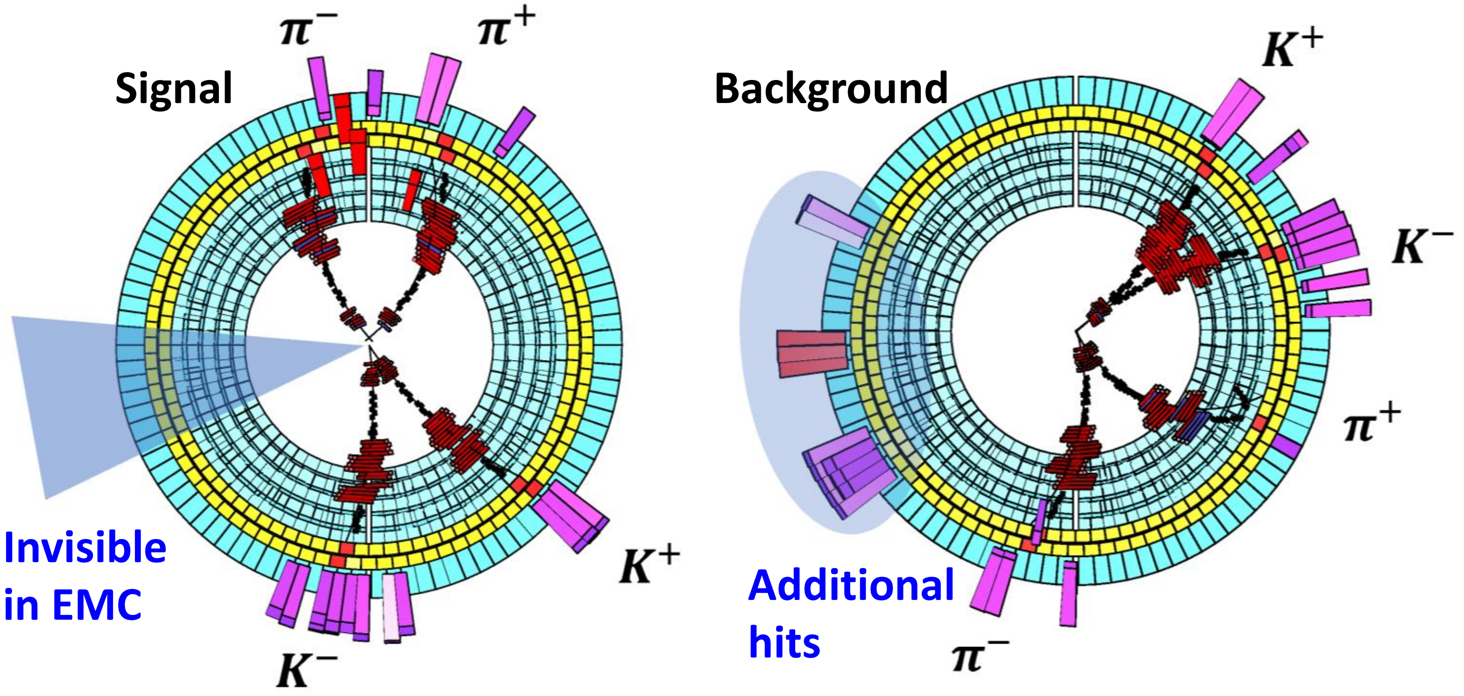
$J/\psi \to \phi K_S^0 K_S^0$ from $(10087 \pm 44) \times 10^6$ J/ψ



Why this channel?

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

Signal feature

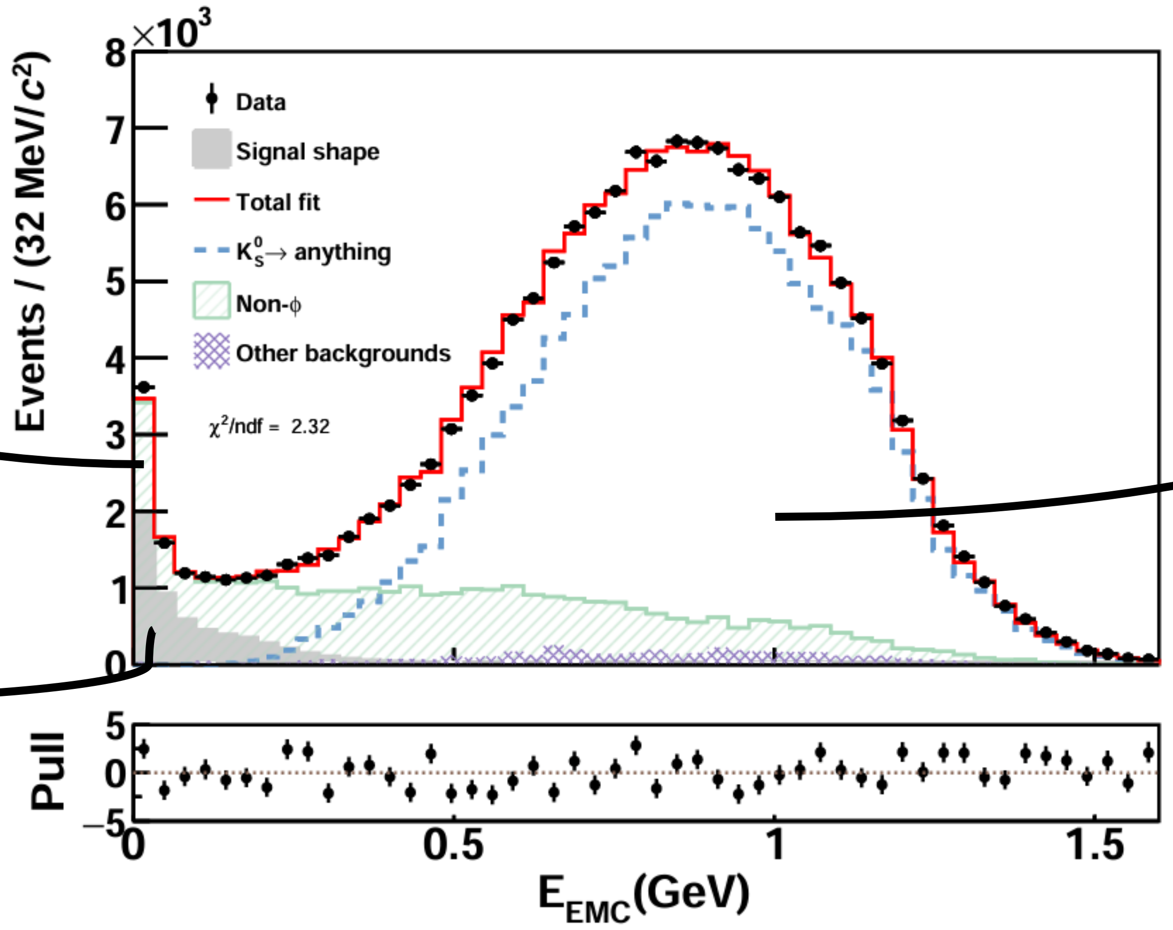


- **Using the deposited energy in EMC to identify the invisible signal**
- **An alternative method for invisible signal search at BESIII**

Search for K_S^0 invisible decay at BESIII

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

Invisible Signal peaks around zero



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

$N_{\mathrm{sig}} = 56 \pm 201$

$\mathcal{B}(K_S^0 \to \mathrm{invisible}) < 8.4 \times 10^{-4}$

(90% C.L.)

arXiv: 2501.06426

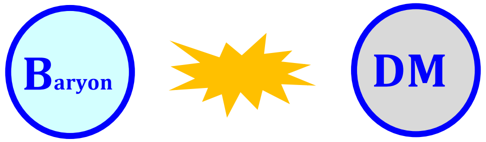
First direct measurement of $K_S^0 \to$ invisible; the UL still lies above the NP prediction

Dark baryon

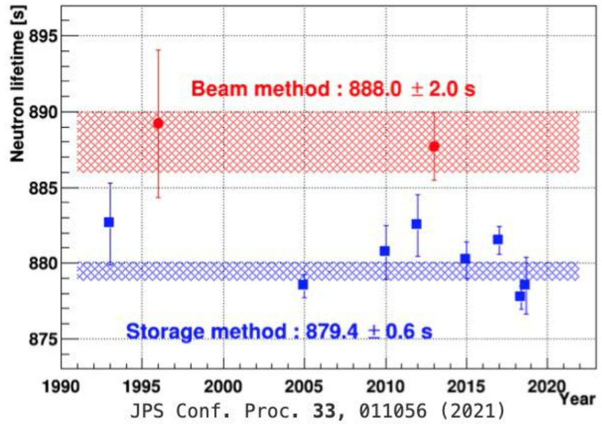
Coincidence problem

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

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



Neutron lifetime puzzle



JPS Conf. Proc. 33, 011056 (2021)

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

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

- **Motivates the existence of dark baryon**

B-Mesogenesis mechanism

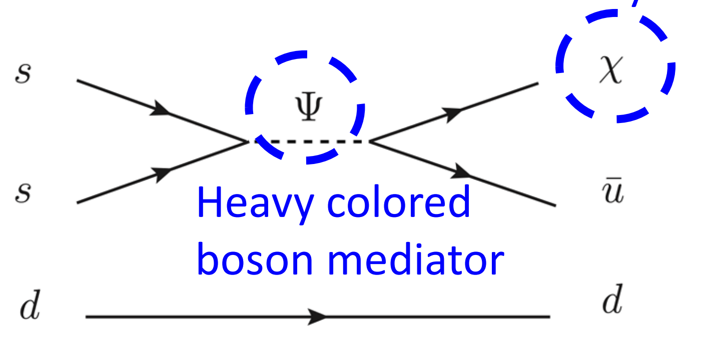
CP asymmetry
in $B \to \text{baryon} + \text{dark baryon}$

1. **Explain matter anti-matter asymmetry**
2. **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**

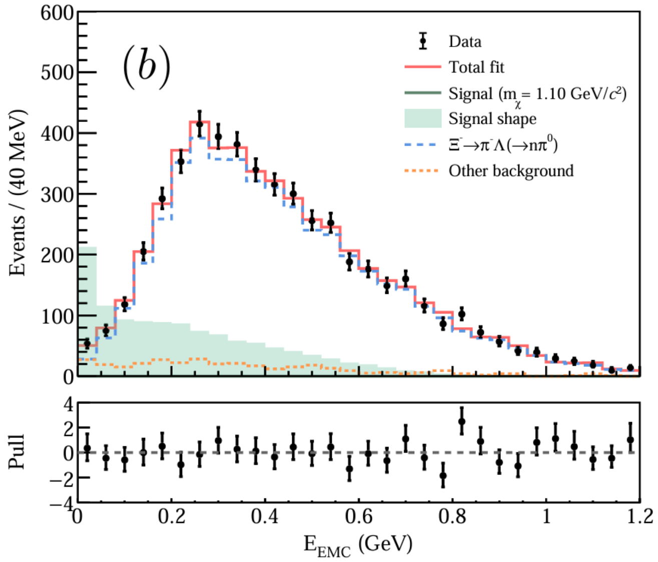
Phys. Lett. B 872 (2026) 140099

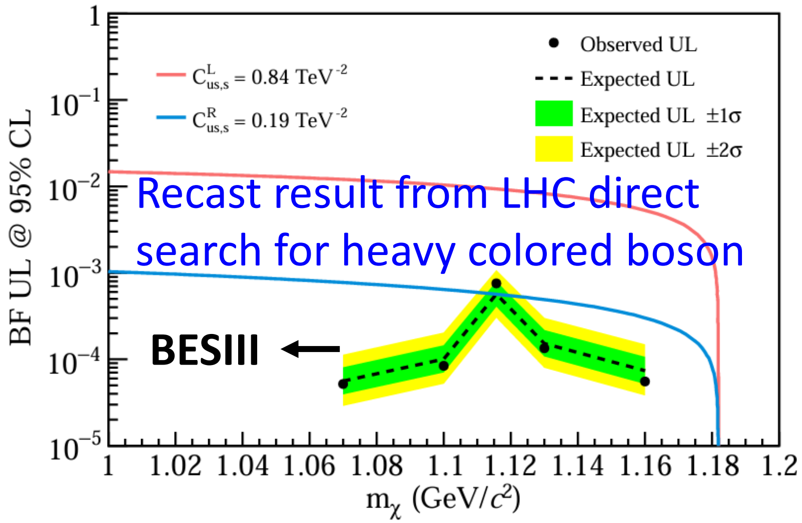
Search for $\Xi^- \to \pi^- +$ invisible at BESIII

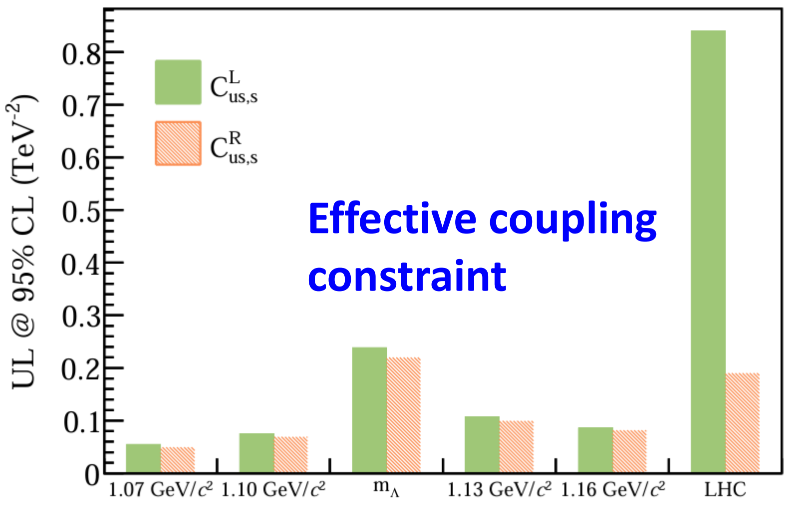


- $J/\psi \to \bar{\Xi}^+\Xi^-$ from 10^{10} J/ψ

- $\bar{\Xi}^+ \to$ SM, $\Xi^- \to \pi^-\chi$
- 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





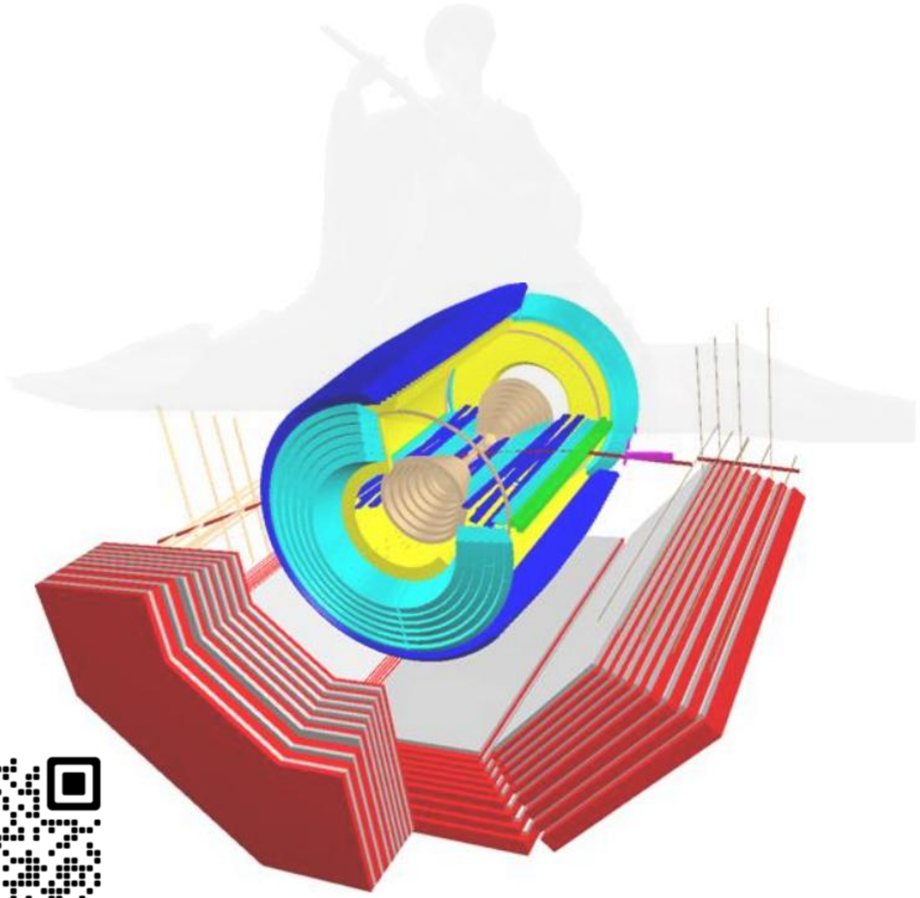


Better effective coupling constraints

Summary

- **New results of sub-GeV dark sector at BESIII**
  - $\eta \to \pi^0 + \text{invisible}, J/\psi \to \phi + \text{invisible}$
  - $K_S^0 \to \text{invisible}, \eta \to \text{invisible}$
  - $\Xi^- \to \pi^- + \text{invisible}$
  - **Unique stringent constraints on the sub-GeV DM**

- **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**



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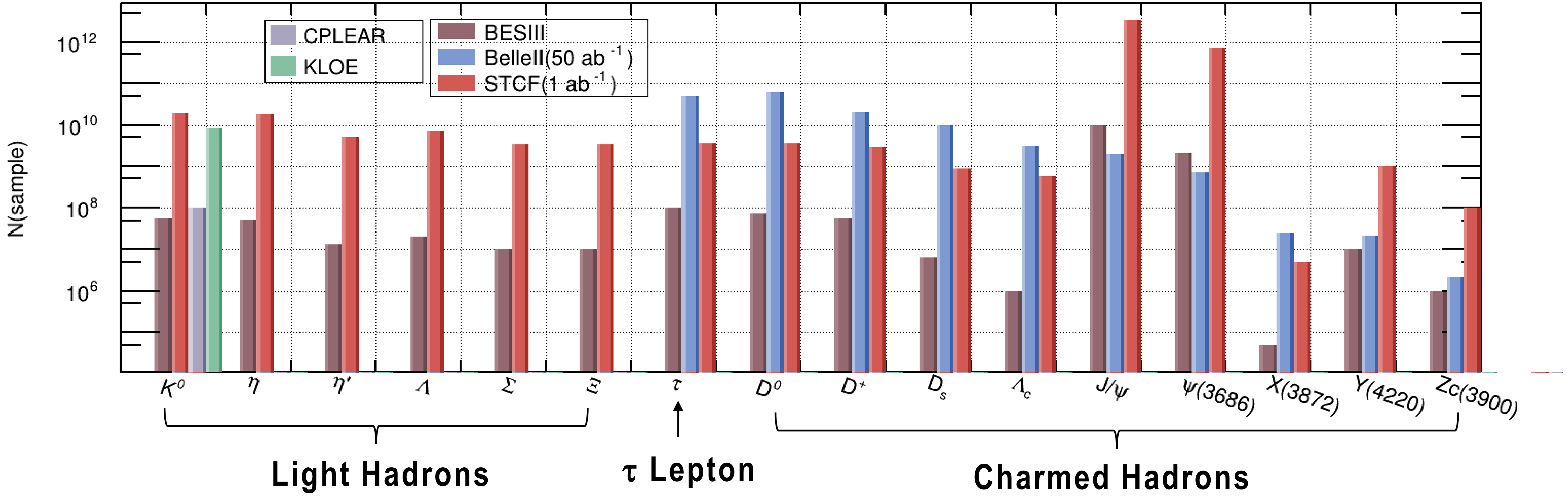
Appendix

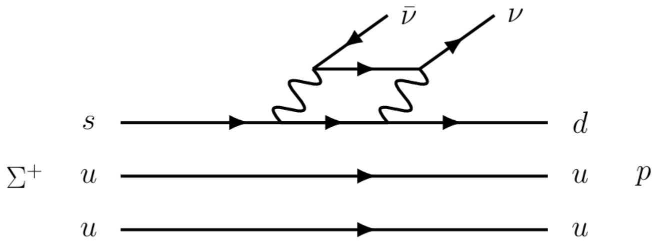
Super Tau-Charm Facility (STCF)



Statistic improved by ~300, BF or σ's sensitivity improved by ~17, coupling strength's sensitivity improved by ~4

$\Sigma^+ \to p$ + 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**
- $m_a \sim g \sim \frac{1}{F_a} \Rightarrow \boldsymbol{m_a \ll 1\ \mathrm{eV}}$;
  g: coupling strength;
  F_a: decay constant

➢ Naturally allow the FCNC coupling

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

Vector coupling **Axial coupling**

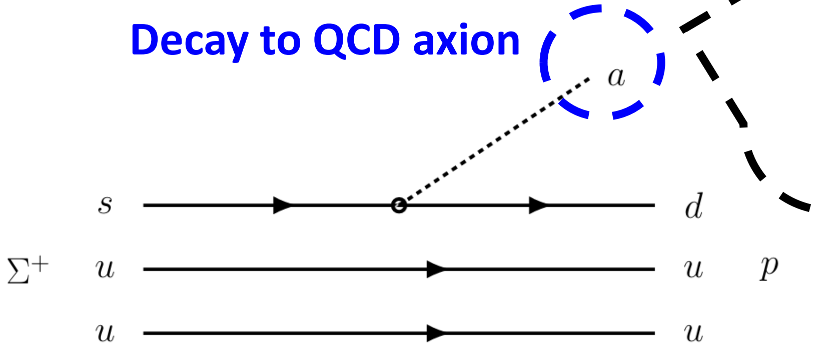
sensitive

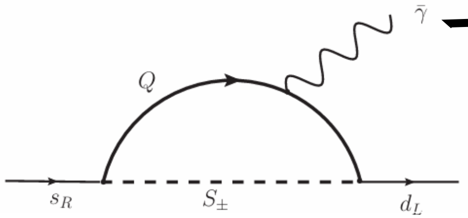
$K^+ \to \pi^+ a$

Both sensitive

Hyperon decay

Decay to QCD axion





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

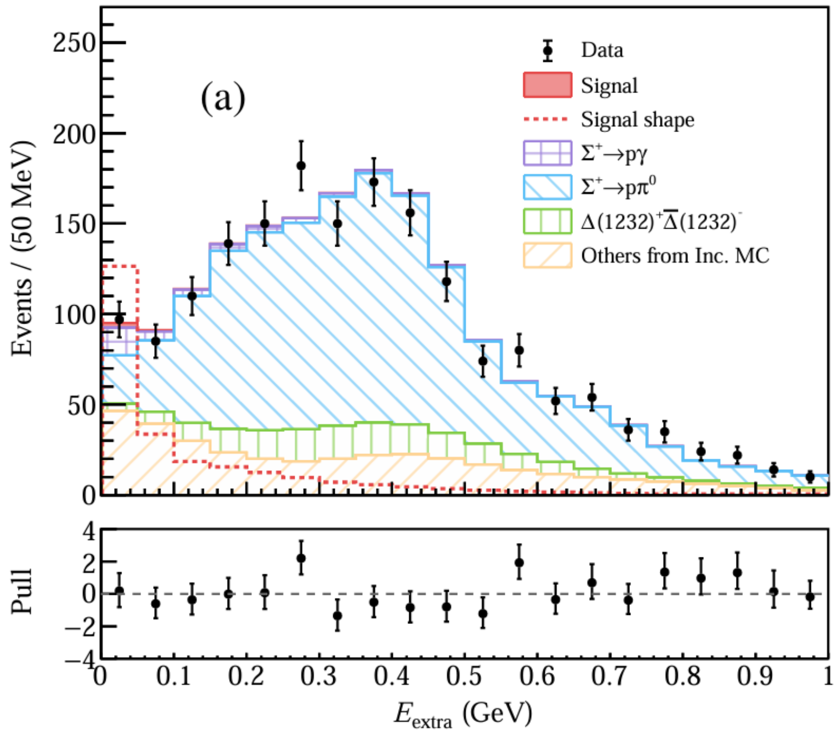
Phys.Rev.D 102 (2020) 1, 015023

Phys.Lett.B 852 (2024) 138614

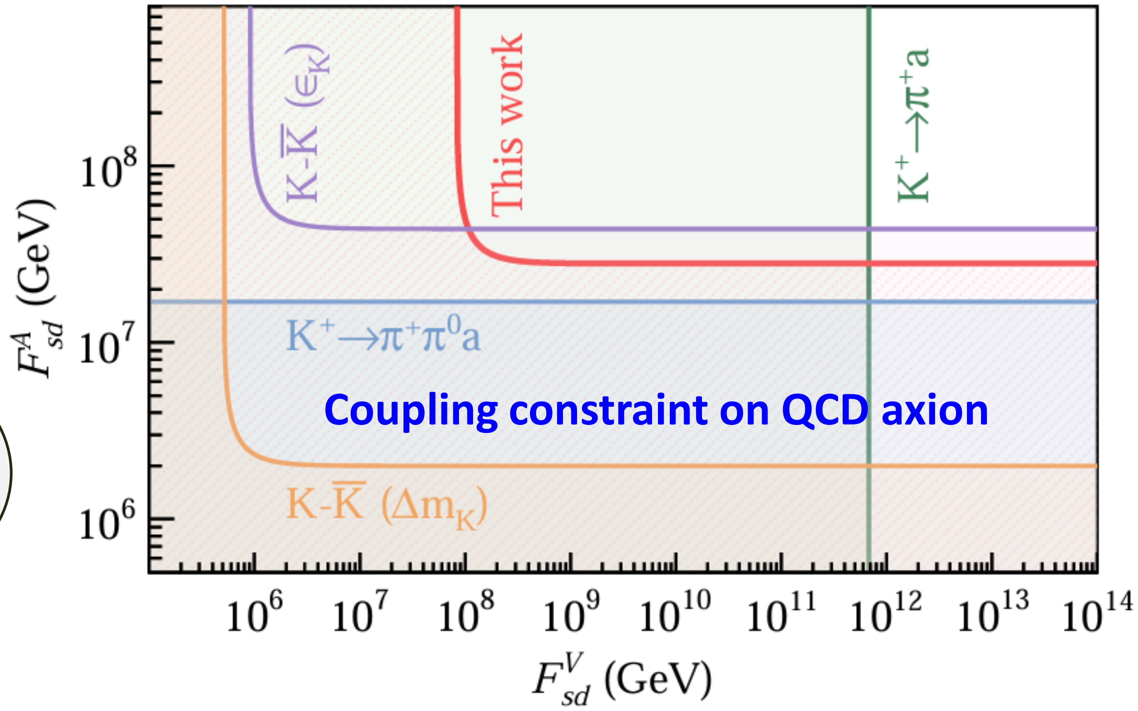
Search for $\Sigma^+ \to p$ + invisible at BESIII

- $J/\psi \to \Sigma^+\bar{\Sigma}^-$ 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.



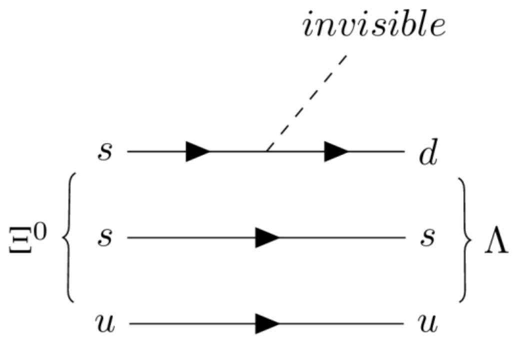
- Competitive constraint on the axial coupling temp F^A_{sd} of QCD axion

- The BF UL lies below the maximum allowed BF of massless dark photon decay (3.8×10^{-5})

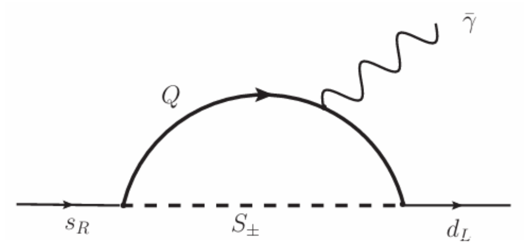
arXiv:2603.03199

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

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



QCD axion a



Massless dark photon γ'

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

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

$m_a \ll 1$ eV motivated by

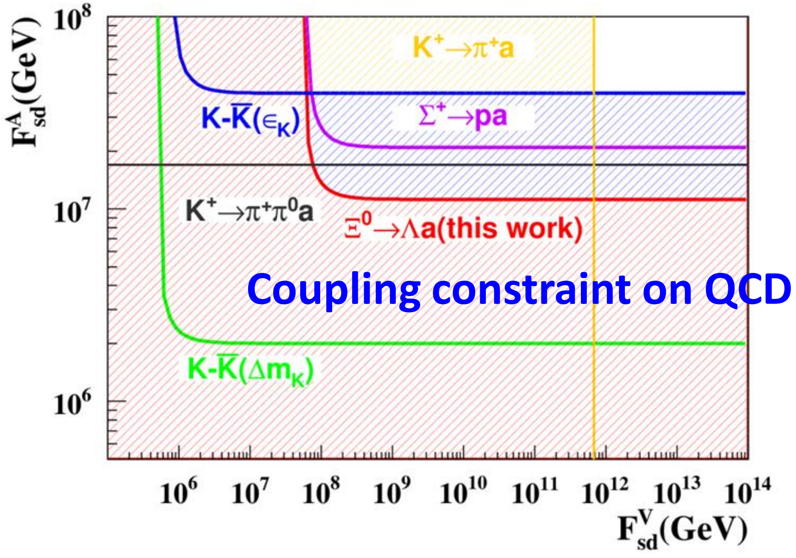
$m_a \propto \frac{1}{F_a}$ with $F_a \gg$ PeV

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

Allowed BF: 1.2×10^{-4}

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

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



Coupling constraint on QCD axion

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

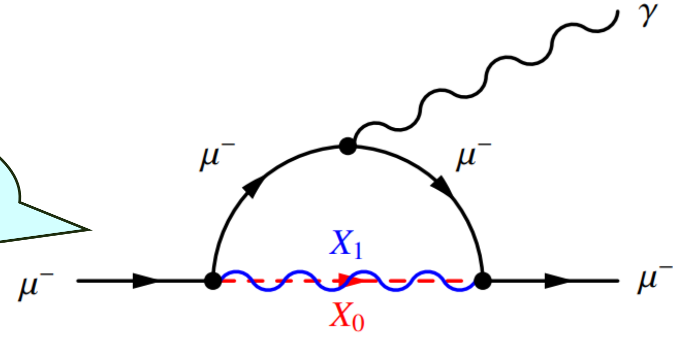
Phys.Rev.D 109 (2024) 3, L031102

Search for $J/\psi \to \mu^+\mu^-$ + invisible at BESIII

$$\mathcal{L}_{\mu}^{\rm scalar} = -g_0\, X_0\, \overline{\mu}\, \mu,$$
$$\mathcal{L}_{\mu}^{\rm vector} = -g_1\, X_{1\alpha}\, \overline{\mu}\, \gamma^{\alpha}\, \mu.$$

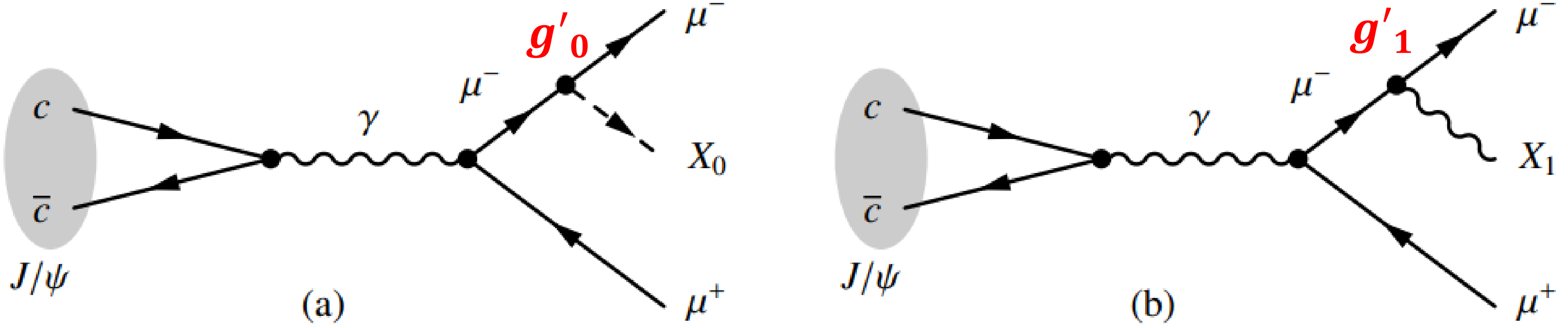
- **$U(1)_{L\mu-L\tau}$ model**: A new massive scalar boson X_0 or vector boson X_1 **only couples to the second and third generations** of leptons $(\mu, \nu_\mu, \tau, \nu_\tau)$ with the **coupling strength $g'_{0,1}$**

explain $(g-2)_\mu$ anomaly



- **The main muon source at BESIII: $J/\psi \to \mu^+\mu^-$**
- **Search for $J/\psi \to \mu^+\mu^- X_{0,1}$** → **Invisible $X_{0,1}$ at this time**

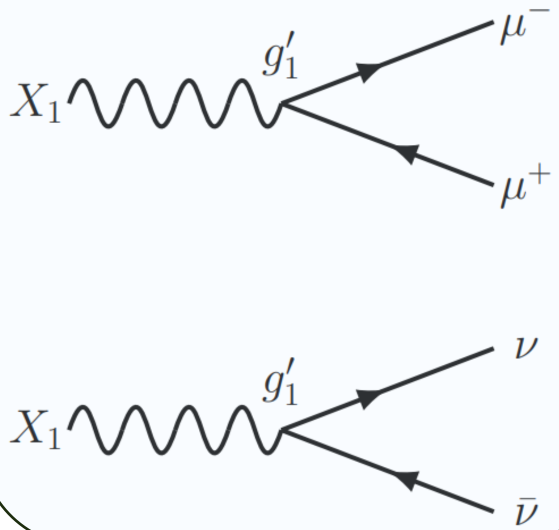
JHEP10(2020)207



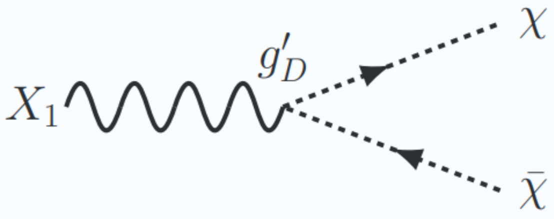
Phys.Rev.D 109 (2024) 3, L031102

Search for $J/\psi \to \mu^+\mu^- + $ invisible at BESIII

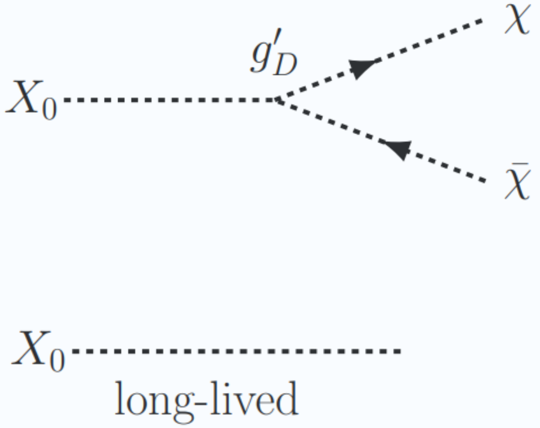
"vanilla" $L_\mu - L_\tau$ model



"invisible" $L_\mu - L_\tau$ model



"scalar" $U(1)$ model



- Large mass of dark matter kind:
  $$m_\chi > m_{X_1}/2$$
- $\mathcal{B}(X_1 \to \upsilon\bar{\upsilon}) = 33\% - 100\%$ with different m_{X_1}

- Light dark matter kind:
  $$m_\chi < m_{X_1}/2$$
- $g'_D \gg g'_1$
- $\mathcal{B}(X_1 \to \chi\bar{\chi}) \sim 100\%$

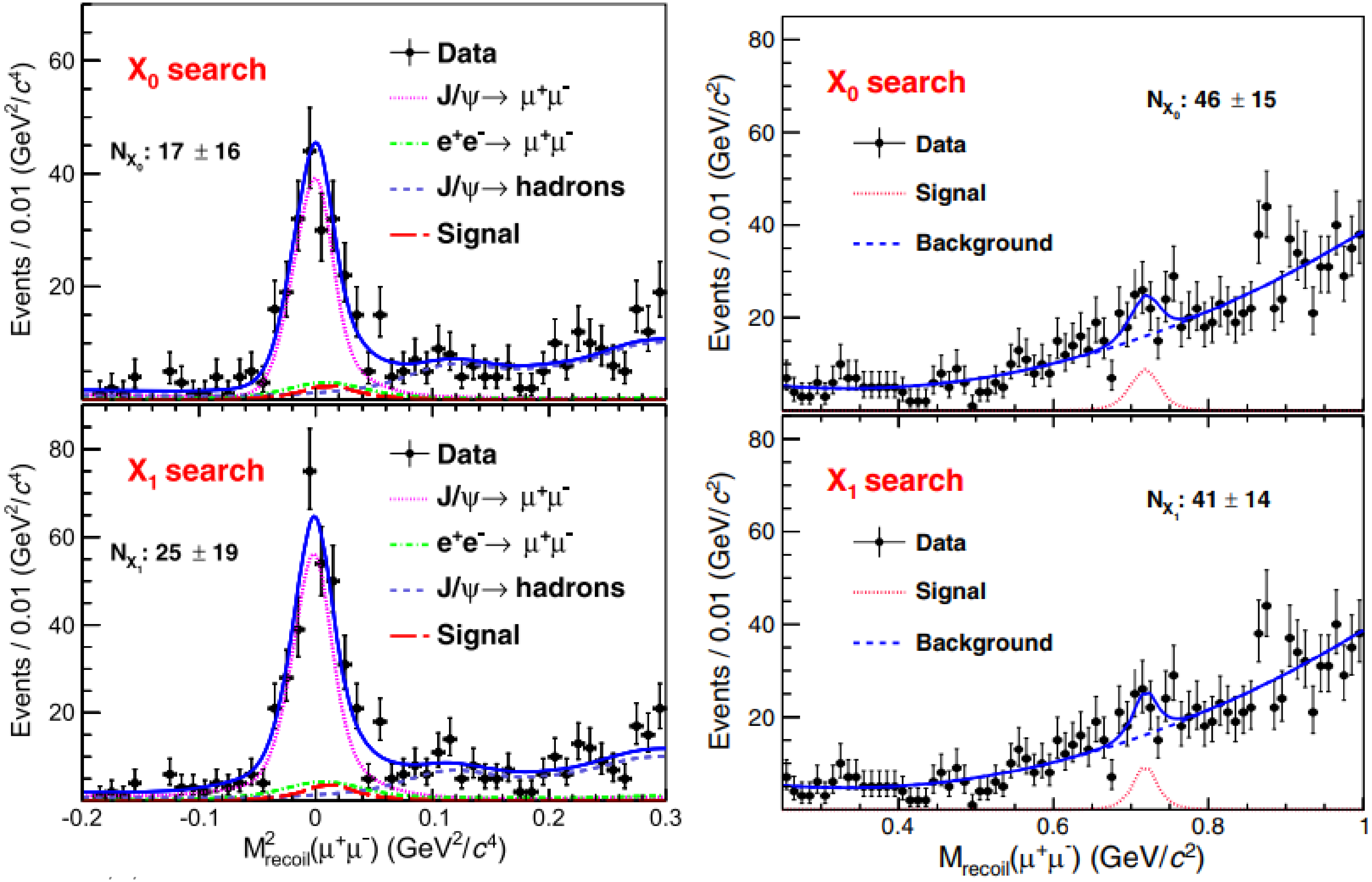
- Assuming the X_0 is long-lived or only decay to invisible final states

Search for muon-philic scalar X_0 or vector X_1 via $J/\psi \to \mu^+\mu^- X_{0,1}$ with $X_{0,1}$ invisible

Phys.Rev.D 109 (2024) 3, L031102

Search for $J/\psi \to \mu^+\mu^- +$ invisible at BESIII

Low mass region **High mass region**



- Data samples: $\sim 9 \times 10^9\ J/\psi$ events
- **No evidence** for invisible $X_{0,1}$

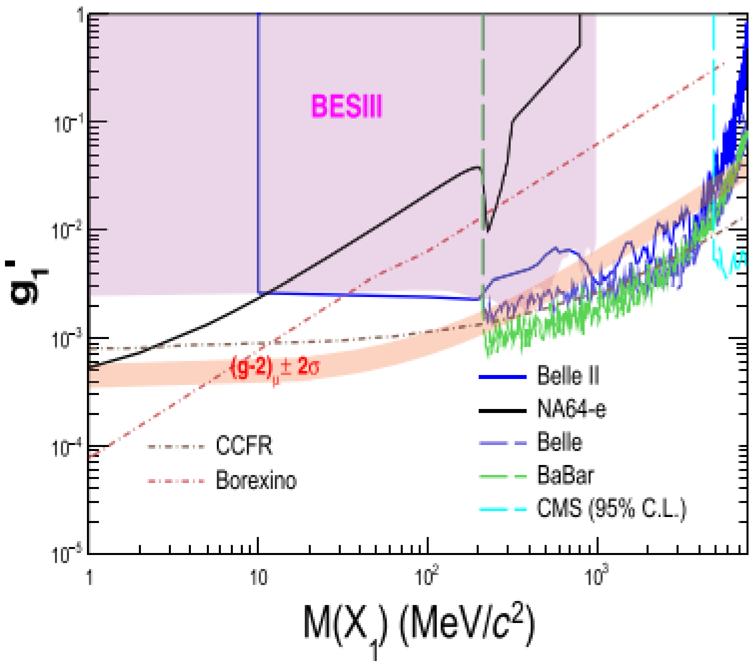
Maximum local signal significance:
2.5σ at $\mathrm{M}(X_{0,1}) = 720\ MeV/c^2$

UL on the BF: 10^{-7} to 10^{-9} order

Phys.Rev.D 109 (2024) 3, L031102

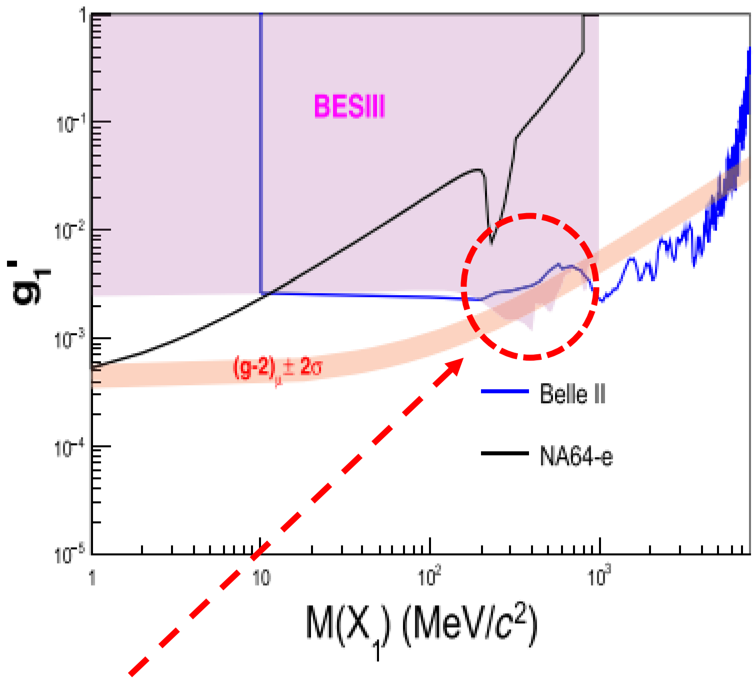
Search for $J/\psi \to \mu^+\mu^- +$ invisible at BESIII

“vanilla” $L_\mu - L_\tau$ model



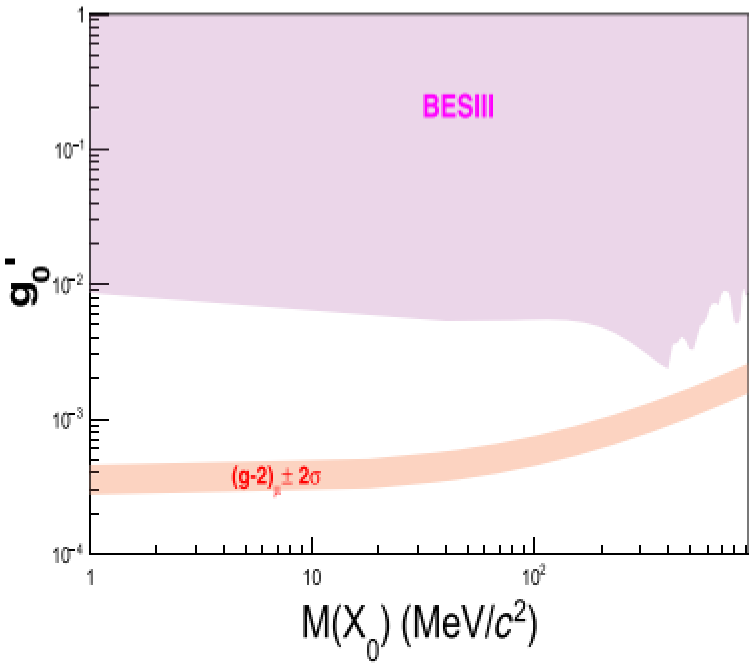
BarBar, CMS, Belle: $X_1 \to \mu^+\mu^-$
Belle II, BESIII: $X_1 \to \upsilon\bar{\upsilon}$
(Taking $\mathcal{B}(X_1 \to \upsilon\bar{\upsilon})$ into account)

“invisible” $L_\mu - L_\tau$ model



Better sensitivity in the range 200-860 MeV/c^2

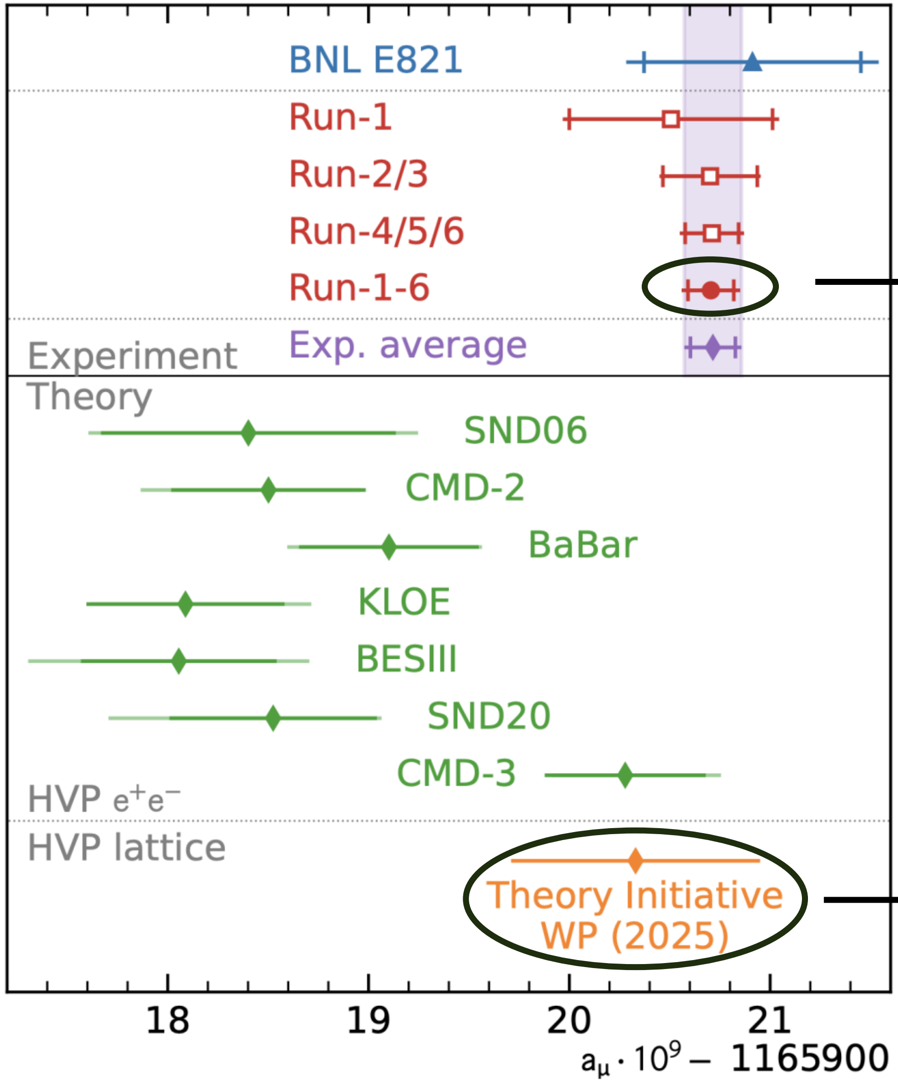
“scalar” $U(1)$ model



First constraint for the “scalar” invisible X_0 case
Belle II can also give the constraint

“Significant Room Remaining for $g_\mu - 2$ Anomaly; Big Potential!” —— from my talk in 2025.3

Newest state of $(g-2)_\mu$



New exp. value
arXiv:2506.03069

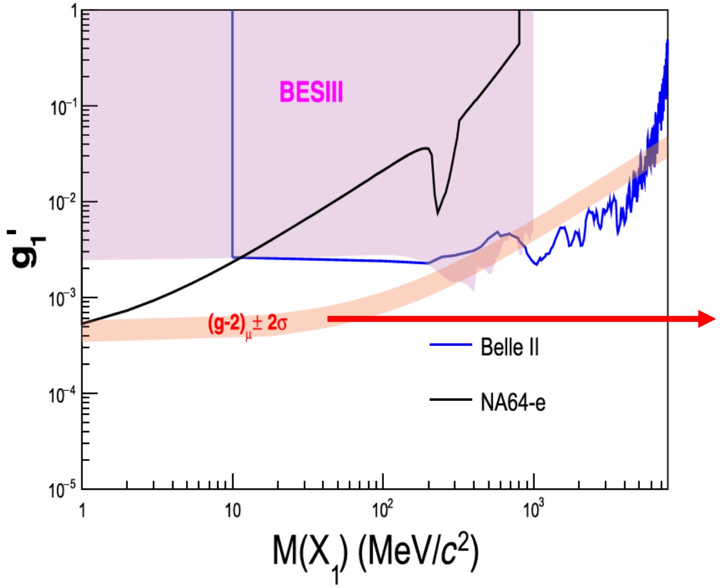
New Lattice value
arXiv: 2505.21476

Before 2025.5:

$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (\mathbf{249 \pm 48}) \times 10^{-11}$$

After 2025.5:

$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (\mathbf{38.5 \pm 64}) \times 10^{-11}$$



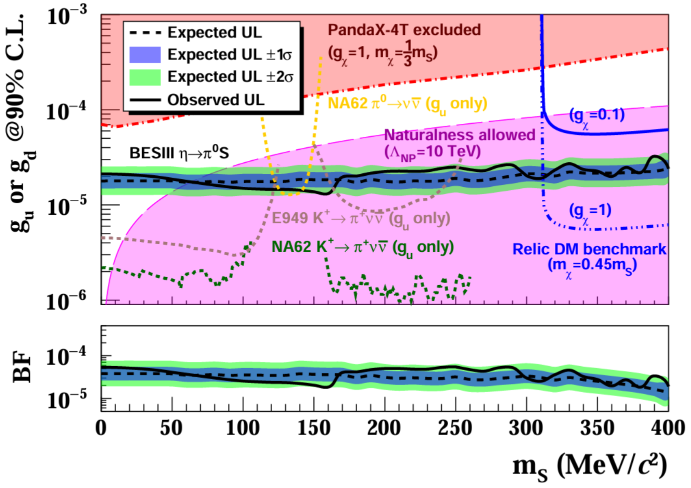
Before 2025.5:
Allowed region

After 2025.5:
Upper limit

Not only muon-philic, others like dark photon, dark higg, axion… are also changed to an UL

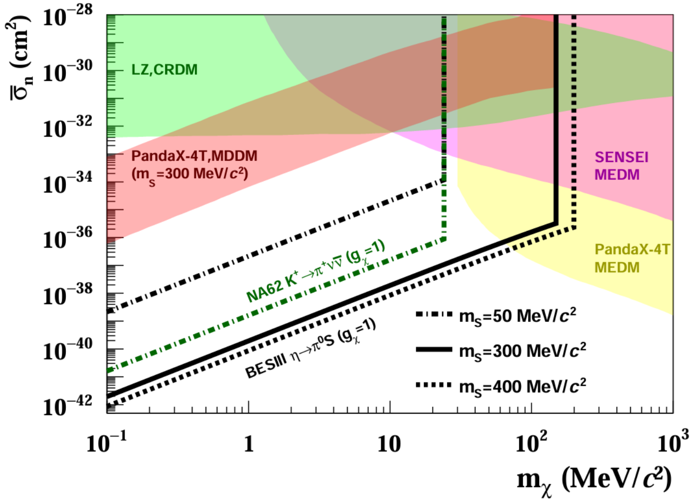
Discussion within the specific model

- $\mathcal{L} \supset -g_\chi S \bar{\chi}_L \chi_R - g_u S \bar{u}_L u_R + h.c., \quad g_u \equiv \frac{c_S v}{\sqrt{2}\Lambda_{NP}}$
  - The coupling strength g_u not necessarily proportional to the Higgs Yukawa couplings



$\mathcal{B} \propto g_u^2 \lambda^{\frac{1}{2}}(1, \frac{m_S^2}{m_\eta^2}, \frac{m_{\pi^0}^2}{m_\eta^2})$

- **Relic DM** benchmark
  - Freeze-out by $\chi\bar{\chi} \to \pi\pi$
  - **Excluded when $g_\chi = 0.1$**



$\bar{\sigma}_n \propto \frac{g_u^2 g_\chi^2}{m_S^4}(\frac{m_\chi m_N}{m_\chi + m_N})^2$

- **model-dependent**
  - Scattering mediated by on-shell S

- **UL on g_u @90% C.L.: $(1.3 \sim 3.2) \times 10^{-5}$**
  - Better than the result of atmospheric-boosted DM from PandaX-4T

- Constraint on DM-nucleon cross section ($\bar{\sigma}_n$)
  - **Improved by approximately 5 orders** of magnitude over previous DM-nucleon scattering experiments

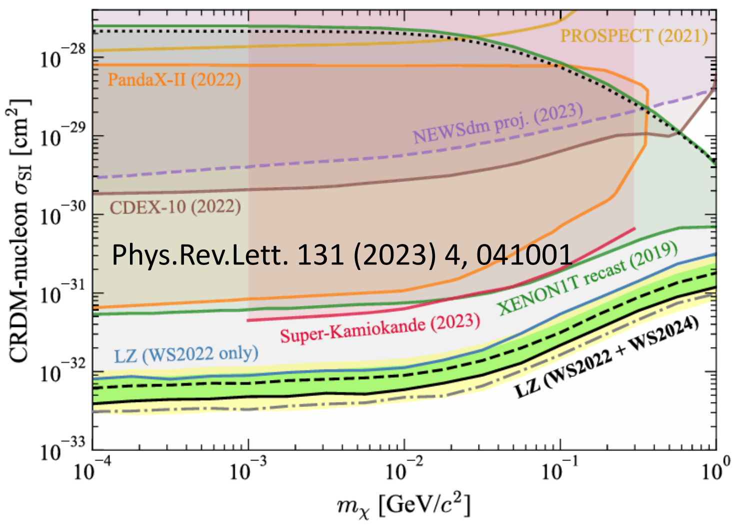
- **Ongoing and Future**
  - Larger S mass in $\eta' \to \pi^0 \chi\bar{\chi}$
  - Off-shell S case in $\eta \to \pi^0 \chi\bar{\chi}$
  - Pseudo-scalar case in $\eta \to \pi^+\pi^- \chi\bar{\chi}$
  - Vector case in $\pi^0/\eta \to \gamma\chi\bar{\chi}$
  - ......

Sub-GeV DM search status

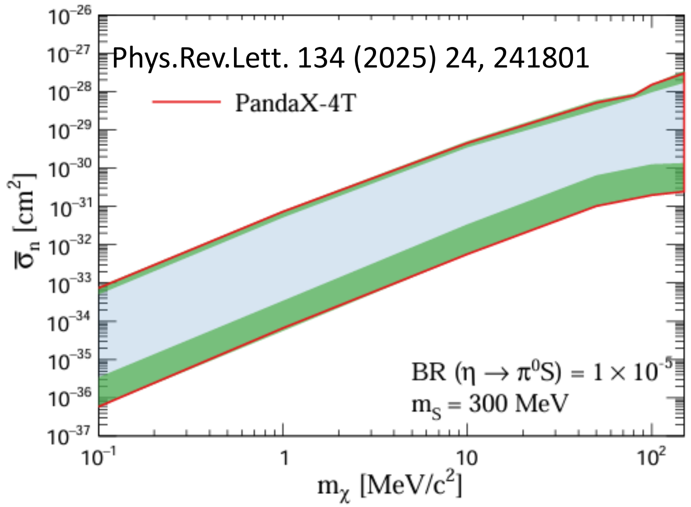
- The challenge of the sub-GeV DM detection

Non-relativistic velocities + Sub-GeV ⇨ Small recoil energy ⇨ Not exceed the detection threshold

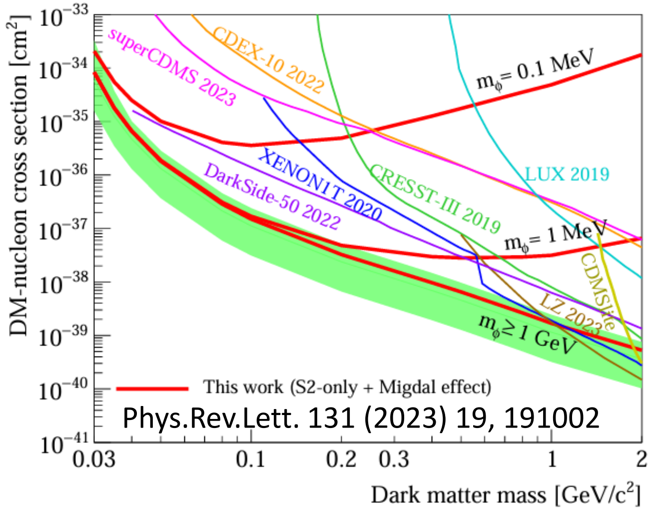
- **Solutions** of the sub-GeV DM detection: **1. boosted DM** **2. low threshold detection**



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 ~GeV region, can offer a unique opportunity to probe sub-GeV DM from the collider**