A new bound on sub-GeV dark matter
—— Search for $\eta \to \pi^0 +$ invisible

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On behalf of BESIII Collaboration

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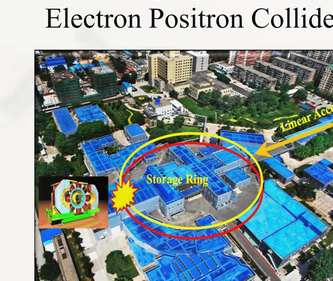
PRL Editors' Suggestion!

南 想新物理的风还是吹到了暗物质 北
S(M) South China Normal University, Guangzhou, 2026.7 N(P)

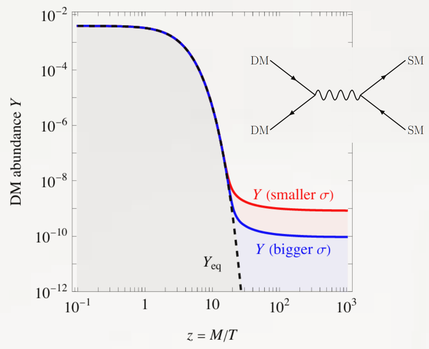
1. INTRODUCTION

- **Dark Matter (DM) benchmark from cosmology**

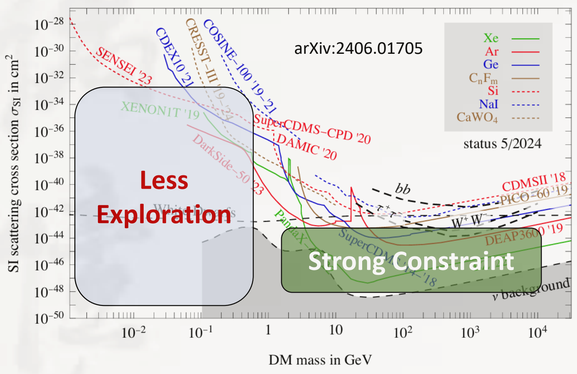


To produce $\Omega_{\rm DM}$ in freeze-out
- $\gg$ GeV DM: coupling~1
- Sub-GeV DM: coupling$\ll$ 1

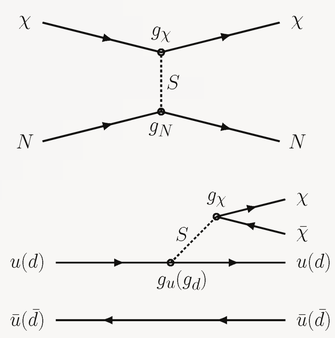
$$\Omega_{\rm DM}h^2 = 0.12 \pm 0.0012$$



- **Challenge in searching for sub-GeV DM**



- **This work: Search for sub-GeV dark matter with $\eta \to \pi^0 S \to \pi^0 \chi\bar{\chi}$ with 10^{10} J/ψ data**



2. BEPCII AND BESIII EXPERIMENT

Beijing Spectrometer III (BESIII) is a general-purpose spectrometer working at the Beijing Electron Positron Collider II (BEPCII) and has collected large data in $\tau - c$ energy region.

Main drift chamber (MDC)
- $\Delta P/P = 0.5\%, dE/dx \sim 6\%$

Time-of-Flight system (TOF)
- $\sigma_T = 60 \sim 68$ ps

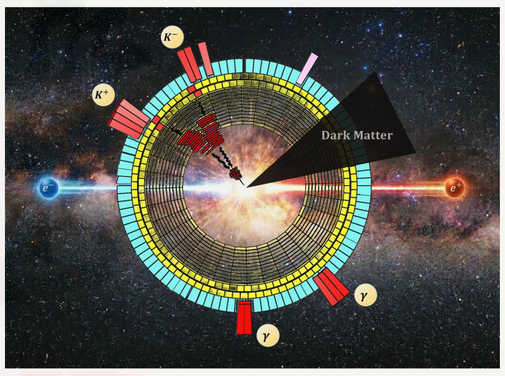
Electromagnetic Calorimeter (EMC)
- $\Delta E/E = 2.5\% \sim 5.0\%$

Muon chamber system (MUC)
- $\sigma_{z,\phi} = 2$ cm

Fig.1 (left) Beijing Electron Positron Collider II (BEPCII). (right) Beijing Spectrometer III (BESIII).

3. EVENT SELECTIONS

- Decay chain: $e^+e^- \to J/\psi$, $J/\psi \to \phi\eta, \phi \to K^+K^-, \eta \to \pi^0 S \to \pi^0 \chi\bar{\chi}$
- Select two charged kaons and one neutral pion in the final states



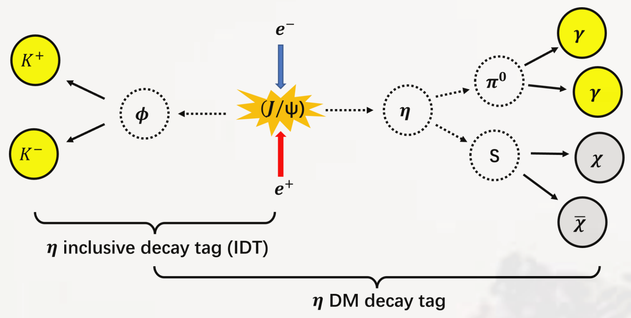
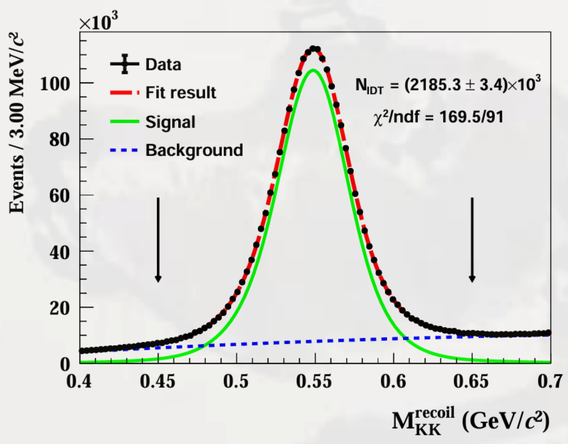


Fig.2 An event display (left) and the decay chain (right) of sub-GeV DM search at BESIII

- **Two-Steps Analysis**

1. Tag $J/\psi \to \phi\eta, \phi \to K^+K^-, \eta \to$ anything
- M_{KK} in [1.00, 1.04] GeV
- Fit in the distribution of $M_{KK}^{\rm recoil}$
- Not the world largest η set, but the cleanest one

2. Further tag $\eta \to \pi^0 +$ invisible
- $M_{\gamma\gamma}$ in [0.115, 0.150] GeV
- $E_{\rm oth.\gamma}^{\rm tot} < 0.1$ GeV & $|\cos\theta_{KK\pi^0}^{\rm recoil}| < 0.7$
- Special selections on $M_{KK\pi^0}$



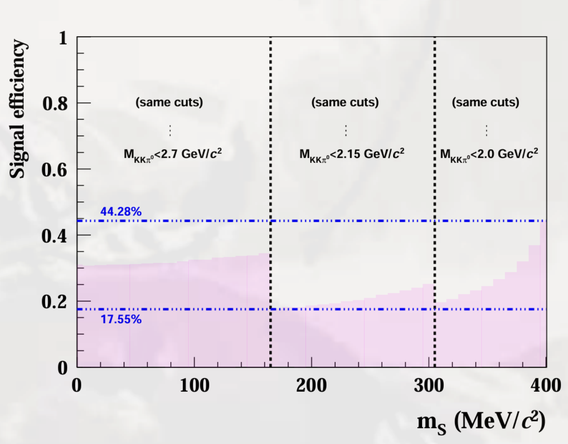


Fig.3 (left) The inclusive-decay-η yield extracted in $M_{KK}^{\rm recoil}$ distribution. (right) The signal efficiency ($\hat{\epsilon}$) estimated from the signal MC samples for different mass hypothesis.

4. SIGNAL EXTRACTION

The signal yield of $\eta \to \pi^0 S$ is extracted from an unbinned extended maximum likelihood fit to the distribution of missing mass square ($M_{\rm miss}^2$), with m_S ranging from 0 to 400 MeV.

The maximum signal significance ($m_S = 240$ MeV) is found to be less than 2σ.

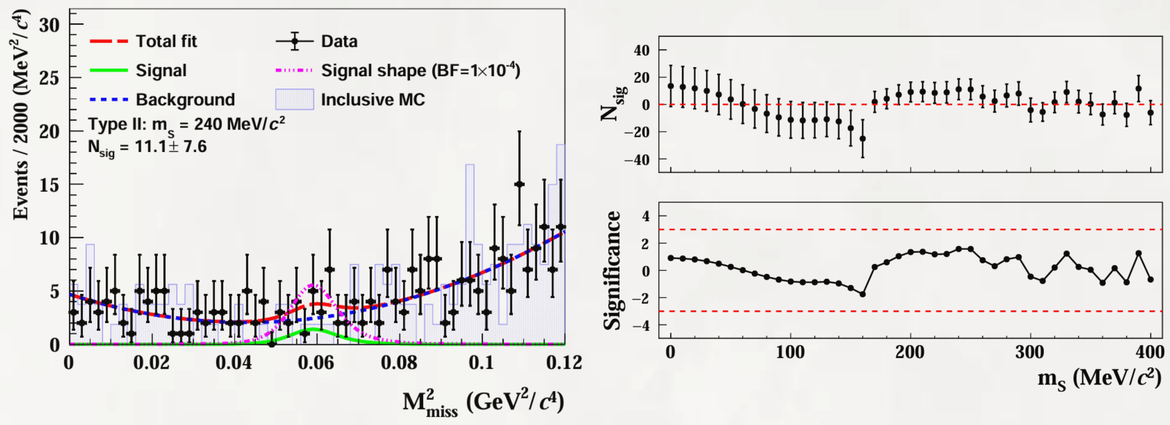
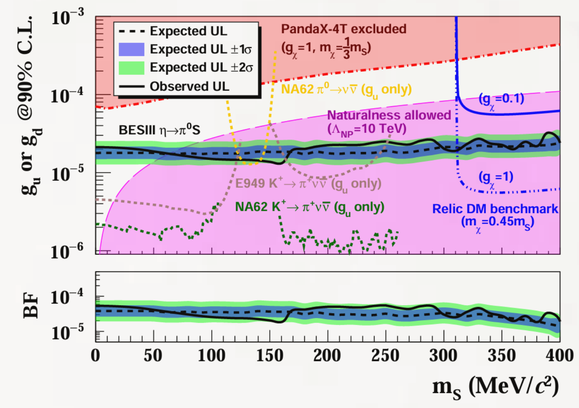


Fig.4 (left) The signal extraction in $m_{\rm miss}^2$ distribution, taking $m_S = 240$ MeV as the example. (right) The signal yield and signal significance for total mass hypothesis.

The systematic uncertainty related to the inclusive-decay-η selection can be canceled in the two-steps analysis. The total other uncertainties range from 2.1~2.5% for different S masses.

5. BRANCHING FRACTION AND COUPLING STRENGTH

The absolute branching fraction (BF) of $\eta \to \pi^0 S$ is calculated as $\mathcal{B}(\eta \to \pi^0 S) = \frac{N_{\rm sig}}{\mathcal{B}(\pi^0 \to \gamma\gamma) \cdot N_{\rm IDT} \cdot \hat{\epsilon}}$, and the upper limits (ULs) on the BFs are determined using a Bayesian approach by scanning the likelihood distribution in the fit.



- **Flavored-specific scalar model**
- $\mathcal{L} \supset -g_\chi S \bar{\chi}_L \chi_R - g_u S \bar{u}_L u_R + h.c.$
- $g_u \equiv \frac{c_S v}{\sqrt{2}\Lambda_{\rm NP}}$
- g_u not necessarily proportional to the Higgs Yukawa couplings

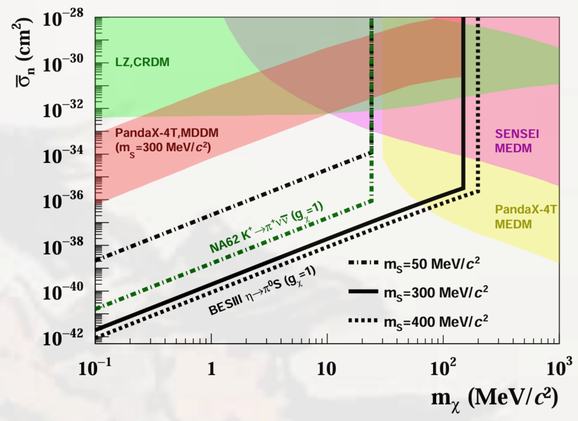
$$\mathcal{B}(\eta \to \pi^0 S) \propto g_u^2 \lambda^{\frac{1}{2}}(1, \frac{m_S^2}{m_\eta^2}, \frac{m_{\pi^0}^2}{m_\eta^2})$$

Fig.5 The ULs on the BFs of $\eta \to \pi^0 S$ and the constraint on the coupling strength of g_u or g_d.

- **The coupling constraint is better** than that of atmospheric-boosted DM search from PandaX
- $K^+ \to \pi^+ S$ is only sensitive to g_u, while $\eta \to \pi^0 S$ is sensitive to both g_u and g_d
- Exploring the allowed naturalness region in EFT with $\Lambda_{\rm NP} = 10$ TeV
- **Exclude thermal relic DM** in freeze-out mechanism by $\chi\bar{\chi} \to \pi\pi$ when $g_\chi = 0.1$

6. DM-NUCLEON SCATTERING CROSS-SECTION

Considering DM interacting with the SM quark through a new force mediated by the exchange of S, we can provide a **model-dependent constraint** on DM-nucleon cross-section.



- **Improve by about 5 orders of magnitude** over previous direct detection exps.
- Although model-dependent, fortunately collider search can explore many different processes to cover most of the models

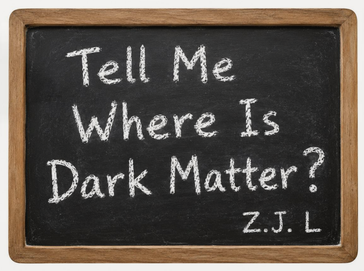
$$\bar{\sigma}_n \propto \frac{g_u^2 g_\chi^2}{m_S^4} \left(\frac{m_\chi m_N}{m_\chi + m_N}\right)^2$$

Fig.6 The constraints on the sub-GeV DM-nucleon scattering cross-section.

7. SUMMARY

- We search for sub-GeV DM at collider but no signal
- No signal but better unique constraint and new bound
- New bound but still need future effort

➢ Future sub-GeV DM at collider
- Require larger data to explore the benchmark of thermal relic DM when $g_\chi \sim 1$
- Explore other channels to probe other portals of vector, pseudo-scalar …, with both on-shell and off-shell case
- **Or, DM is not in the sub-GeV region? We have no idea at all!**



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