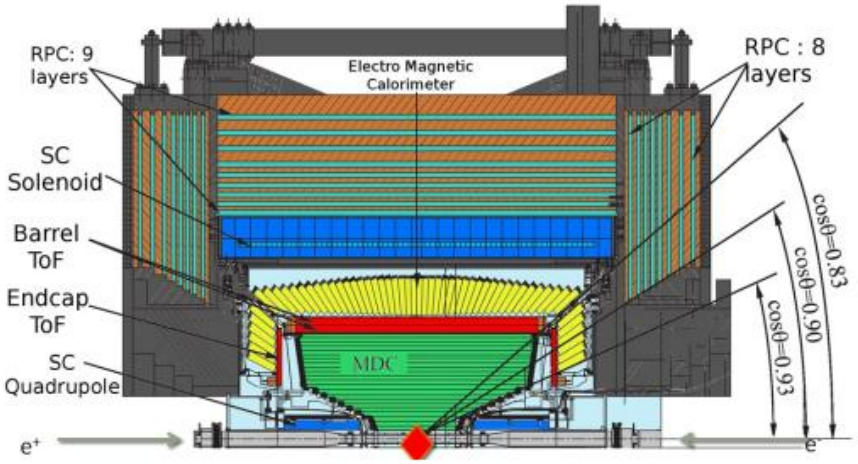
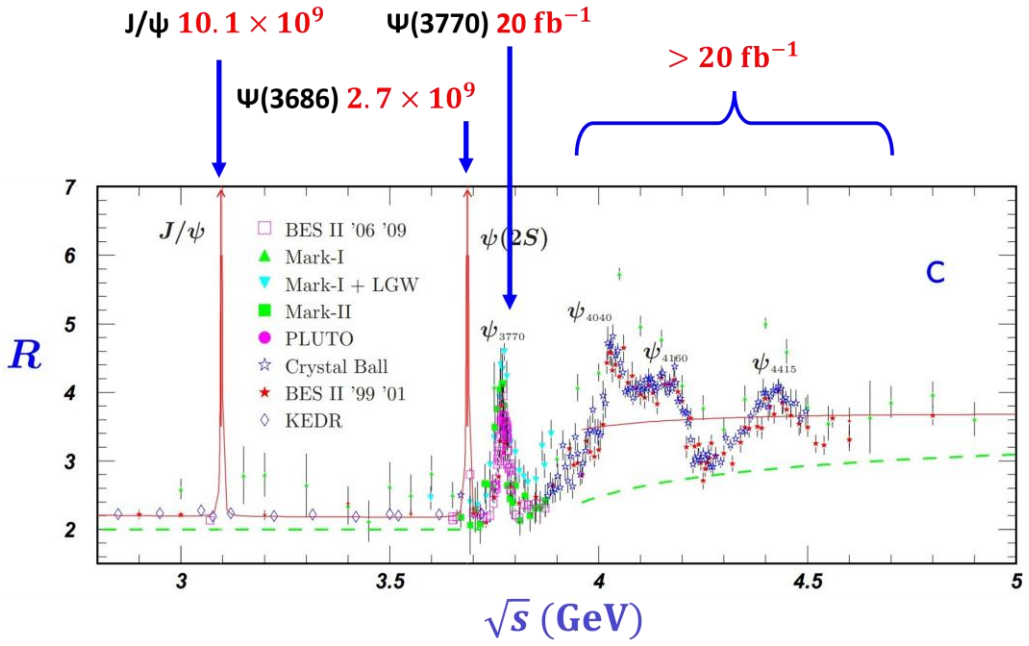
Search for dark sector at BESIII

Jin Zhang, Zhijun Li
Sun Yat-sen University
On behalf of the BESIII Collaboration
2026.7.16

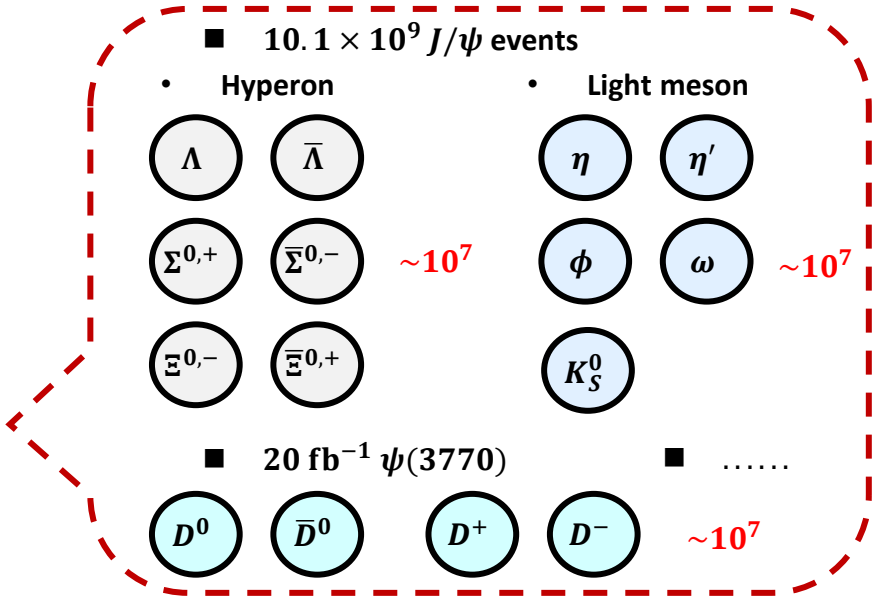
High Energy Physics Branch of CPS, Guangzhou

BESIII experiment

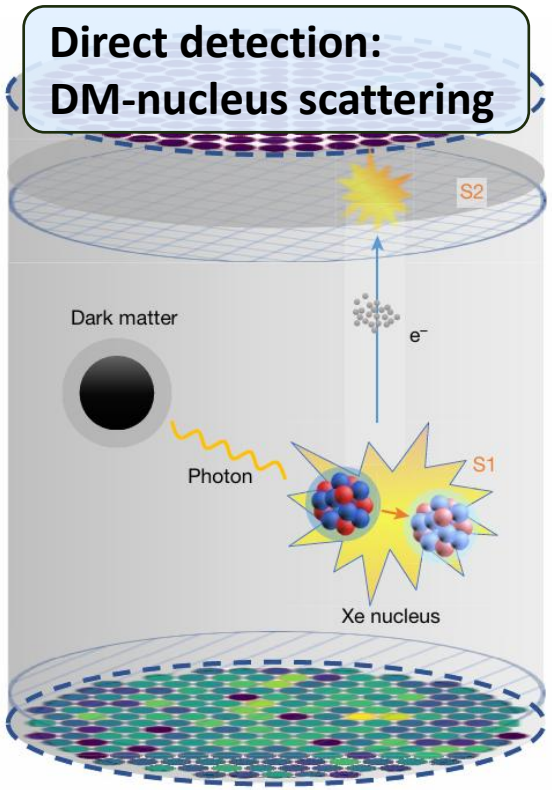


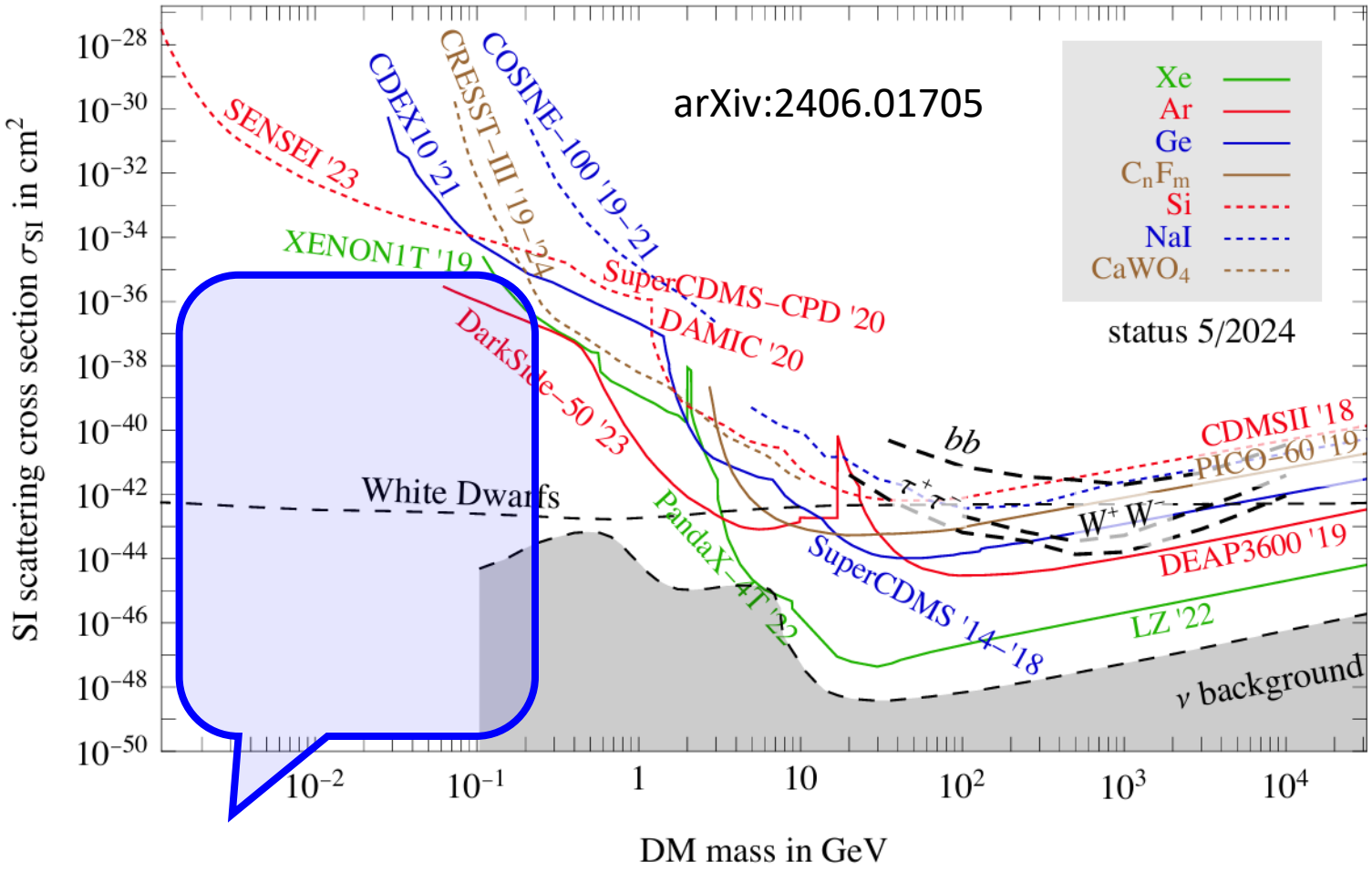


- Beijing electron-positron collider (BEPCII)
  - Peak luminosity : $1.1 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - CMS: 1.84 - 4.95 GeV, τ-charm region
- Good detector performance
  - MDC $\frac{\sigma_P}{P} = 0.5\%$ @1GeV/c
  - EMC Barrel(Endcap) $\frac{\sigma_E}{E} = 2.5\%(5.0\%)$ @1GeV/c
  - TOF Barrel(Endcap) $\sigma_T = 68(60)\mathrm{ps}$



DM search status





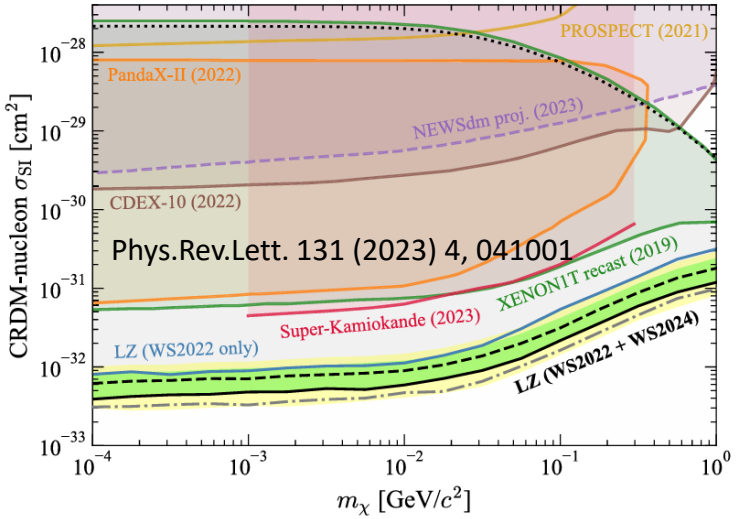
- GeV to TeV scale: strong constraint, not found any WIMP signal
- Sub-GeV: insufficient nuclear recoil energy to be detected, less exploration

Sub-GeV DM search status

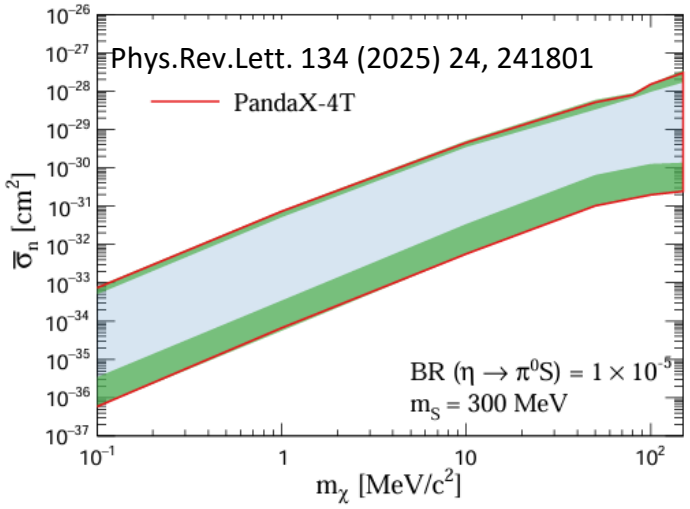
- The challenge of the sub-GeV DM detection

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

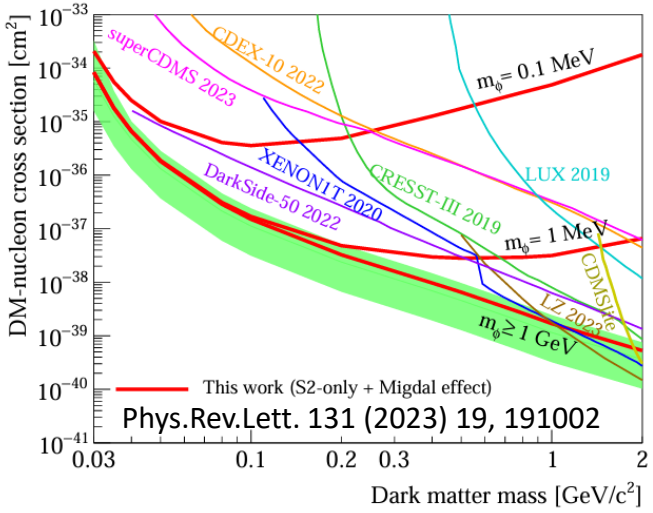
- **Solutions** of the sub-GeV DM detection: **1. boosted DM** **2. low threshold detection**



Cosmic-ray boosted DM



Atmospheric-meson-decay boosted DM

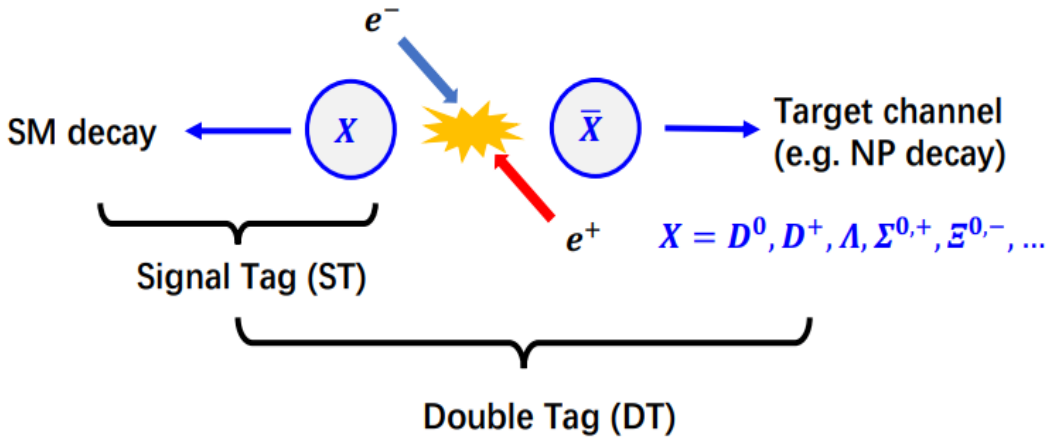


Migdal effect to lower the threshold

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

Dark sector search in BESIII

- Advantages for searching dark sector and rare decays
  - clean sample with low background
  - absolute branching fraction measurement, $\mathcal{B} = \frac{N_{DT}/\epsilon_{DT}}{N_{ST}/\epsilon_{ST}}$
  - Missing energy/mass for invisible particle



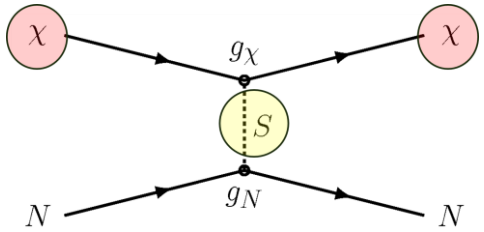
- New researches for dark sector in this talk:
  - $\eta \to \pi^0 + \text{invisible}$
  - $J/\psi \to \phi + \text{invisible}$
  - $K_S^0 \to \text{invisible}$
  - $\Xi^- \to \pi^- + \text{invisible}$
  - $D^0 \to \omega + \text{invisible}$，$D^0 \to \gamma + \text{invisible}$

arXiv: 2601.10597, PRL accepted, editor's suggestion

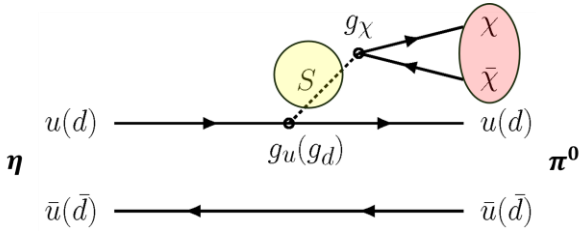
Search for $\eta \to \pi^0 +$ invisible at BESIII

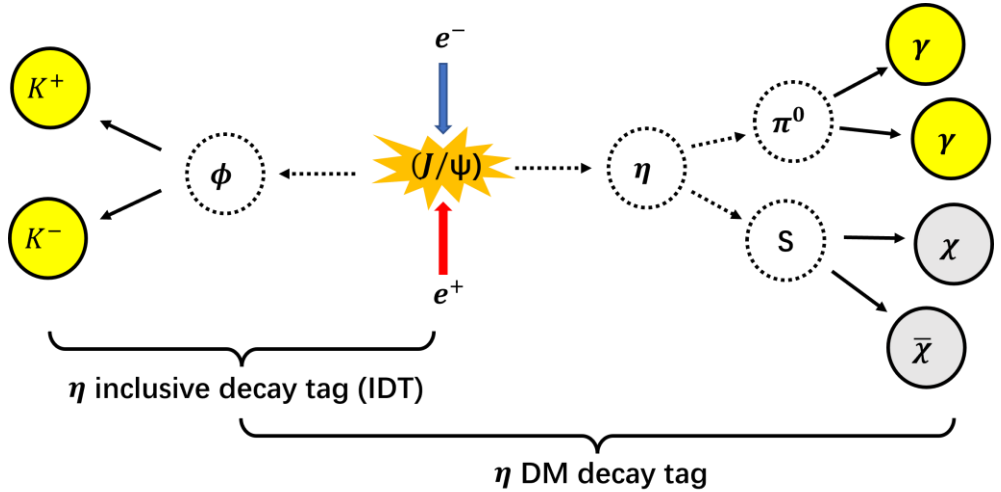
- Data set @ 3.097 GeV $(10087 \pm 44) \times 10^6$ J/ψ, $J/\psi \to K^+K^-\eta$; $\sim 2 \times 10^6$ η events are tagged
- On-shell $S \to \chi\bar{\chi}$, S mass from ~0 to 400 MeV
- **UL on $\mathcal{B}(\eta \to \pi^0 S)$ @90% C.L.: $(1.8 \sim 5.5) \times 10^{-5}$**

DM-nucleon scattering

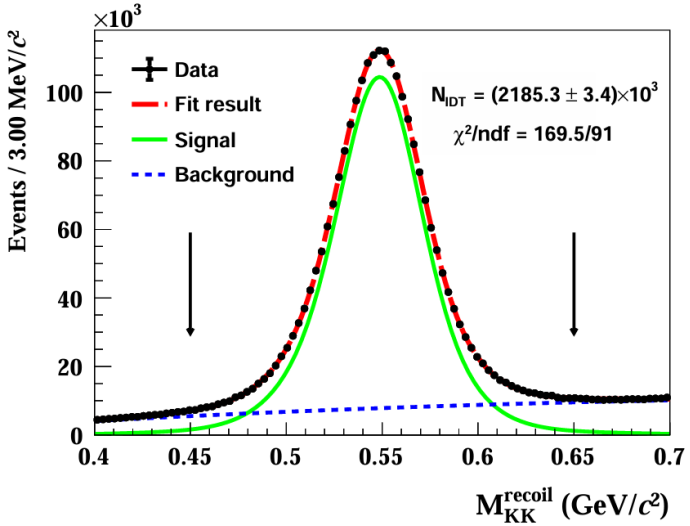


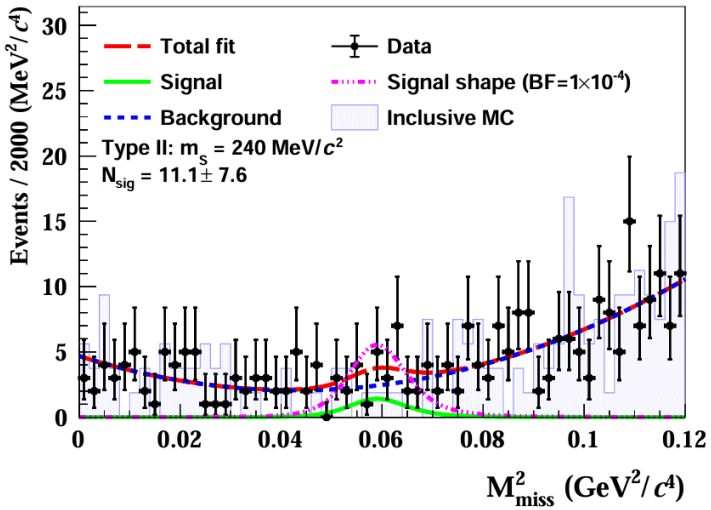
$\eta \to \pi^0 S \to \pi^0 \chi\bar{\chi}$ decay

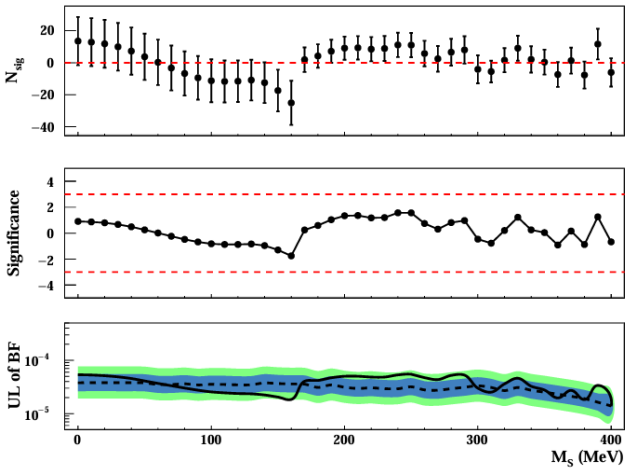




- The two processes involve the same new physics







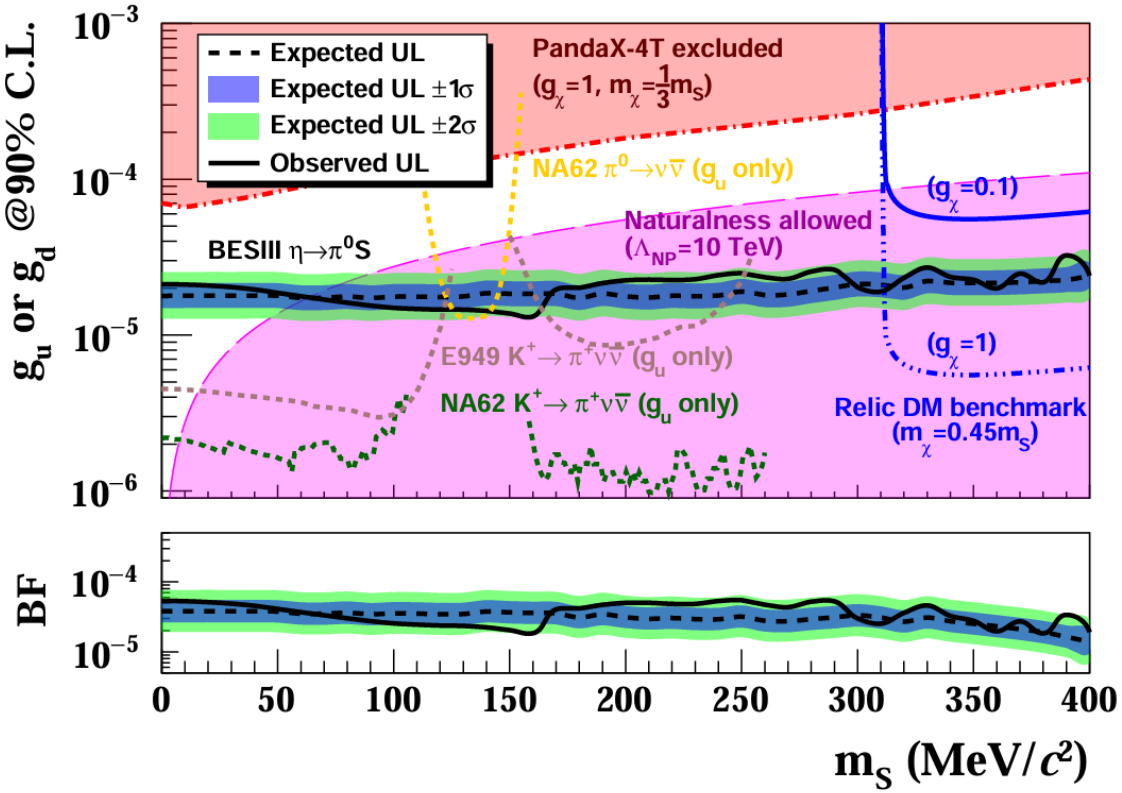
arXiv: 2601.10597, PRL accepted, editor's suggestion

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

- **Flavor-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

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

- **UL on g_u or g_d @90% C.L.: $(1.3 \sim 3.2) \times 10^{-5}$**
  - 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 $g_\chi = 0.1$**



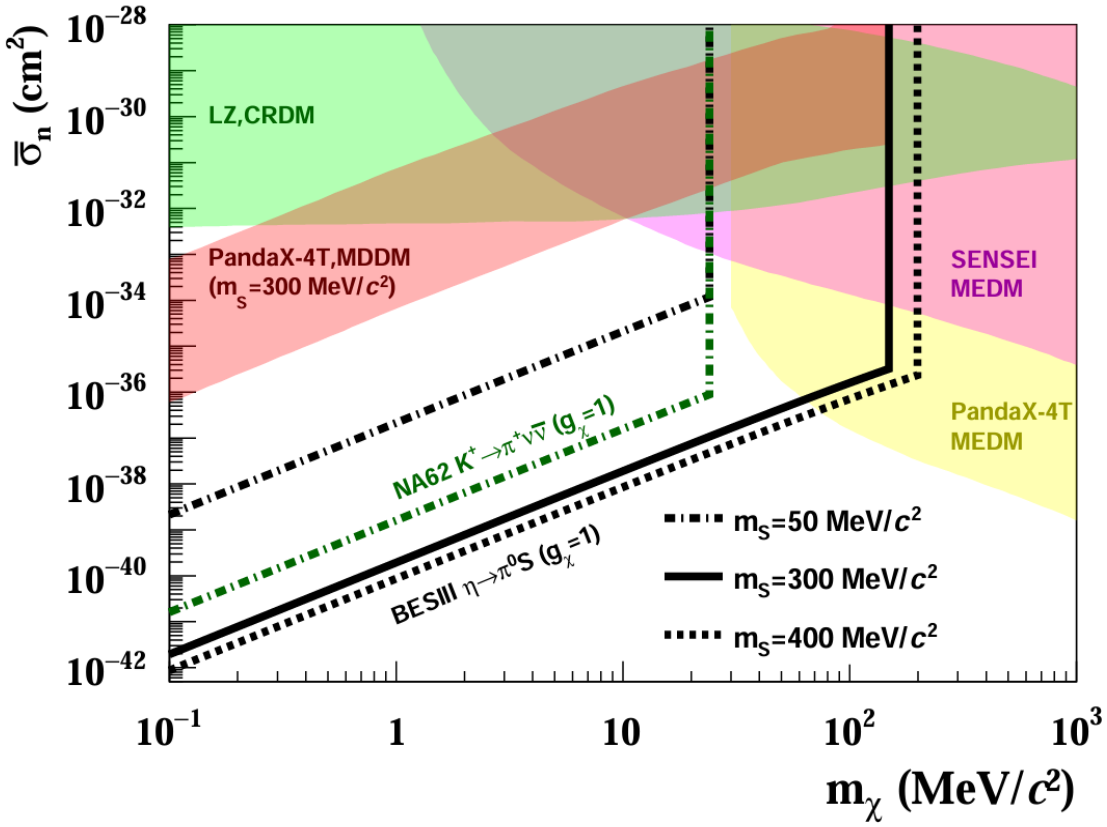
arXiv: 2601.10597, PRL accepted, editor's suggestion

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

- **Flavor-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

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

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

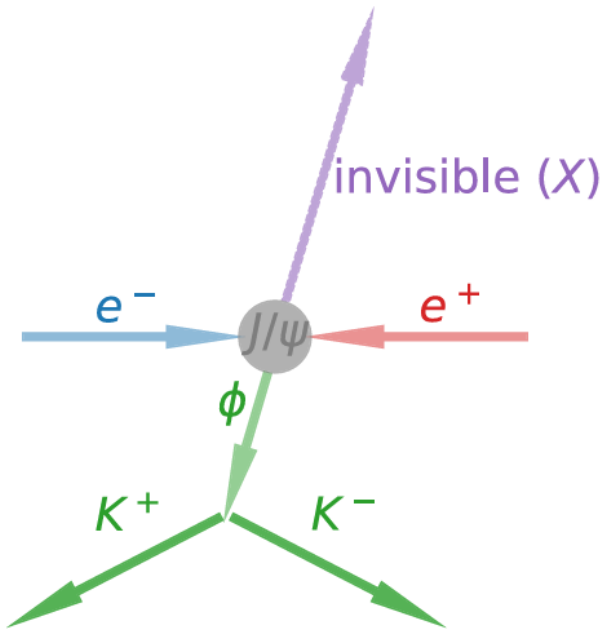


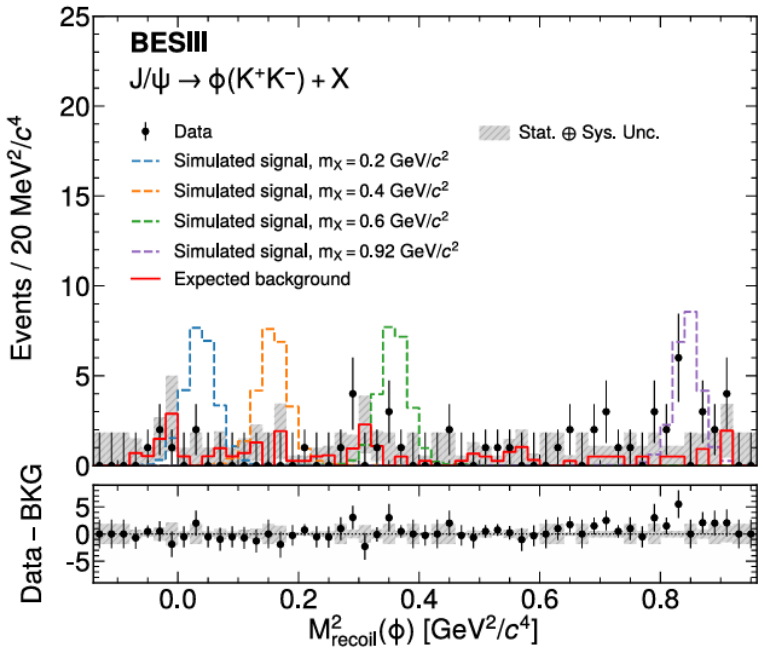
- **Model-dependent constraint**:
- Scattering mediated by on-shell S
  - **Ongoing and Future**
  - Off-shell S case in $\eta \to \pi^0 \chi \bar{\chi}$
  - Larger S mass in $\eta' \to \pi^0 \chi \bar{\chi}$
  - Pseudo-scalar case in $\eta \to \pi^+ \pi^- \chi \bar{\chi}$
  - Vector case in $\pi^0/\eta \to \gamma \chi \bar{\chi}$
  - ……

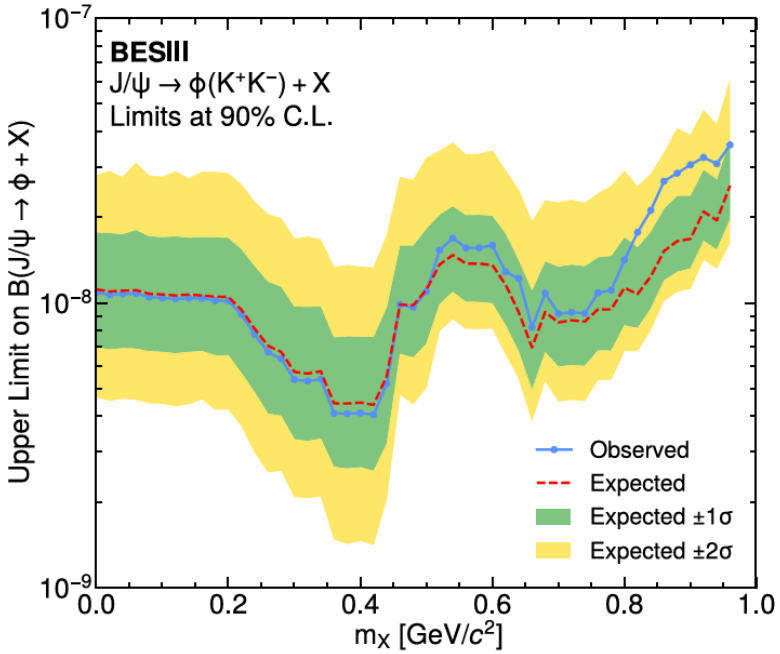
Phys.Rev.Lett. 135, 151804 (2025)

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

- $(8774.0 \pm 39.4) \times 10^6$ J/ψ events
- **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 $J/\psi \to \phi X$: $\mathbf{7.0 \times 10^{-8}}$ @90% C.L.
  - Taking $X = \eta$, **UL on $\mathcal{B}(\eta \to$ invisible$)$: $\mathbf{2.4 \times 10^{-5}}$**@90% C.L., improved by more than 4 times



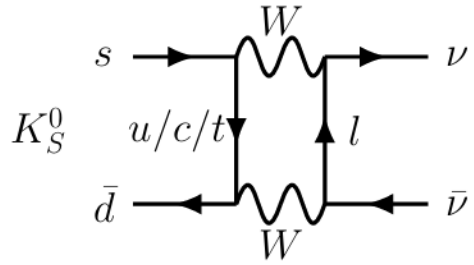




K_S invisible decay

◆ **Why search for K_S -> invisible**

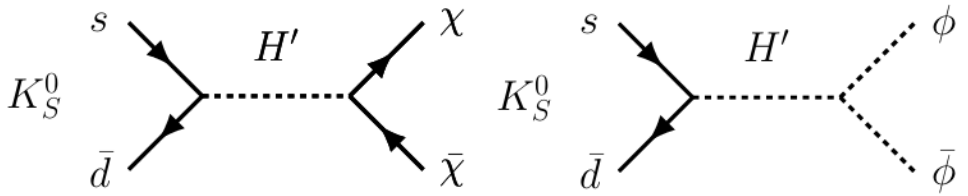
SM decay



$BF < 10^{-16}$
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

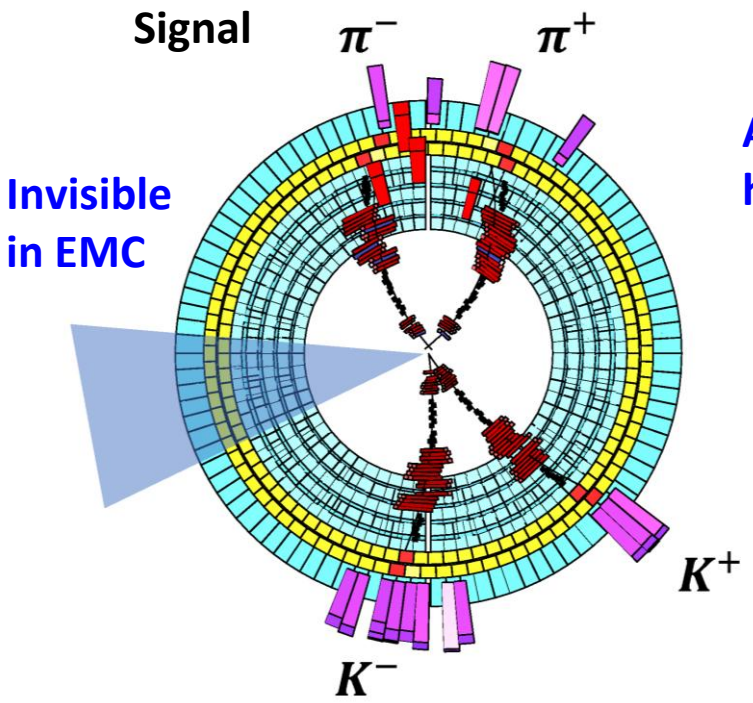
Input for CPT test

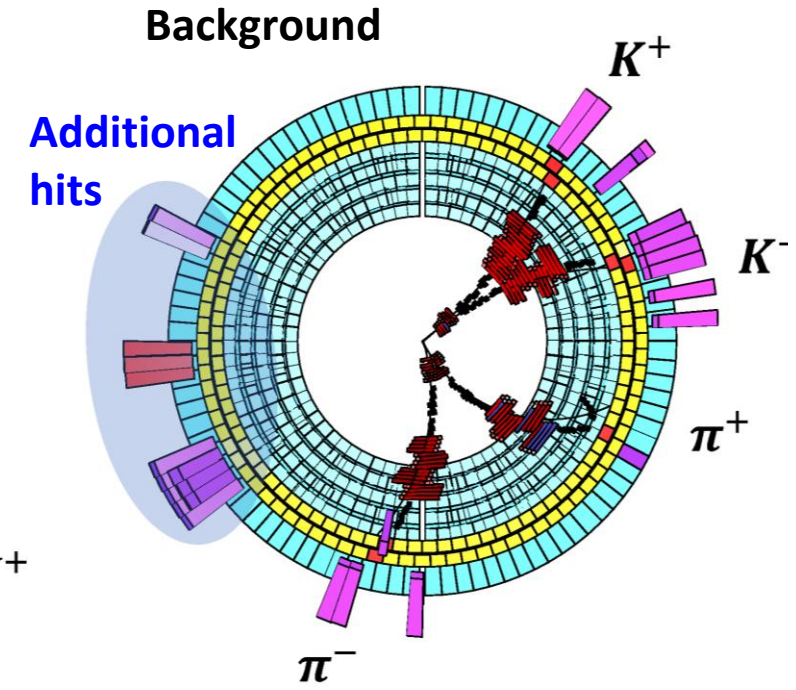
Bell-Steinberger relation **connects CPTV** to the amplitudes of all decay channels of neutral kaons.
BUT currently assumes no invisible modes

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

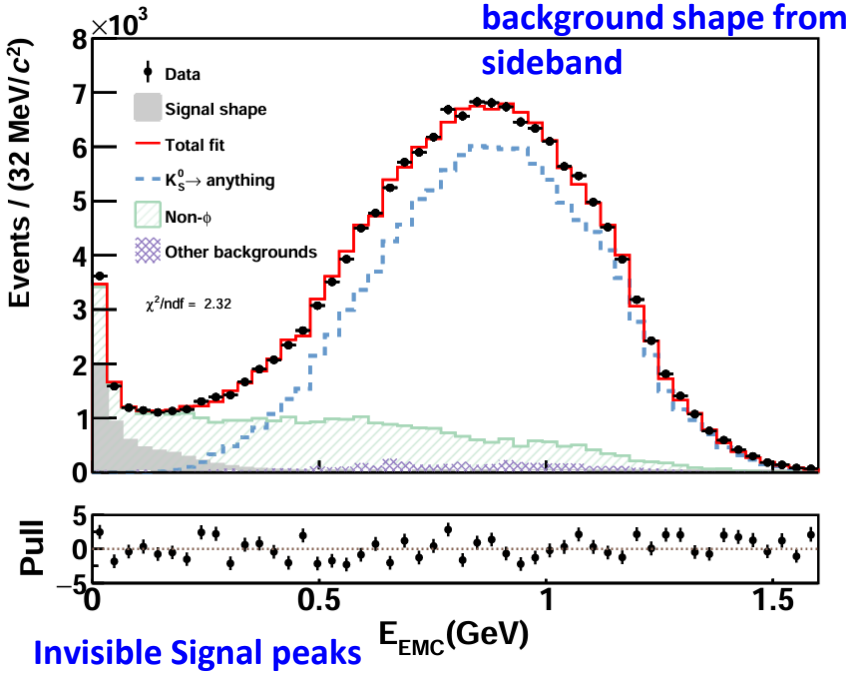
Search for $K_S \to$ invisible at BESIII

- $J/\psi \to \phi K_S^0 K_S^0$ from $\mathbf{10^{10}}$ **J/ψ**
- $J/\psi \to \phi K_S^0 \boldsymbol{K_L^0}$ is forbidden with C Parity conservation, lower background still have $J/\psi \to K^+K^-K_S^0K_L^0$
- $N_{\rm sig} = 56 \pm 201$ UL: $\boldsymbol{\mathcal{B}(K_S^0 \to \text{invisible}) < 8.4 \times 10^{-4}}$ @90% C.L.
- **First direct measurement of $K_S^0 \to$ invisible**; **the UL still lies above the NP prediction**





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



Invisible Signal peaks around zero

Dark baryon

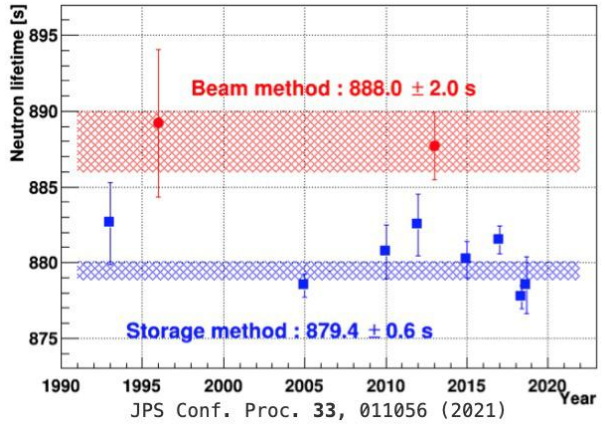
Coincidence problem

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



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

- **Motivates the existence of dark baryon**

B-Mesogenesis mechanism

CP asymmetry in $B \to$ baryon + dark baryon

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

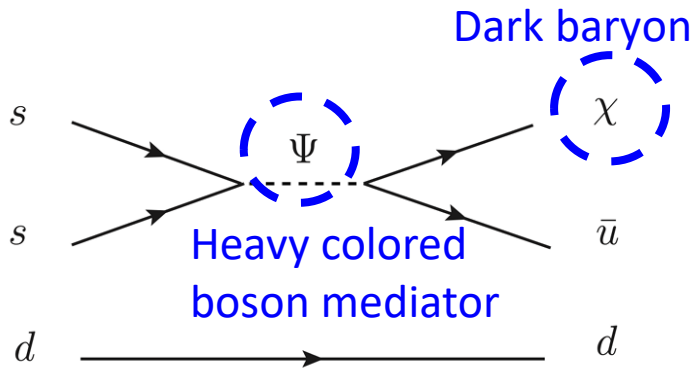
Naturally, dark baryon interacts with all SM quark flavor

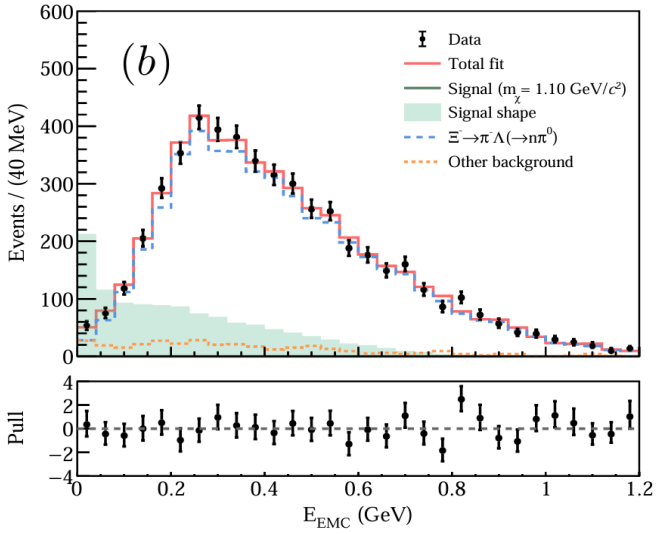
$\Longrightarrow$ **Search for dark baryon in hyperon decay at BESIII**

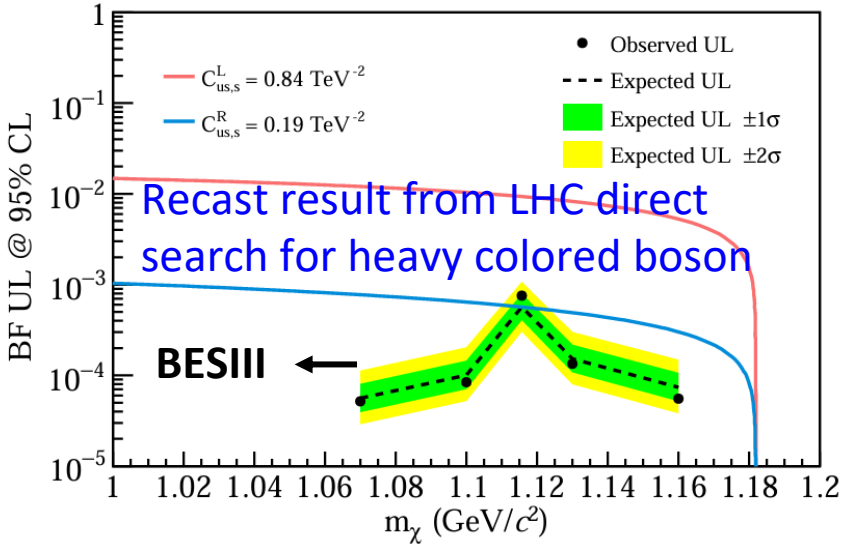
Phys. Lett. B 872 (2026) 140099

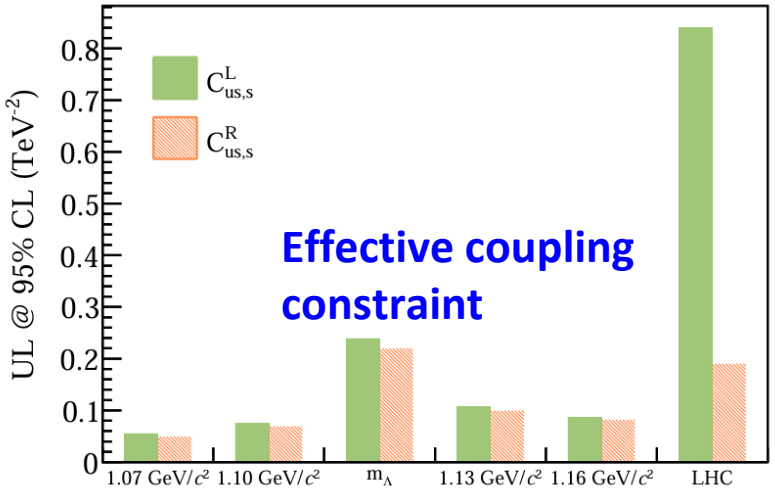
Search for $\Xi^- \to \pi^- +$ invisible at BESIII

- $J/\psi \to \bar{\Xi}^+\Xi^-$ from 10^{10} J/ψ
- $\bar{\Xi}^+ \to$ SM, $\Xi^- \to \pi^-\chi$
- Deposited energy in EMC used to identify the invisible signal
- Dark baryon χ with mass hypothesis of **1.07, 1.10, m_Λ, 1.13, 1.16 GeV**



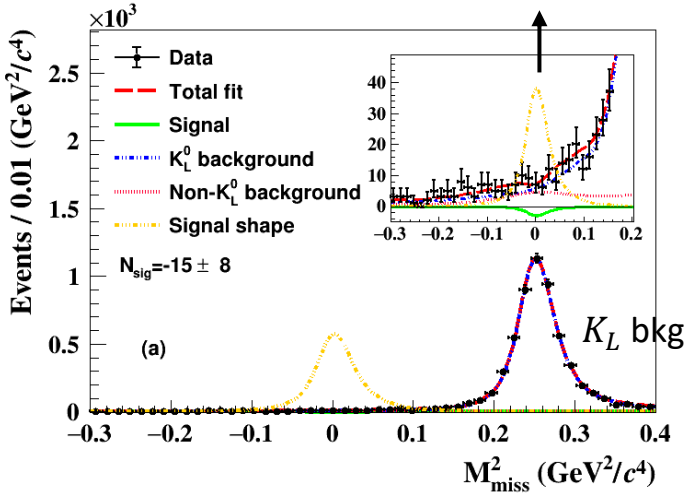




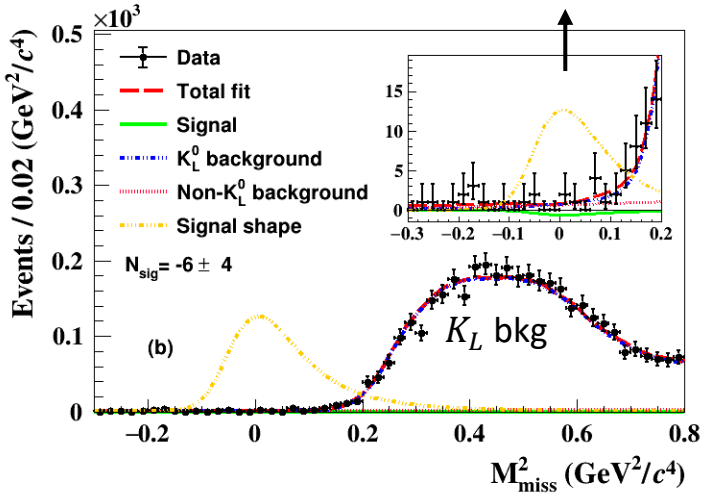


Search for $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$ at BESIII

Signal should peak at zero



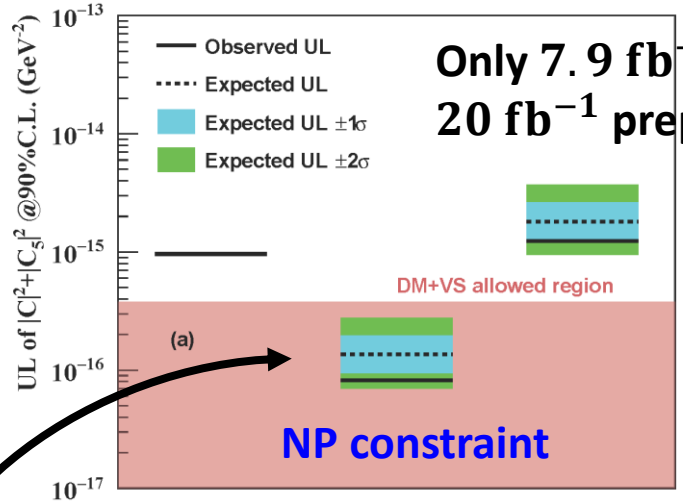
Signal should peak at zero

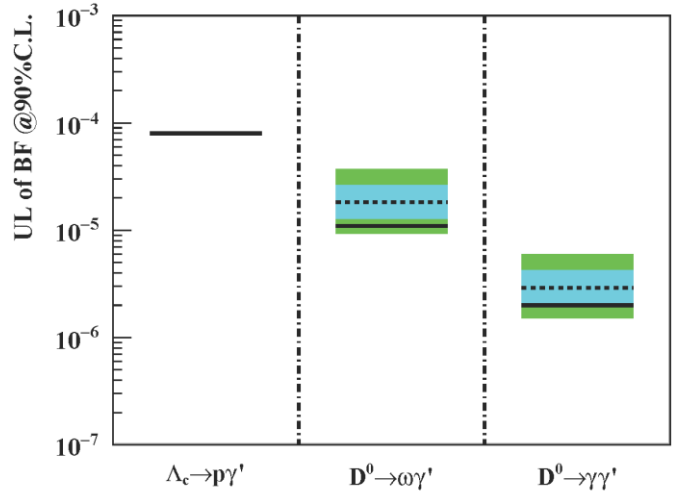


Signal extraction of $D^0 \to \omega\gamma'$

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

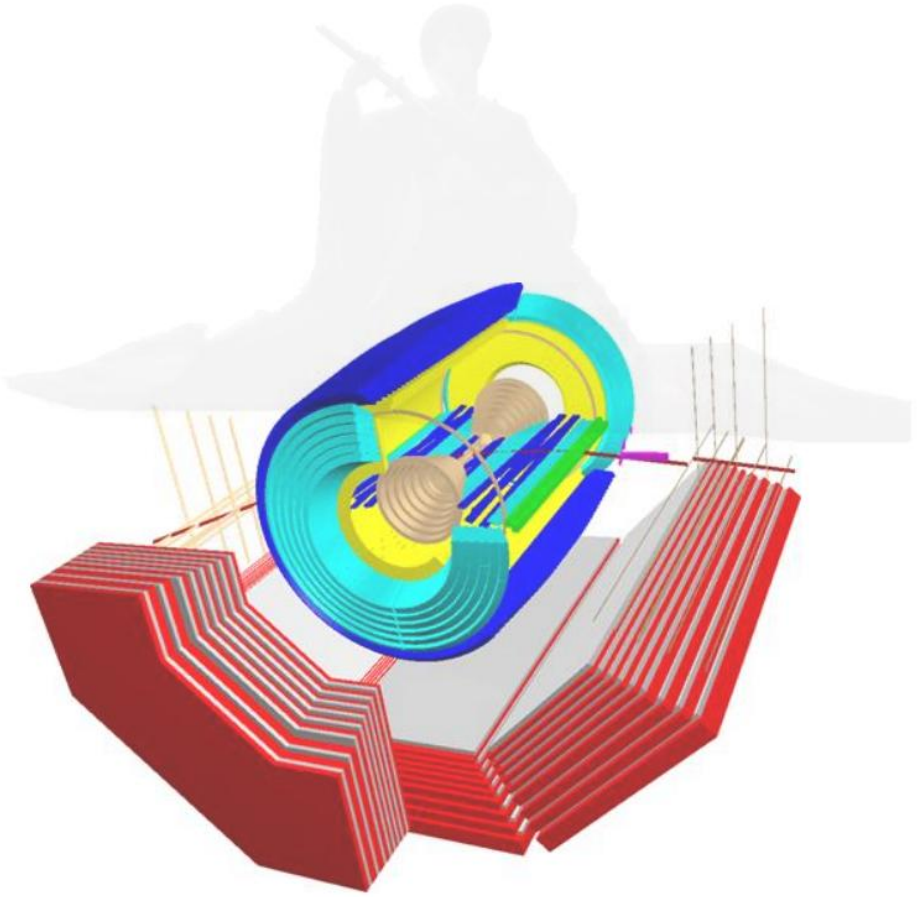
- **First search** for massless dark photon in D meson decay
- The constraint from $D^0 \to \omega\gamma'$ goes into the dark matter (DM) and vacuum stability (VS) allowed region for the first time, **improved by more than 1 order**





Summary

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

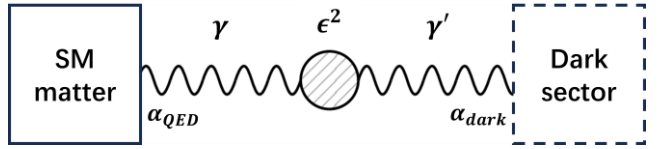


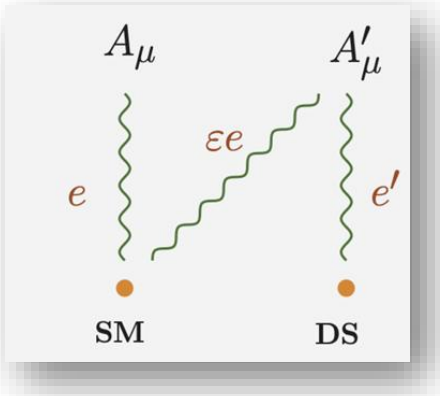
- **BESIII has collected 10^{10} J/ψ, 2.7×10^9 ψ', 20 fb^{-1} @ 3.77 GeV data ($D\bar{D}$) and more…**
- **More & better results are coming soon**

Backup

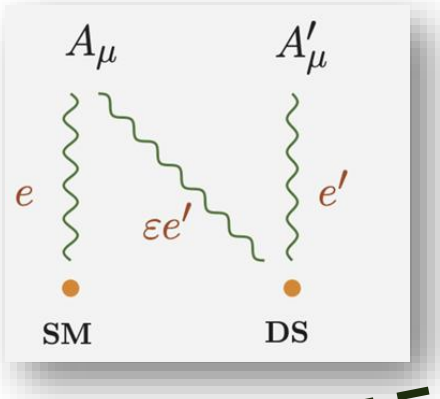
Massless dark photon

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





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



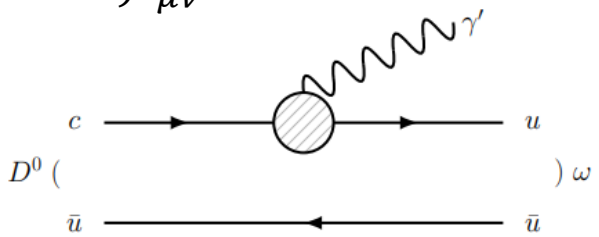
- **Massless dark photon**
- No direct coupling with SM fermion
- Less constraint
- Also important role in dark sector

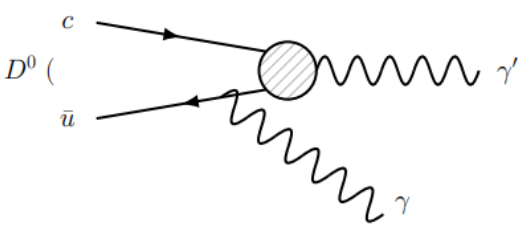
Searching for the massless case can only be in the higher dimension operator:

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

PRL 94, 151802 (2005)

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



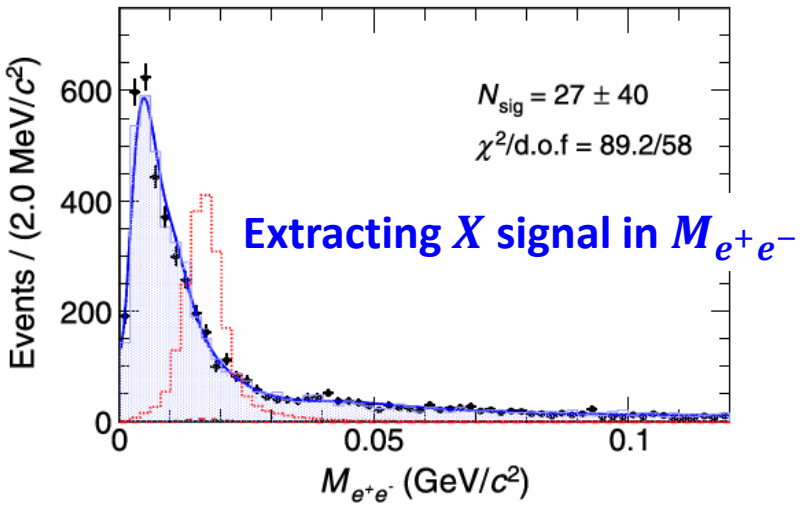


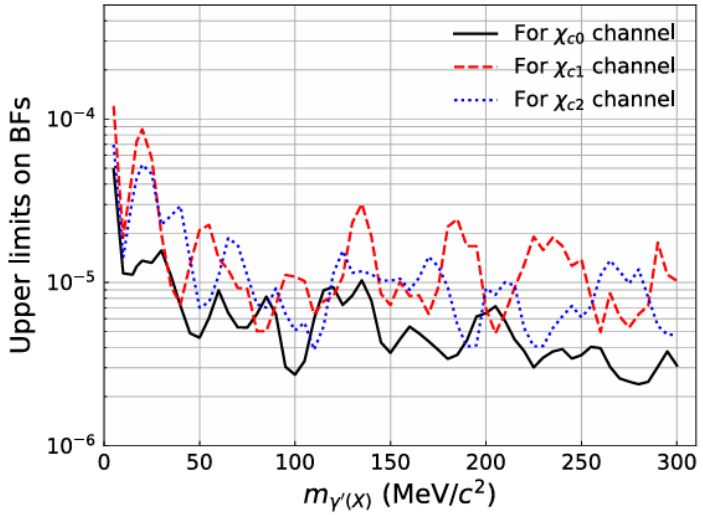
New searches at BESIII: through $cu\gamma'$ coupling in $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$

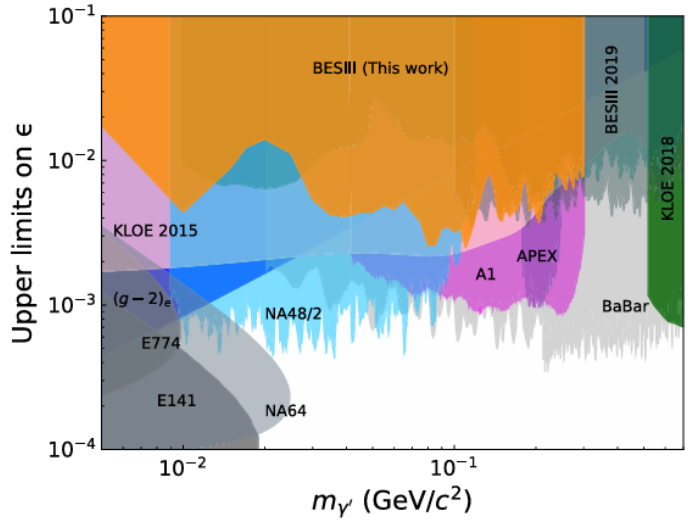
Phys.Rev.D 113 (2026) 3, 032009

Search for $\chi_{cJ} \to J/\psi\, X, X \to e^+e^-$ 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 $X \to f\bar{f}$
- Data set: 2.7×10^9 **$\psi(2S)$**
  - χ_{cJ} from $\psi(2S) \to \gamma\chi_{cJ}$







- UL on $\mathcal{B}(\chi_{cJ} \to J/\psi\, X) \times \mathcal{B}(X \to e^+e^-)$ @90% C.L.: $\mathbf{2 \times 10^{-6} \sim 10^{-4}}$ for X mass ranging from 5 to 300 MeV
- **Coupling strength with charm quark** @90% C.L.: $\mathbf{(2.5 \sim 17.5) \times 10^{-3}}$ (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