



BESIII

Search for dark sector at BESIII

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On behalf of BESIII Collaboration

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BESIII experiment

- ◆ Beijing electron-positron collider (BEPCII)

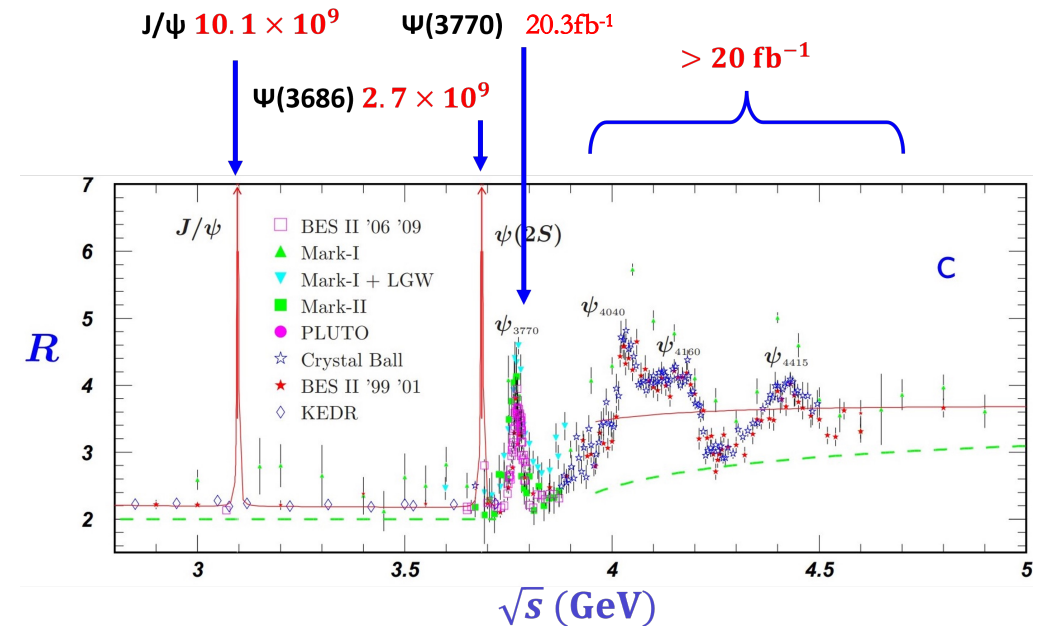
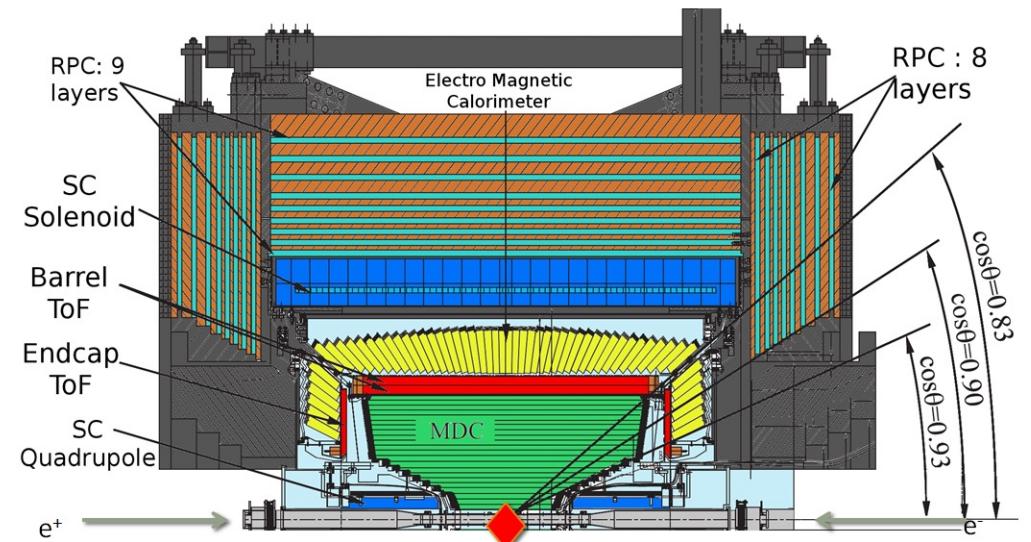
- Peak luminosity : $1.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- CMS: 1.84 - 4.95 GeV, τ -charm region

- ◆ Good detector performance

- Main Drift Chamber (MDC) $\sigma_P/P = 0.5\% @ 1 \text{ GeV}/c$
- EMC Barrel(Endcap) $\sigma_E/E = 2.5\%(5.0\%) @ 1 \text{ GeV}/c$
- TOF Barrel(Endcap) $\sigma_T = 68(60) \text{ ps}$
- MUC $P_{\text{cut-off}} = 0.4 \text{ GeV}$

- ◆ Large and clean sample

- 10 billion J/ψ , 2.7 billion $\psi(2S)$ events
 - hyperon $\Lambda, \Sigma^{0,+}, \Xi^{0,-} \sim 10^7$
 - light meson $\eta, \eta', \phi, \omega, K_S^0 \sim 10^7$
- $20.3 \text{ fb}^{-1} \psi(3770)$ events
 - D meson pair $\sim 10^7$

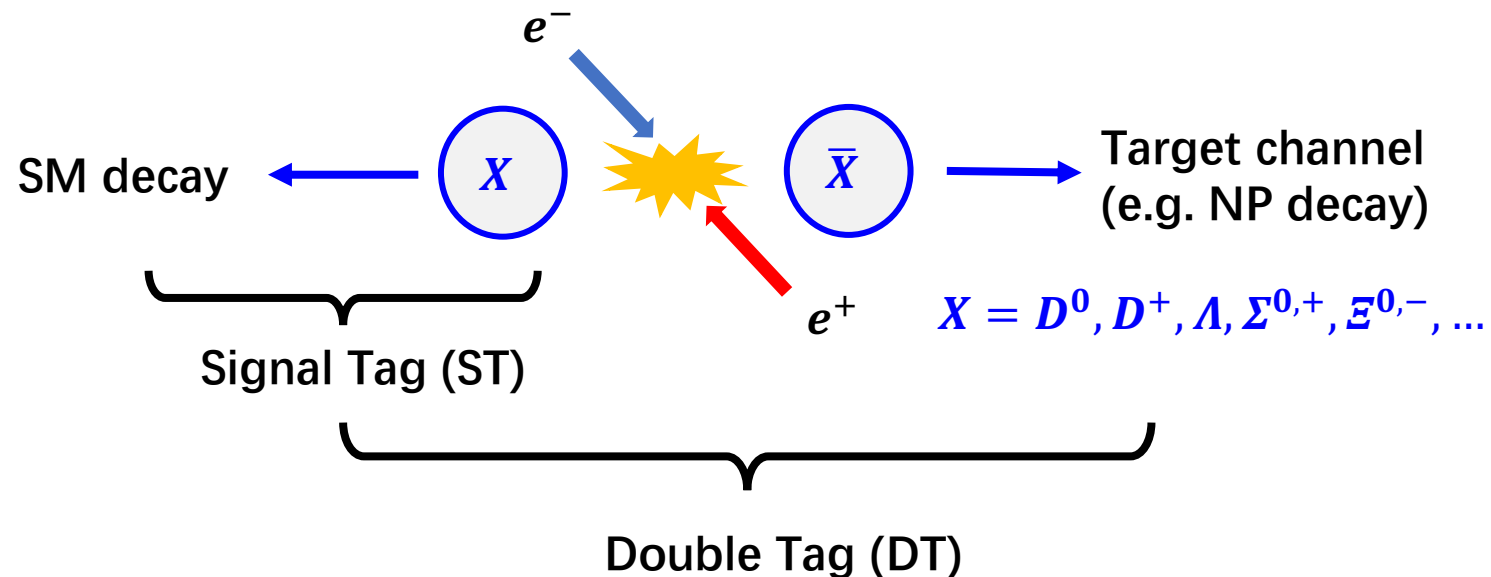


Double tag analysis at BESIII

◆ Advantages for searching dark sector and rare decays

- absolute branching fraction measurement, $\mathcal{B} = \frac{N_{DT}/\epsilon_{DT}}{N_{ST}/\epsilon_{ST}}$
- systematic uncertainty cancellation
- clean sample, low background
- partial reconstruction, recoil system
- missing mass, missing deposited energy (invisible particle)

dark sector search



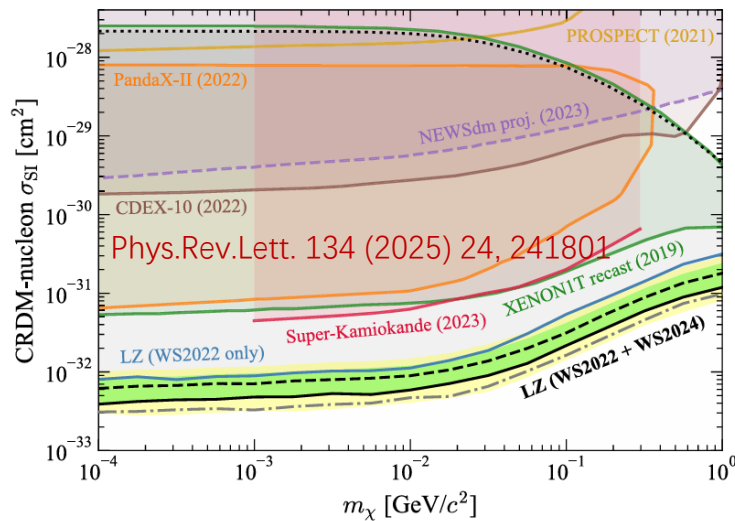
Sub-GeV DM search status

◆ The challenge of the sub-GeV DM detection

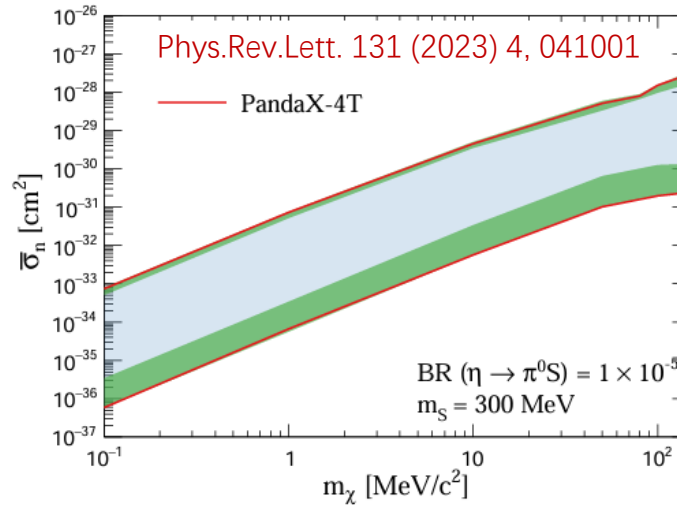
- small recoil energy
- below the detection threshold

◆ Solutions of the sub-GeV DM detection:

1. boosted DM

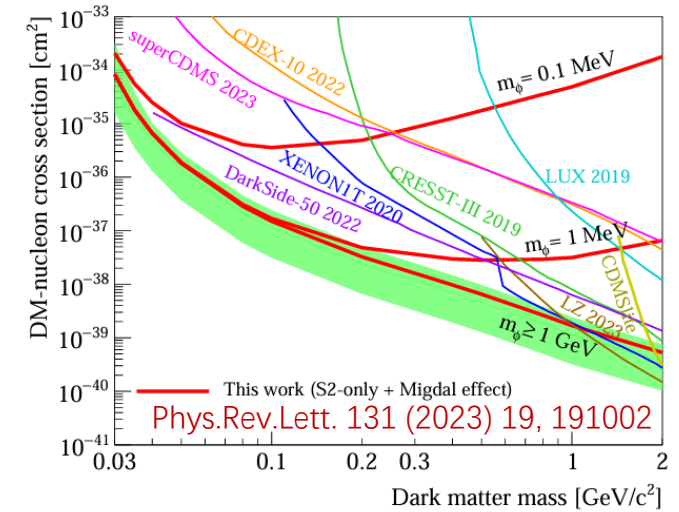


Cosmic-ray boosted DM



Atmospheric-meson-decay boosted DM

2. low threshold detection



Migdal effect to lower the threshold

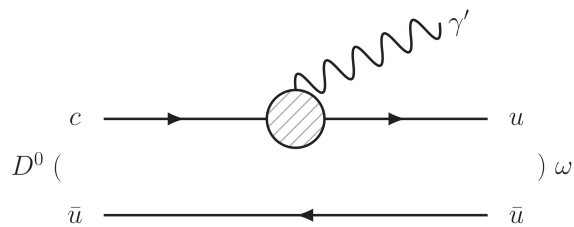
◆ BESIII operates in \sim GeV region, offers a unique opportunity to probe sub-GeV DM from the collider

Some new searches for dark sector at BESIII

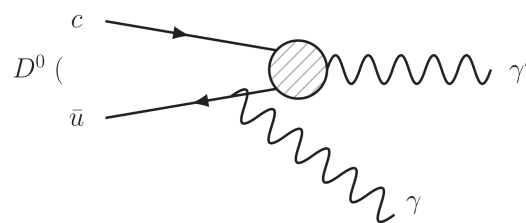
- ◆ FCNC $c \rightarrow u\gamma'$ process: $D^0 \rightarrow \omega\gamma'$ and $D^0 \rightarrow \gamma\gamma$
- ◆ $\eta \rightarrow \pi^0 + \text{invisible}$, $J/\psi \rightarrow \phi + \text{invisible}$ ($\eta \rightarrow \text{invisible}$)
- ◆ K_S invisible decay
- ◆ Dark baryon: $\Xi^- \rightarrow \pi^- + \text{invisible}$
- ◆ Light vector boson X / dark photon γ' in $\chi_{cJ} \rightarrow J/\psi X(\gamma')$, $X(\gamma') \rightarrow e^+e^-$
- ◆ Axion like particle: $J/\psi \rightarrow \gamma a_{\gamma\gamma}$

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

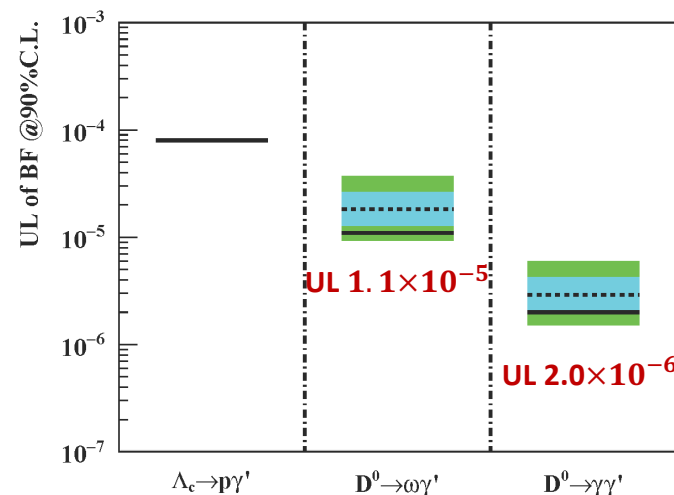
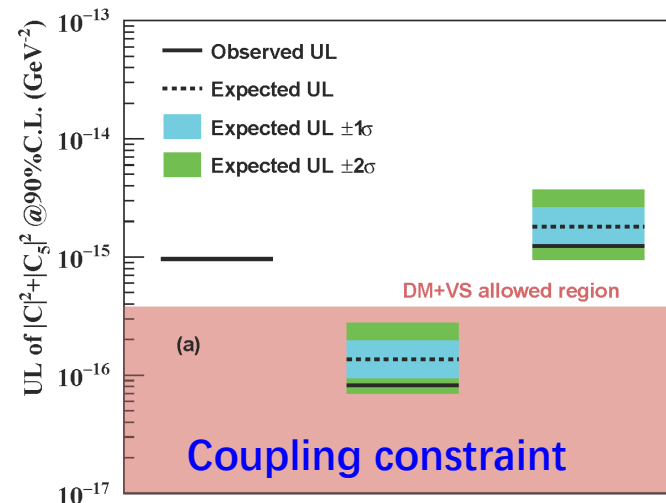
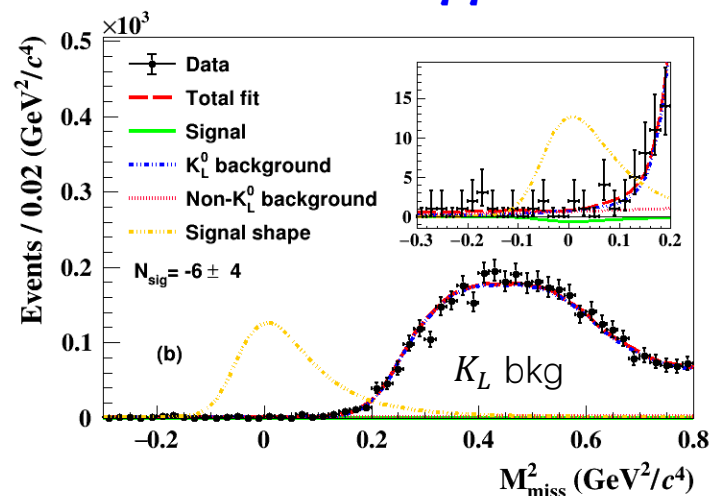
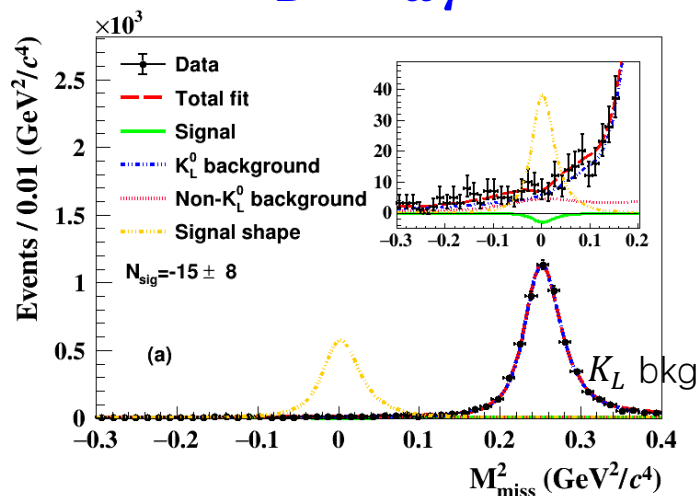
- ◆ FCNC process $c \rightarrow u\gamma'$
- ◆ $7.9 \text{ fb}^{-1}\psi(3770)$ data used, 20.3 fb^{-1} prepared
- ◆ First search for massless dark photon in D meson decay
- ◆ The constraint from $D^0 \rightarrow \omega\gamma'$ goes into the DM and vacuum stability allowed region for the first time, improved by more than 1 order



$D^0 \rightarrow \omega\gamma'$

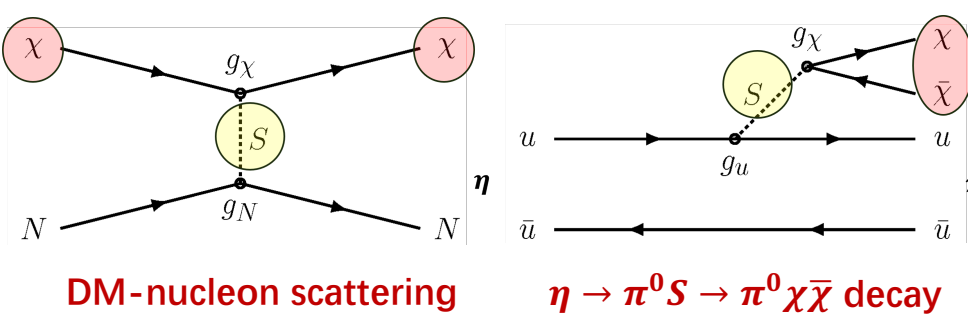


$D^0 \rightarrow \gamma\gamma'$

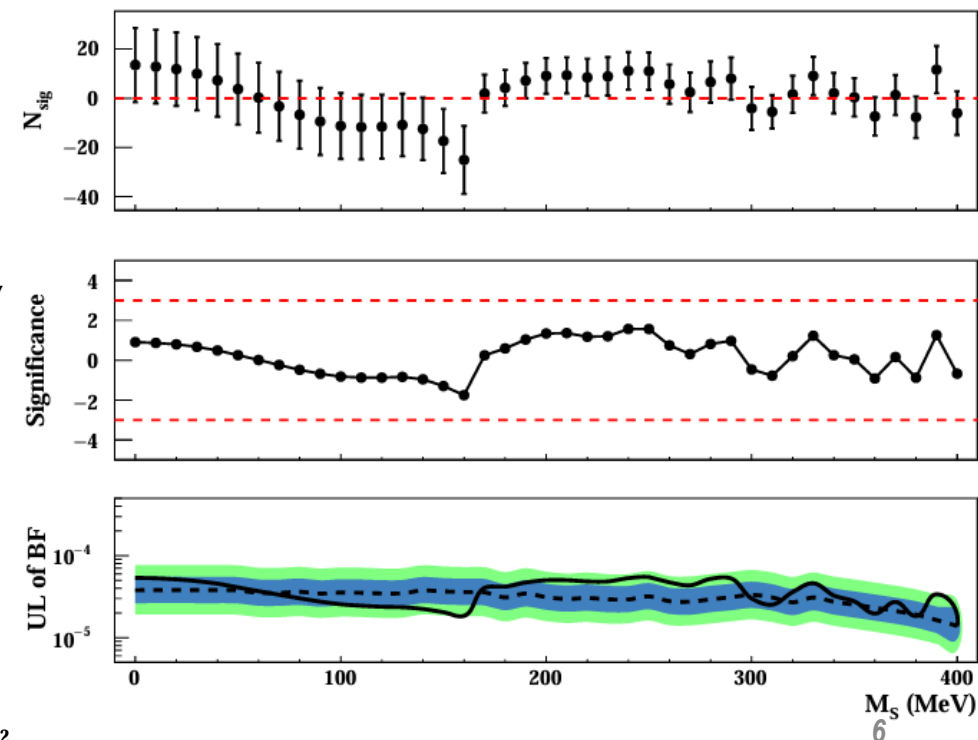
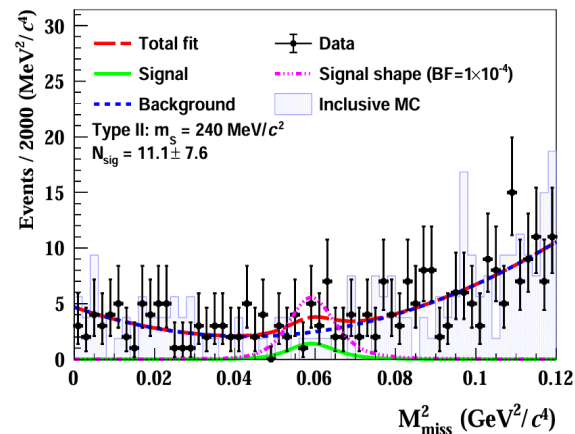
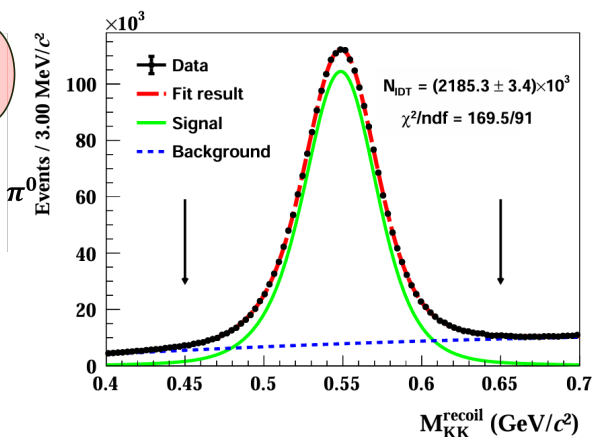
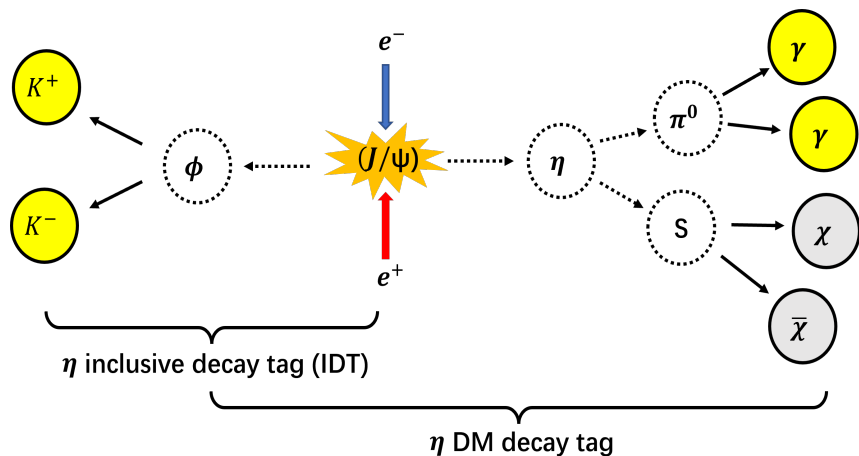


Search for $\eta \rightarrow \pi^0 +$ invisible at BESIII

- ◆ Data set $(10087 \pm 44) \times 10^6 J/\psi, \eta$ from $J/\psi \rightarrow K^+ K^- \eta$
- ◆ $\eta \rightarrow \pi^0 S \rightarrow \pi^0 \chi \bar{\chi}$ has the largest BF under the equal coupling strength
- ◆ $\sim 2 \times 10^6$ clean tagged η events from the recoiling mass of $K^+ K^-$
- ◆ On-shell $S \rightarrow \chi \bar{\chi}$, $m_S: \sim 0$ to 400 MeV, UL on $\mathcal{B}(\eta \rightarrow \pi^0 S)$ @90% C.L.: $(1.8 \sim 5.5) \times 10^{-5}$



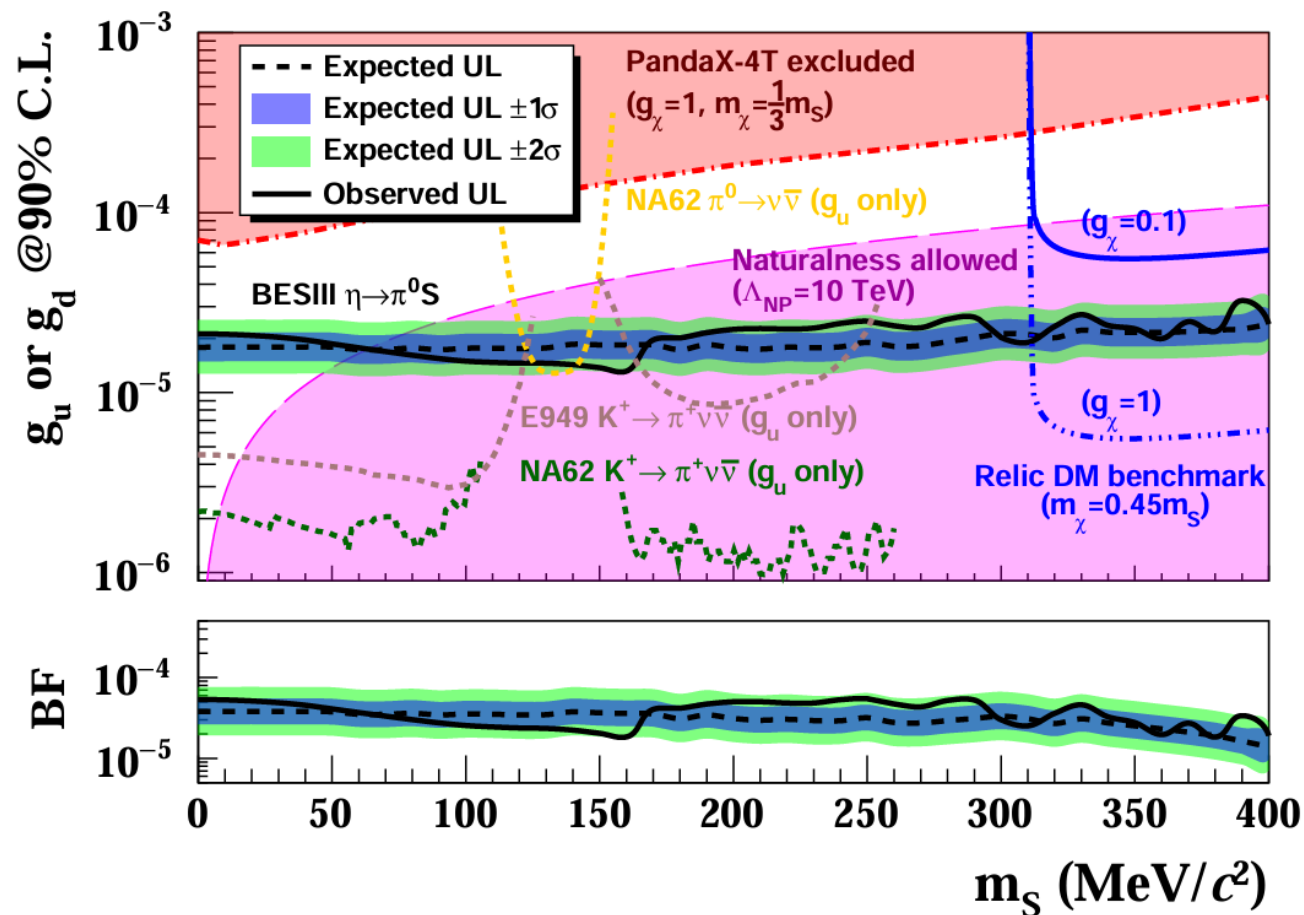
S is a dark scalar boson, and χ is the DM



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

- ◆ Flavor-specific model: $\mathcal{L} \supset -g_\chi S \bar{\chi}_L \chi_R - g_u S \bar{u}_L u_R + h.c.$, $g_u \equiv \frac{c_S v}{\sqrt{2} \Lambda_{\text{NP}}}$ $B \propto g_u^2 \lambda^{\frac{1}{2}} \left(1, \frac{m_S^2}{m_\eta^2}, \frac{m_{\pi^0}^2}{m_\eta^2}\right)$
- ◆ UL on g_u or g_d @ 90% C.L.: $(1.3 \sim 3.2) \times 10^{-5}$

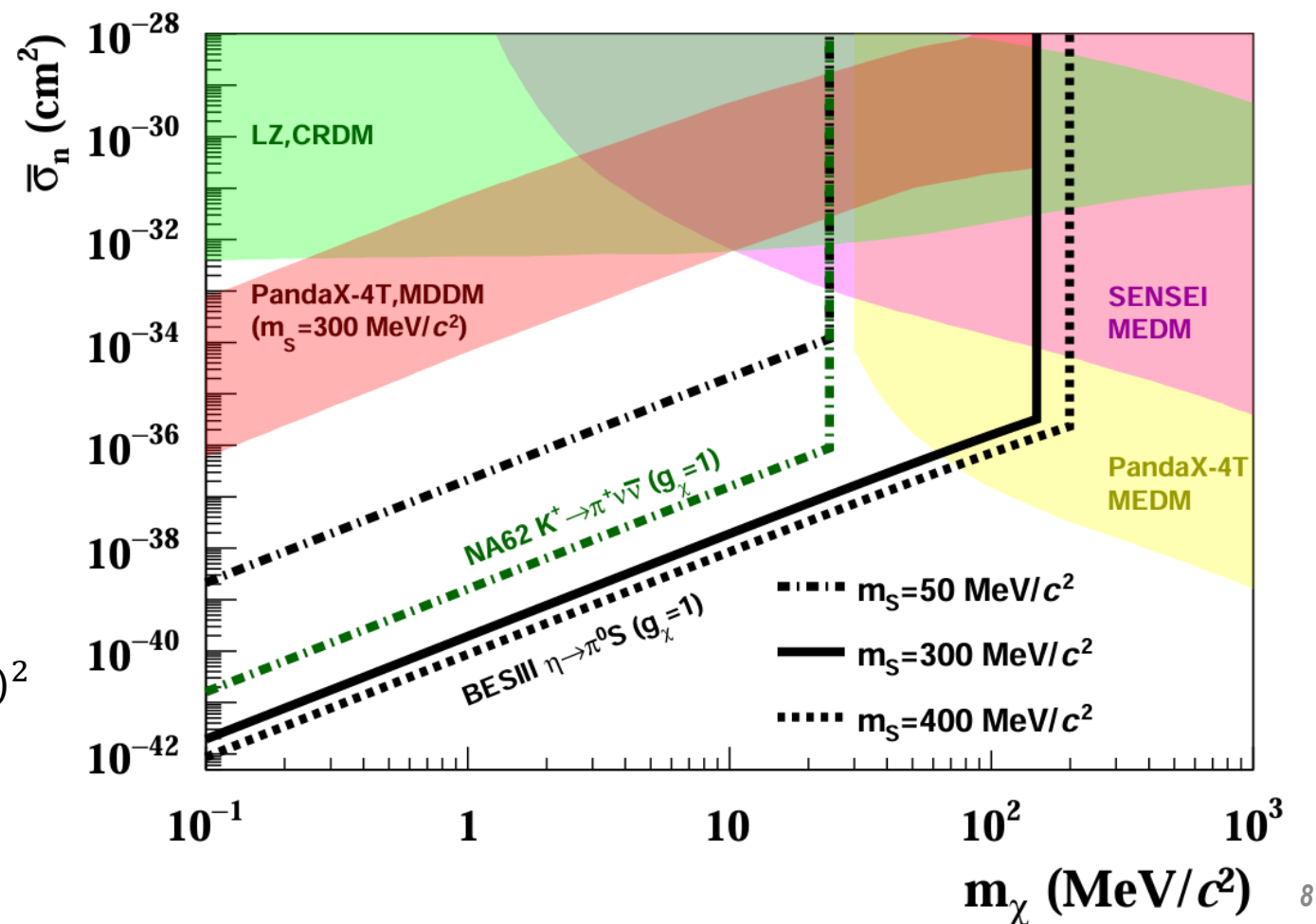
- ◆ Result better than atmospheric-boosted DM from PandaX-4T
- ◆ Constraints only for g_u from $K^+ \rightarrow \pi^+ + \text{invisible}$
- ◆ Naturalness bound from EFT
 - setting $\Lambda_{\text{NP}} = 10 \text{ TeV}$
 - $g_u \leq \frac{16\pi^2 m_S v}{\sqrt{2} \Lambda_{\text{NP}}^2}$
 - $\eta \rightarrow \pi^0 S$ can probe the allowed space
- ◆ Thermal relic DM benchmark:
 - freeze-out mechanism, $\chi \bar{\chi} \rightarrow S \rightarrow \pi\pi$
 - excluded when $g_\chi = 0.1$



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

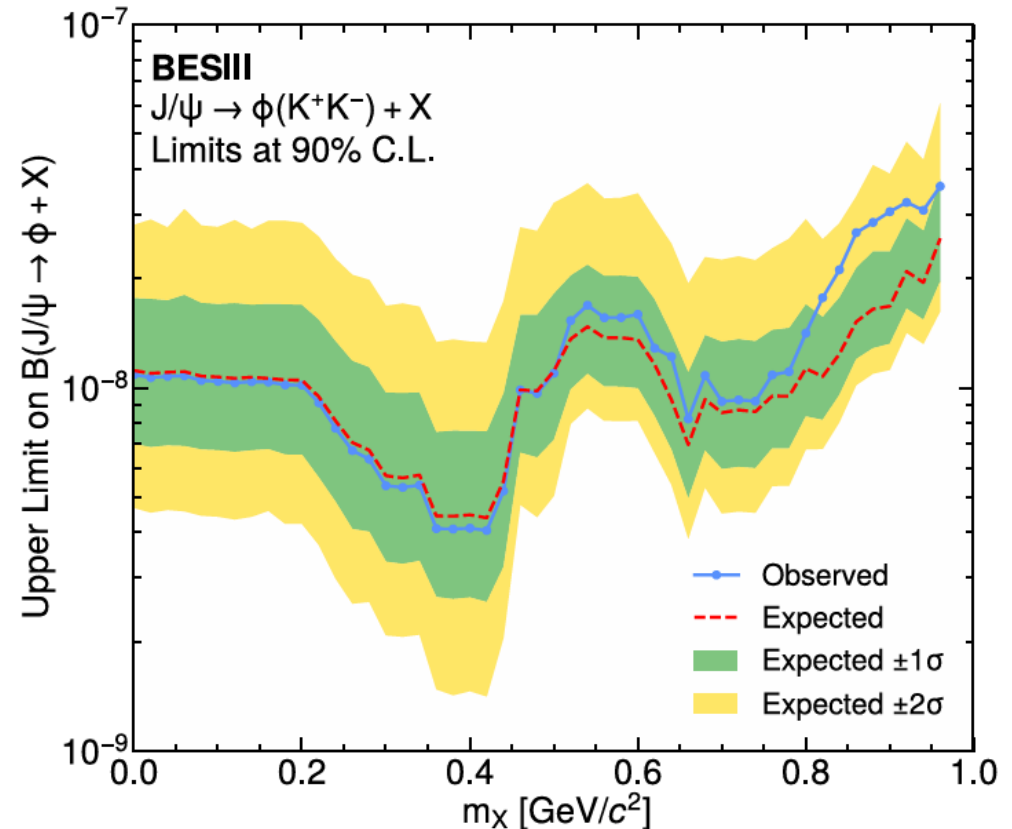
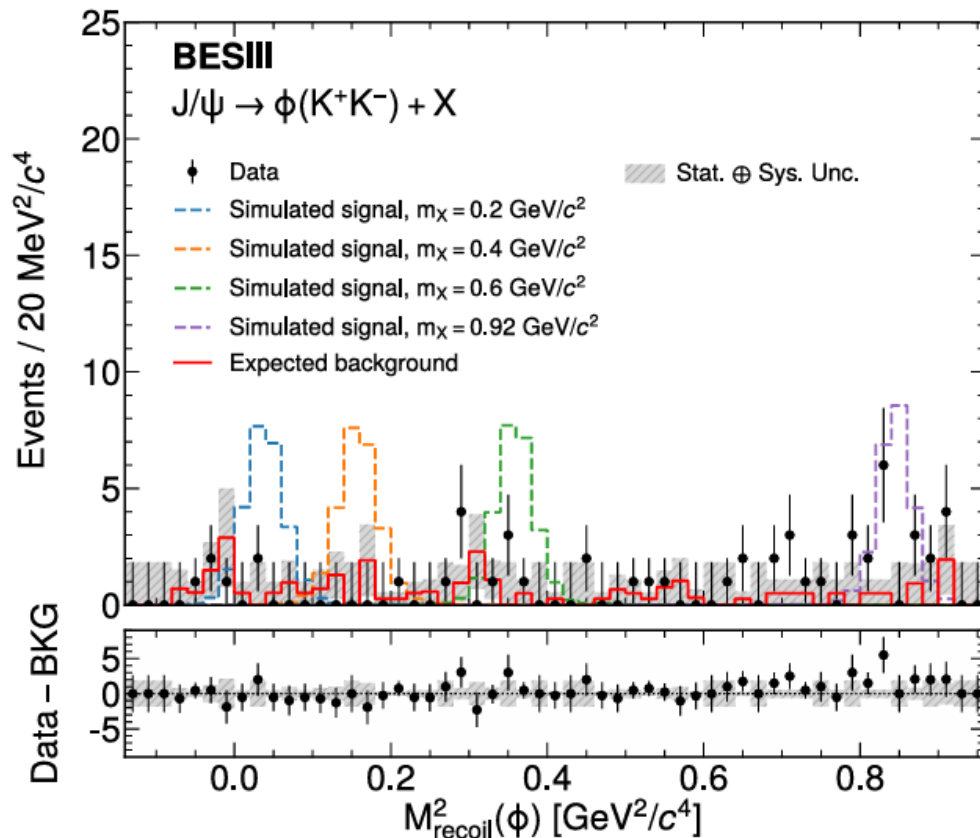
- ◆ Constraint on DM-nucleon cross section ($\bar{\sigma}_n$)
- ◆ Improved by ~ 5 orders of magnitude over previous DM-nucleon scattering experiments
 - $m_S = 300 \text{ MeV}/c^2$, on-shell S
 - Model-dependent constraint
- ◆ Ongoing and Future
 - Off-shell S case in $\eta \rightarrow \pi^0 \chi \bar{\chi}$
 - Larger S mass in $\eta' \rightarrow \pi^0 \chi \bar{\chi}$
 - Pseudo-scalar case in $\eta \rightarrow \pi^+ \pi^- \chi \bar{\chi}$
 - Vector case in $\pi^0/\eta \rightarrow \gamma \chi \bar{\chi}$
 -

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



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

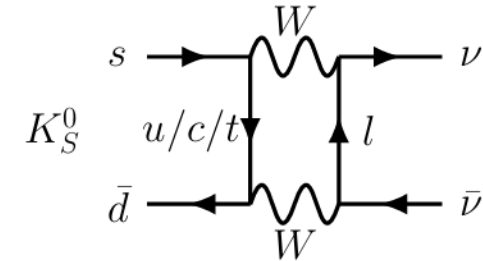
- ◆ Dataset: $(8774.0 \pm 39.4) \times 10^6 J/\psi$ events
- ◆ m_X : < 0.96 GeV, **UL on $\mathcal{B}(J/\psi \rightarrow \phi X)$ @90% C.L.: $4 \times 10^{-9} \sim 4 \times 10^{-8}$**
 - UL on the inclusive invisible BF of $J/\psi \rightarrow \phi X$: 7.0×10^{-8} @90% C.L.
 - Taking $X = \eta$, **UL on $\mathcal{B}(\eta \rightarrow \text{invisible})$: 2.4×10^{-5} @90% C.L.**, improved by more than 4 times



K_S invisible decay

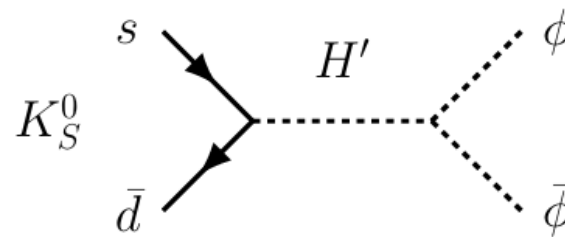
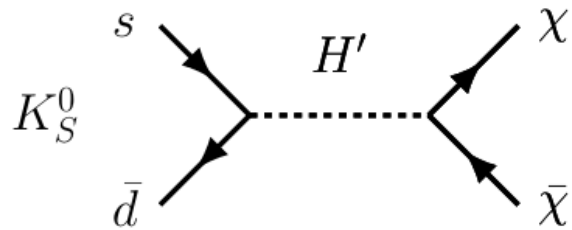
◆ Probe to new physics and dark matter

◆ SM decay, FCNC & Helicity suppression, $BF < 10^{-16}$



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◆ Decay to DM, 2HDM model, $BF \sim \mathcal{O}(10^{-6})$



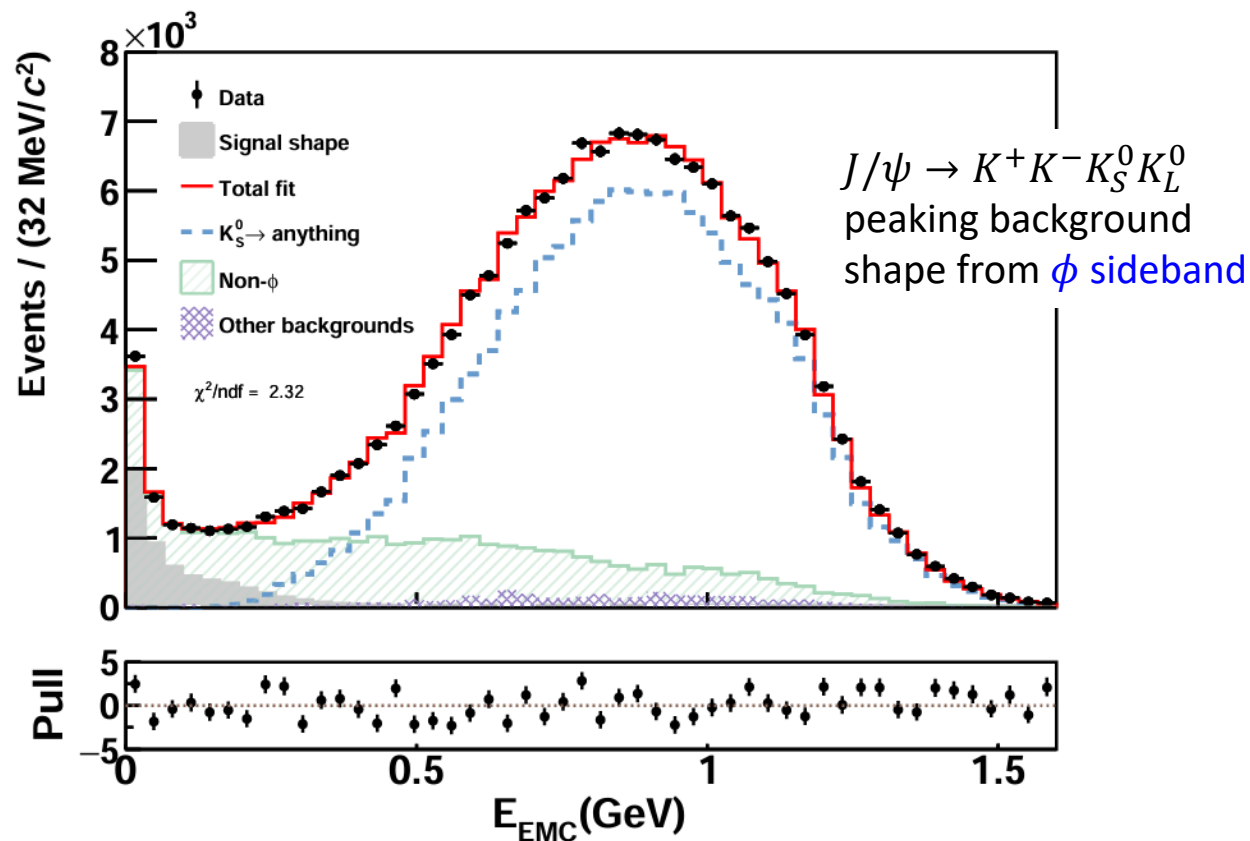
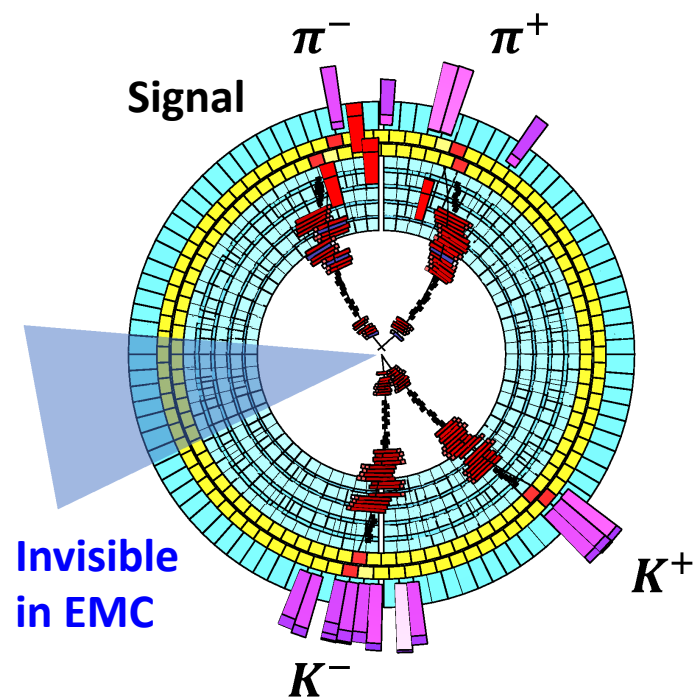
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◆ Ordinary-mirror particle oscillations, $K_S^0 \leftrightarrow K_S^{0'}$, $BF \sim \mathcal{O}(10^{-6})$

arXiv: 2006.10746

Search for K_S^0 invisible decay at BESIII

- ◆ $J/\psi \rightarrow \phi K_S^0 K_S^0$ from $(10087 \pm 44) \times 10^6$ J/ψ
- ◆ $J/\psi \rightarrow \phi K_S^0 K_L^0$ is forbidden with C Parity conservation, lower background, still have $J/\psi \rightarrow K^+ K^- K_S^0 K_L^0$
- ◆ Using the deposited energy in EMC to identify the invisible signal
- ◆ $N_{sig} = 56 \pm 201$ UL @ 90% C.L.: $\mathcal{B}(K_S^0 \rightarrow \text{invisible}) < 8.4 \times 10^{-4}$
- ◆ UL still lies above the NP prediction



Dark baryon

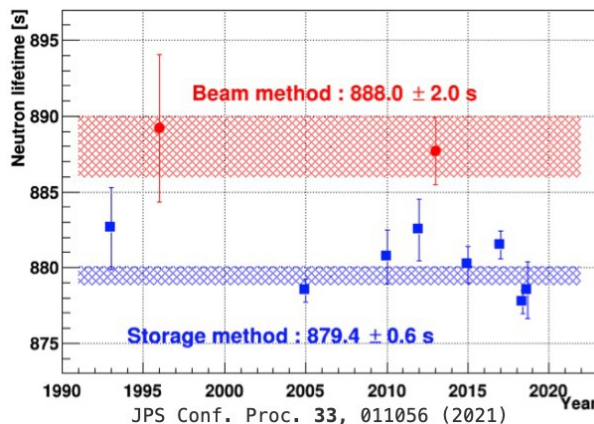
- ◆ Dark baryon might interact with all SM quark flavor → **search for dark baryon in hyperon decay**

Coincidence problem

The baryon and dark matter energy densities are fairly similar

$$\Omega_{DM}/\Omega_b \cong 5.36 \pm 0.06$$

Neutron lifetime puzzle



B-Mesogenesis mechanism

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

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



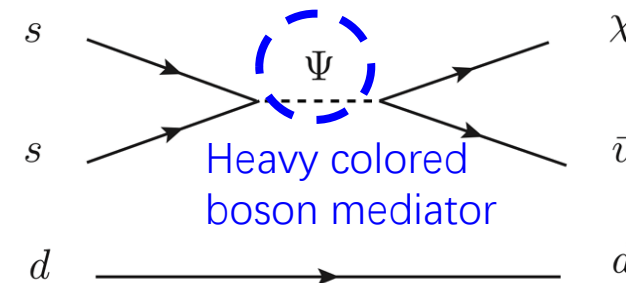
$$\tau_n^{\text{beam}} = \frac{\tau_n^{\text{bottle}}}{\text{Br}(n \rightarrow p + \text{anything})} \quad \mathcal{B}(n \rightarrow \text{dark}) \sim 1\%$$

- ◆ Motivates the existence of dark baryon

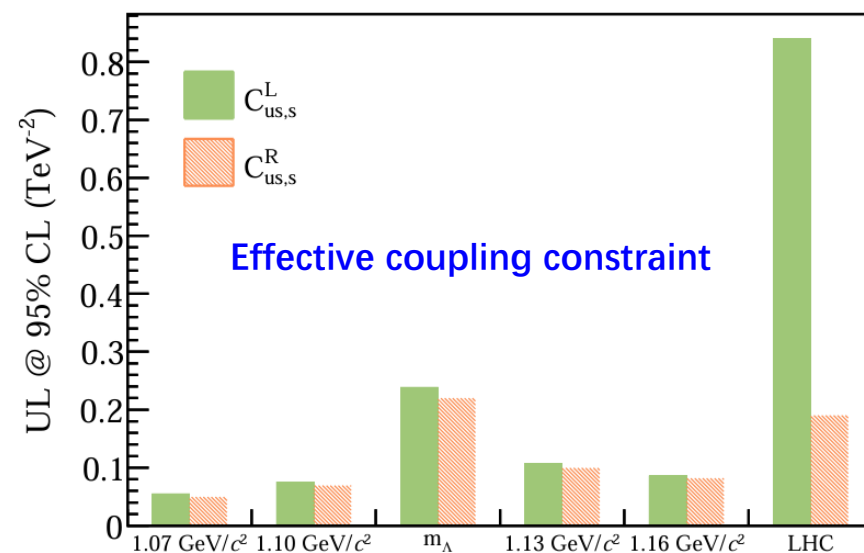
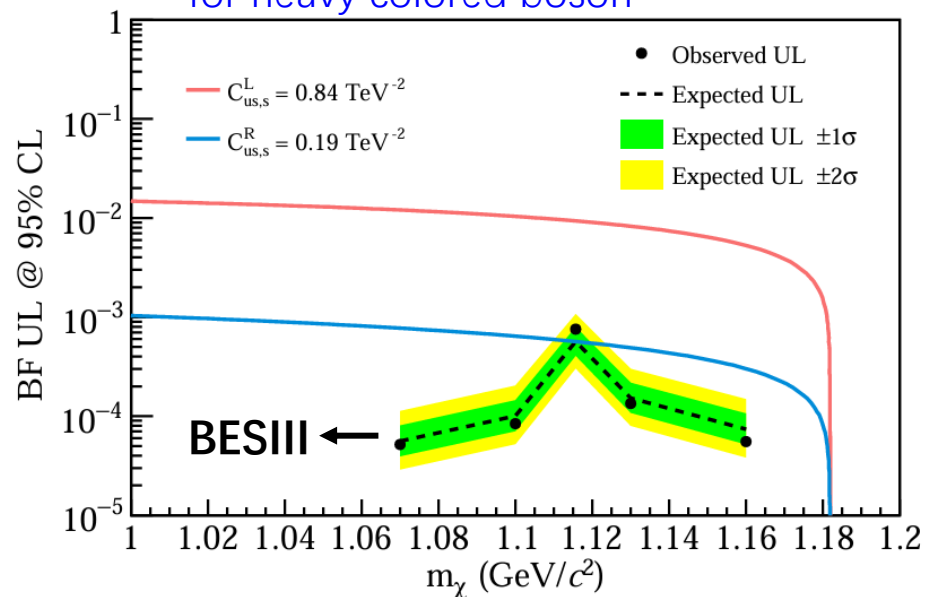
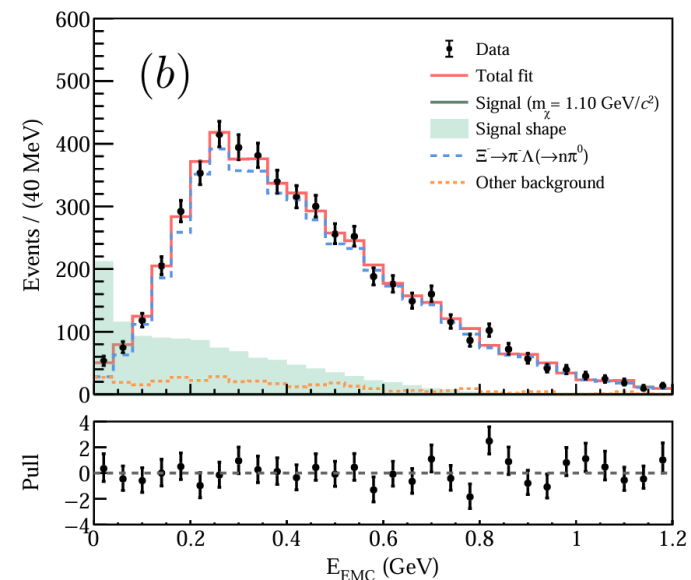
- ◆ Explain matter anti-matter asymmetry
- ◆ The origin of the dark matter

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
- ◆ More stringent constrain on the Wilson coefficients $C_{us,s}^L, C_{us,s}^R$ than LHC searches for colored mediators

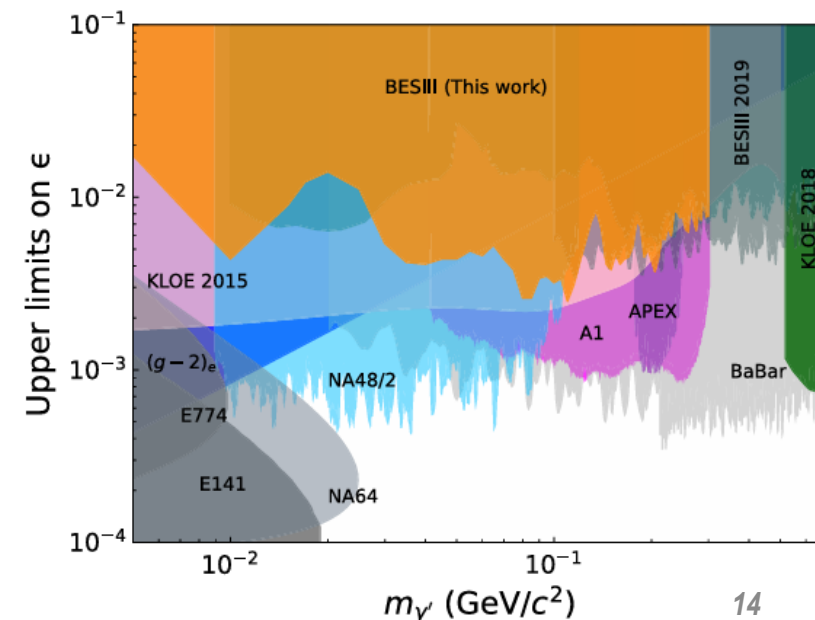
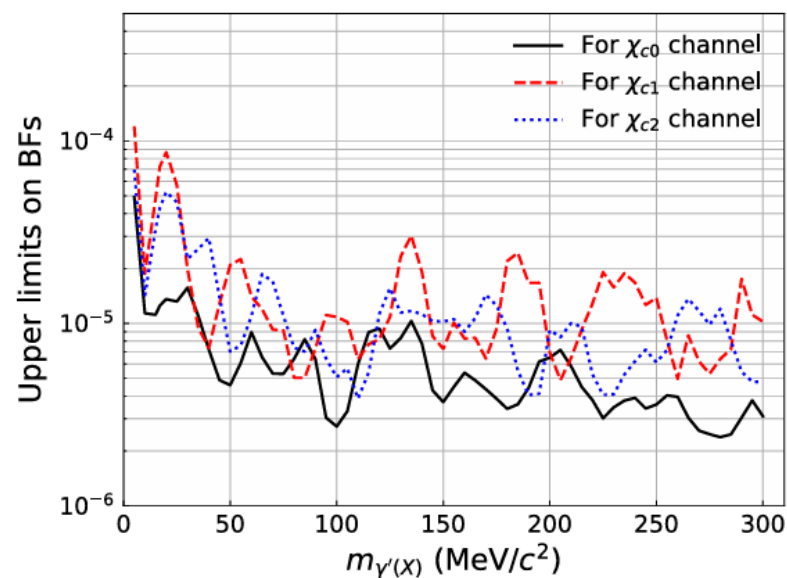
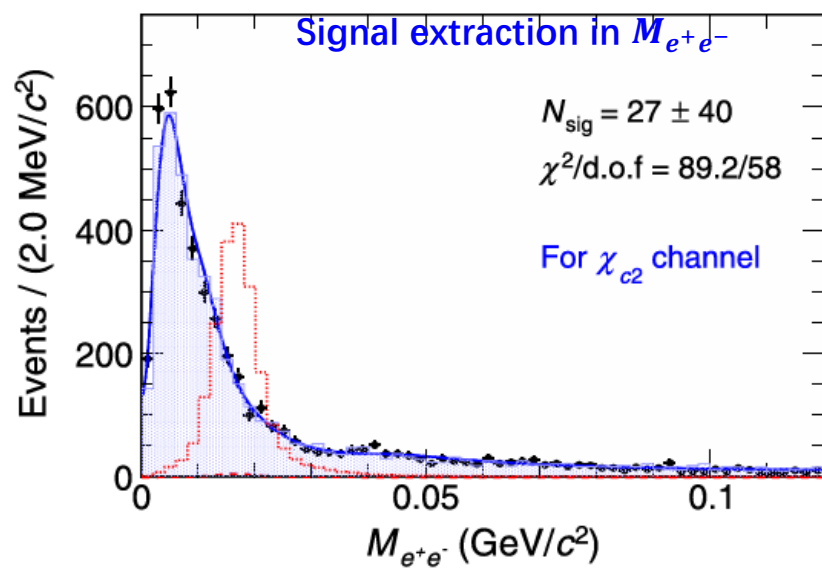


Recast result from LHC direct search for heavy colored boson



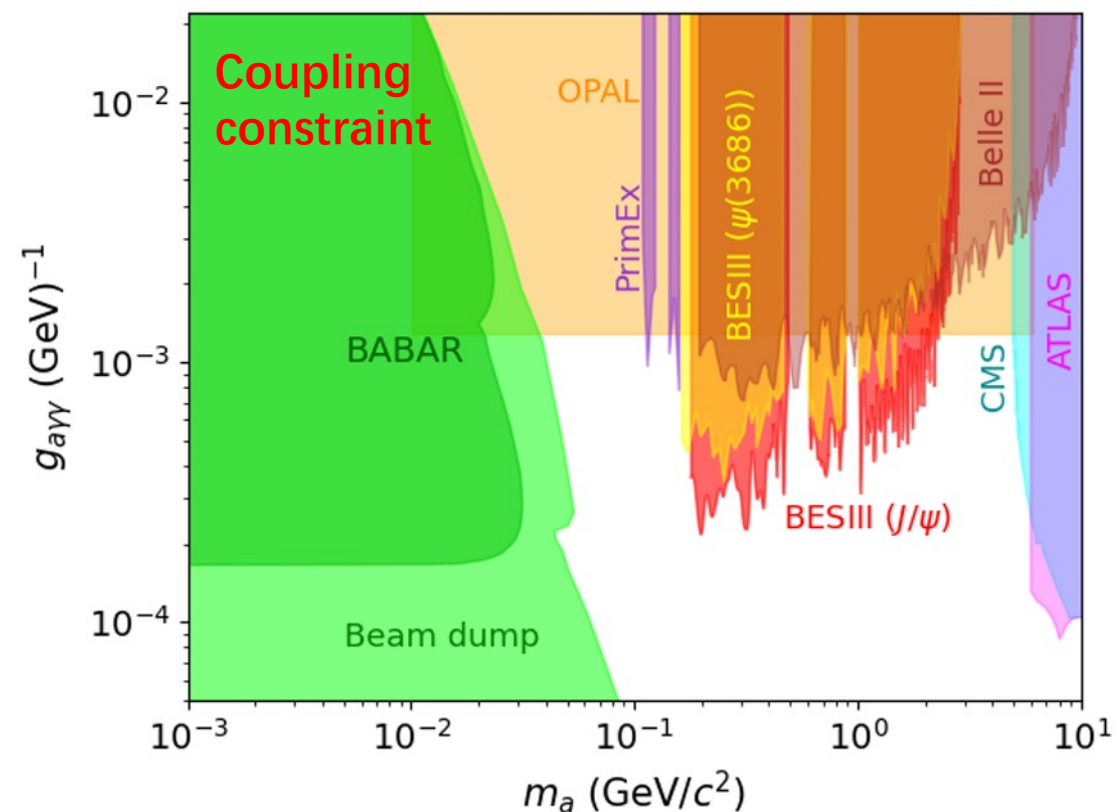
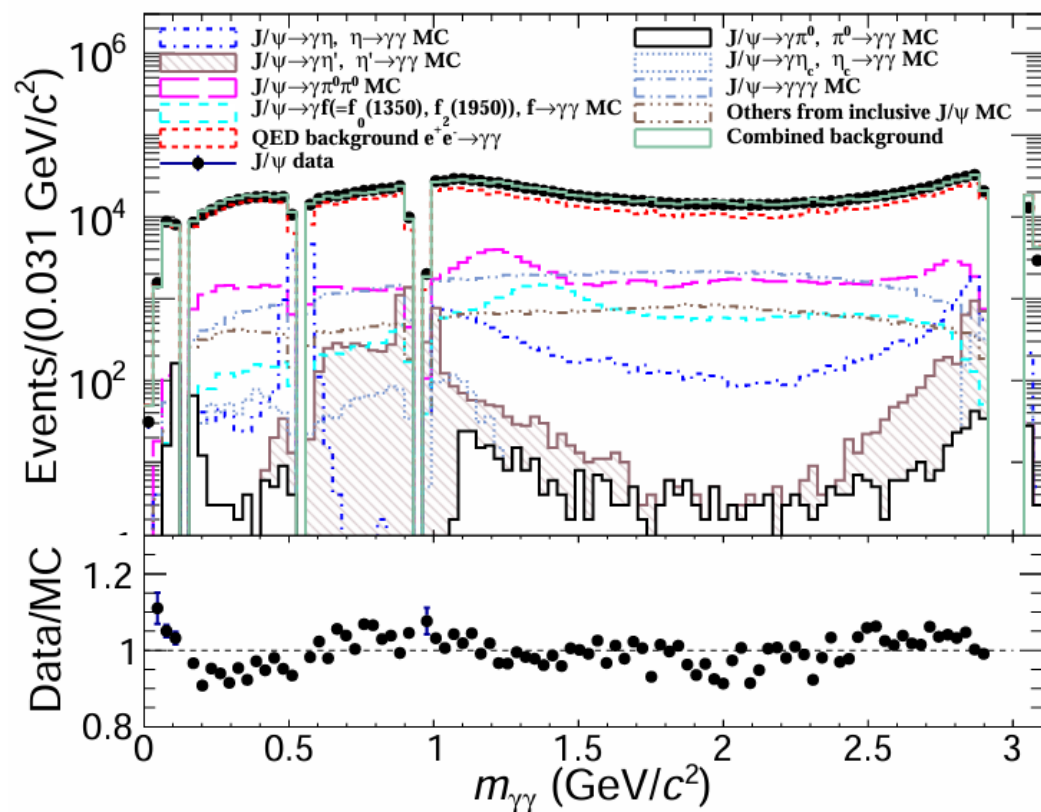
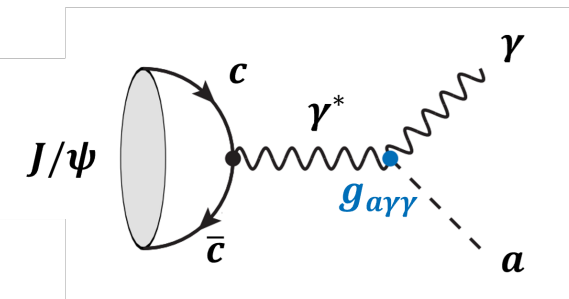
Search for $\chi_{cJ} \rightarrow J/\psi X, X \rightarrow e^+e^-$ at BESIII

- ◆ $X(17)$: light vector boson hinted from anomalous excesses in the distributions of opening angles between e^+e^- pairs from ${}^8\text{Be}$, ${}^4\text{He}$, and ${}^{12}\text{C}$ nuclear transitions
- ◆ BESIII Data set: $2.7 \times 10^9 \psi(2S)$, search for dark photon γ' / light vector boson X ($X \rightarrow f\bar{f}$)
- ◆ $\gamma'(X)$ mass 5 ~ 300 MeV, UL on $\mathcal{B}(\chi_{cJ} \rightarrow J/\psi X) \times \mathcal{B}(X \rightarrow e^+e^-)$ @90% C.L.: $2 \times 10^{-6} \sim 10^{-4}$
- ◆ Coupling strength of $X(17)$ with charm quark $|\epsilon_c| < 1.2 \times 10^{-2}$ @90% C.L.
- ◆ Coupling strength of γ' with SM photon @90% C.L.: $(2.5 \sim 17.5) \times 10^{-3}$
- ◆ Provides unique probe on coupling with charm in some un-universal coupling models
 - In dark photon model, X shares a universal ϵ_f for different fermion



Search for axion-like particle in $J/\psi \rightarrow \gamma a_{\gamma\gamma}$ at BESIII

- ◆ Dataset: 10^{10} J/ψ events, search for axion like particle
- ◆ Main background from pseudoscalar, maximum signal significance: $< 3\sigma$
- ◆ UL on the BF of $\mathcal{B}(J/\psi \rightarrow \gamma a) \times \mathcal{B}(a \rightarrow \gamma\gamma)$: $(3.6 \sim 53.1) \times 10^{-8}$ @ 90% C.L.
- ◆ New stringent constraints on ALP-photon coupling for $0.18 \leq m_a \leq 2.85$ GeV



Summary

- ◆ New searches for sub-GeV dark sector at BESIII
 - FCNC process $c \rightarrow u\gamma'$
 - $\eta \rightarrow \pi^0 + \text{invisible}$, $J/\psi \rightarrow \phi + \text{invisible}$ ($\eta \rightarrow \text{invisible}$)
 - $K_S^0 \rightarrow \text{invisible}$
 - dark baryon: $\Xi^- \rightarrow \pi^- + \text{invisible}$
 - dark photon γ' / light vector boson X search in $\chi_{cJ} \rightarrow J/\psi X$, $X \rightarrow e^+e^-$
 - ALP search in $J/\psi \rightarrow \gamma a_{\gamma\gamma}$
- ◆ Benefit from clean sample and tag techniques, unique stringent constraints
- ◆ BESIII has collected $10^{10} J/\psi$, $2.7 \times 10^9 \psi'$, 20.3 fb^{-1} data @ 3.773 GeV and more...
- ◆ More & better results are coming soon

Thanks for your attention!