Light dark matter searches at BESIII & KLOE

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Outline

- ✓ Motivation
- ✓ BESIII and KLOE experiments
- ✓ Search for dark gauge bosons
 - Dark photon
 - Dark Higgs boson
- \checkmark Search for invisible decays of light mesons
- ✓ Search for a light Higgs boson
- ✓ Summary

Motivation



Galaxy Rotation Curve (M33)

https://en.wikipedia.org/wiki/Galaxy_rotation_curve





Motivation

- New physics models beyond the Standard Model (SM) include the possibility of light weak interacting DM hidden sectors
- ✓ The DM hidden sectors couple to the SM particles via the so called "portals"



✓ These new particles can be accessible by high intensity e⁺e⁻ collider experiments, such as **BESIII and KLOE experiments**, if their masses are in the MeV-GeV range.



R. Essig et al., arXiv: 1311.0029 (2013)

BESIII and KLOE Experiments

Symmetric e⁺e⁻ collider experiments running at tau-charm and $\phi(1019)$ mass regions, respectively.

Physics objectives: study the light hadron spectroscopy and search for new physics phenomena.



**BESIII also plans to replace the inner part of the drift chamber by the three layers of the CGEM detector soon.



KLOE-2 run

- $DA\Phi NE:$ new interaction scheme
- × Large angle beam crossing
- Crabbed waist sextupoles

KLOE-2:

- X Detector upgrade (γγ taggers + GEM inner tracker + low-θ EMCs)
- ★ Extension of the KLOE physics program [Eur. Phys. J. C 68 (2010), 619]

DAONE (KLOE run)

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DAONE Upgrad

Datasets





KLOE/KLOE-2 experiment (the Frascati ϕ factory): collected the data at $\sqrt{s} = m_{\phi} \approx 1.019$ GeV

- ✓ KLOE (2001 2006)
 - 2.5 fb⁻¹ data at ϕ peak
 - 250 pb⁻¹ off-peak
- ✓ KLOE-2 (2014 2018)
 - 5.5 fb⁻¹ data at ϕ peak

IDEAL ENVIRONMENT TO STUDY THE LIGHT HADRON SPECTROSCOPY & SEARCH FOR NEW PHYSICS PHENOMENA!!

Dark gauge boson

DM hidden sector introduces a new U(1) interaction or dark force carrier (e.g. dark-photon A', U or γ').

N. Arkani-Hamad et al, PRD 79, 015014 (2009)



Could explain the features of astrophysical observations (such PAMELA, AMS etc.).



□ The dark U(1) symmetry could be spontaneously broken, by a Higgs mechanism, adding a dark Higgs boson (h') to the theory.

PRD79, 115008 (2009)

Dark gauge boson searches @ BESIII/KLOE

Electromagnetic Dalitz decays



✓ BESIII

 $J/\psi {\rightarrow} \gamma' \eta/\eta', \, \gamma' {\rightarrow} e^+ e^-$

Phys. Rev. D **99**, 012013 (2019) Phys. Rev. D **99**, 012006 (2019) (This talk)

 $J/\psi{\rightarrow}U\eta^{'},\,U{\rightarrow}\gamma\pi^{0}$

Preliminary (This talk)

✓ KLOE/KLOE-2

 $\phi \rightarrow \gamma' \eta$, with $\eta \rightarrow \pi^+ \pi^- \pi^0 / \pi^0 \pi^0 \pi^0$ PLB **706**, 251 (2012) / PLB **720**, 111 (2013)

e⁺e⁻ annihilation



https://physics.aps.org/articles/v7/115

✓ BESIII

 $e^+e^- \rightarrow \gamma_{ISR}\gamma', \gamma' \rightarrow l^+l^-$ Phys. Lett. B **774**, 252 (2017)

(This talk)

✓ KLOE/KLOE-2

 $e^+e^- \rightarrow \gamma_{ISR}\gamma', \gamma' \rightarrow e^+e^-$ PLB **736**, 459 (2014)

 $e^+e^- \rightarrow \gamma_{ISR}\gamma', \gamma' \rightarrow \mu^+\mu^-$ PLB **750**, 633 (2015)

 $e^+e^- \rightarrow \gamma_{ISR} \gamma', \gamma' \rightarrow \pi^+\pi^-$ PLB **757**, 356 (2016)

 $e^+e^- \rightarrow \gamma_{ISR} \gamma', \ \gamma' \rightarrow \mu^+\mu^- /\pi^+\pi^-$ PLB **784**, 336 (2018) (**This talk**)

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Search for a dark gauge boson decaying to $\gamma \pi^0$ via $J/\psi \rightarrow \gamma \pi^0 \eta'$ Feliminary

- Many models suggest that a dark gauge boson (U') could also couple predominantly to quark Phys. Rev. D 89, 114008 (2014), Phys. Lett. B 221, 80 (1979)
- > BESIII performs the search for U' in the decay chain: $J/\psi \rightarrow U'\eta'$, $U' \rightarrow \gamma \pi^0$, $\pi^0 \rightarrow \gamma \gamma$ using 1.3 B J/ ψ data



No evidence of U' signal is found

Dark U boson search in $e^+e^- \rightarrow \gamma \pi^+ \pi^-$

- Results based on 1.93 fb⁻¹
- Select two oppositely charged tracks $(50^{\circ} < \theta_{\mu} < 165^{\circ})$
- Use an untagged photon technique ($\theta_{\gamma} < 15^{\circ}, \theta_{\gamma} > 165^{\circ}$)
- Estimated backgrounds from the sideband data.
- Good agreement between data and Monte Carlo in the ρ - ω interference region

PLB 757, 356 (2016)

YOKE S.C. CO

Combined search: $e^+e^- \rightarrow \gamma \pi^+ \pi^- / \gamma \mu^+ \mu^-$ PLB 784, 336 (2018) Search is based on whole KLOE data-set (1.93 fb⁻¹) \geq Analysis is similar to $e^+e^- \rightarrow \gamma \pi^+\pi^-$ (estimated the data from the sideband data) $\times 10^3$ Upper limit @ 90% C.L. 25 10^{-4} 24 Mass bin: 0.789 GeV χ^2 /ndf: 26.34 / 14 23 Events/2 MeV 22 10^{-5} 21 20 side-band fit data 19 excluded data 18 ϵ^2 770 780 790 810 800 760 10^{-6} $M_{\mu\mu}$ (MeV) $\times 10^3$ 120 observed spectrum 100 fit to sidebands 10^{-7} Entries/0.002GeV BaBar — KLOE_{μμ} + ππ ----- KLOE_{μμ} ----- KLOE_{ππ} 80 LHCb 60 Na48 40 10^{-8} 200 20 400 600 800 1000 $M_{\rm II}$ (MeV) 600 700 800 900

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 $M_{\mu\mu}$ (MeV)

Dark photon search via $e^+e^- \rightarrow \gamma_{ISR}\gamma', \gamma' \rightarrow I^+I^-$ Phys. Lett. B 774, 252 (2017) EMC EMC

.2 2.4 2.6 m_{rr} [GeV/c²]

2.8

3.0

3.2 3.4

tagged: untagged: photon hits EMC photon leaves the detector events / 10 mrad JNTAGGED UNTAGGED TAGGED boarders of EMC 10 θ, [rad] 10⁻² BESI **KLOE 2013** KLOE 2015

1.6

1.8

2.0

2.2

-2000

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Nucl.Instrum.Meth., A551, 493-503 (2005)

Search for a dark Higgs boson h' via Higgs-strahlung process e⁺e⁻→h'A'

$$\sigma \propto \epsilon^2 \alpha \alpha_D / E_{CM}^2$$

Three main cases:

 a. m_h, < m_A, where h' is long lived and A' decays to lepton-pair or hadrons. KLOE [Phys. Lett. B 747, 365 (2015)] (This talk)
 b. m_A, < m_h, < 2m_A, where h' → A'A'* and A'* decays into leptons.

c. $m_{h\prime} > 2m_{A\prime}$ where h' \rightarrow A'A' **BaBar** [PRL **108**, 211801 (2012)], **Belle** [PRL **114**, 211801 (2015)]

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Search for dark Higgsstrahlung in $e^+e^- \rightarrow \mu^+\mu^-$ and missing energy Phys. Lett. B 747, 365 (2015)

- Use 5×5 bin method to predict background in each bin. Scale factor from MC.
- Limits on $\alpha_D \epsilon^2$ range from $10^{-9} 10^{-8}$. First limits for $m_{h'} < m_{A'}$

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Search for invisible decays of light mesons in $J/\psi \rightarrow V(=\omega,\phi)P(=\eta('))$

✓ BESIII

Invisible decays of η and η' mesons Phys. Rev. D 87, 012009 (2013)

Invisible decays of ω and ϕ mesons Phys. Rev. D 98, 032001 (2018)

(This talk)

Invisible decays

> Quarkonium states $(q\bar{q})$ can annihilate into $\nu\bar{\nu}$ via virtual Z^0 boson

 $B(\omega \to \nu \bar{\nu}) = (2.79 \pm 0.05) \times 10^{-13}$ $B(\phi \to \nu \bar{\nu}) = (1.67 \pm 0.02) \times 10^{-11}$

mode s-wave *p*-wave 1.8×10^{-3} 4.2×10^{-4} $BR(\Upsilon(1S) \to \chi\chi)$ $BR(\Upsilon(1S) \to \nu \bar{\nu})$ 9.9×10^{-6} 2.5×10^{-5} $BR(J/\Psi \to \chi\chi)$ 1.0×10^{-4} $BR(J/\Psi \to \nu \bar{\nu})$ 2.7×10^{-8} 1.4×10^{-4} $BR(\eta \to \chi \chi)$ 3.4×10^{-5} $BR(\eta' \to \chi \chi)$ 3.7×10^{-7} 1.5×10^{-6} 1.3×10^{-7} 5.3×10^{-7} $BR(\eta_c \to \chi \chi)$ 1.2×10^{-7} 2.7×10^{-8} $BR(\chi_{c0}(1P) \to \chi\chi)$ 7.8×10^{-8} 1.9×10^{-8} $BR(\phi \to \chi \chi)$ 3.0×10^{-8} $BR(\omega \to \chi \chi)$ 7.2×10^{-8}

B. McElrath, eConf C070805, 19 (2007)

Phys. Rev. D 98, 113006 (2018)

Branching fraction of invisible decays of quarkoinum state might be enhanced in the presence of light DM particles.

Computed by assuming the same cross-section for the time reversed processes:

$$\sigma(q\overline{q} \to \chi\chi) \simeq \sigma(\chi\chi \to q\overline{q})$$

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Invisible decays of ∞ and φ mesons in J/ψ→η∞/φ €SⅢ Phys. Rev. D 98, 032001 (2018)

- First search for $J/\psi \rightarrow \eta \omega/\phi$, $\omega/\phi \rightarrow invisible$ using 1.3 billion J/ψ events
- > Define recoiling mass against η : $M_{recoil}^V = \sqrt{(E_{CM} E_{\pi^+\pi^-\pi^0})^2 \vec{p}_{\pi^+\pi^-\pi^0}^2}$

Only $\eta \rightarrow \pi^+ \pi^- \pi^0$ decay mode is utilized for this measurement

- > Fit to M_{recoil}^V to extract the signal yields
- No any obvious signal is found.

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Invisible decays of ω and φ mesons in J/ψ-->ηω/φ €SM Phys. Rev. D 98, 032001 (2018)

Set the 90% C.L. upper limits on the branching fraction after including the systematic uncertainties.

Published in Phys. Rev. D 98, 032001 (2018)

First experimental limits on the invisible decays of ω and ϕ mesons.

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Search for di-muon decays of a light Higgs boson (A⁰)

✓ BESIII

 $\psi(3686) \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \gamma A^0$

Phys. Rev. D 85, 092012 (2012)

 $J/\psi \to \gamma A^0$

Phys. Rev. D **93**, 052005 (2016) (This talk)

An introduction to the light Higgs boson

- A light Higgs boson is predicted by many extensions of Standard Model, such as Next-to-Minimal Supersymmetric Standard Model (NMSSM).
- NMSSM contains a total of three CP-even, two CP-odd and two charged Higgs bosons.

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Light Higgs boson search via $J/\psi \rightarrow \gamma A^0, A^0 \rightarrow$ Phys. Rev. D 93, 052005 (2016)

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(a)

2.5

3

Summary

- ▶ Both BESIII and KLOE have a very rich programs for the new physics searches beyond the SM.
- Produces many results on the Dark matter searches:
- ✓ Dark gauge boson searches:

BESIII

KLOE/KLOE-2

$J/\psi \rightarrow \gamma' \eta/\eta', \gamma' \rightarrow e^+e^-$	Phys. Rev. D 99, 012013 (2019)	$\phi \rightarrow \gamma' \eta$, with $\eta \rightarrow \pi^+ \pi^- \pi^0 / \pi^0 \pi^0 \pi^0$
	Phys. Rev. D 99, 012006 (2019)	PLB 706 , 251 (2012); 720 , 111 (2013)
$J/\psi \rightarrow U\eta', U \rightarrow \gamma \pi^0$	Preliminary	$e^+e^- \rightarrow \gamma_{ISR} \gamma', \gamma' \rightarrow \mu^+\mu^-/\pi^+\pi^-$
		PLB 736, 459 (2014); 750, 633 (2015); 757, 356 (2016); 784, 336 (2018)
$e^+e^- \rightarrow \gamma_{ISR} \gamma', \gamma' \rightarrow l^+l^-$	Phys. Lett. B 774, 252 (2017)	$e^+e^- \rightarrow h'A'$ Phys. Lett. B 747, 365 (2015)]

- ✓ Searches for invisible decay of light mesons via $J/\psi \rightarrow VP$ at BESIII Phys. Rev. D 87, 012009 (2013); 98, 032001 (2018)
- ✓ Search for a light CP-odd Higgs boson at BESIII Phys. Rev. D 85, 092012 (2012); 93, 052005 (2016)
- > Exclude a large fraction of the parameter space of the new physics models beyond SM.
- Ongoing study at BESIII related to the dark-sector:
 - ✓ Light Higgs boson search via J/ ψ → γ A⁰, A⁰→invisible
- Many more to come with recently collected 10 billion of the J/ψ data-set.
 http://bes3.ihep.ac.cn/doc/3313.html

Thank you!

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Back up Slide

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Calculation of ε in Dalitz decays J/ψ→η/η'e⁺e' ₩SII

Branching fraction of
$$J/\psi \rightarrow \gamma' \eta^{(1)}$$
 Dark photon mass

$$\frac{B(J/\psi \rightarrow \gamma' \eta^{(\prime)})}{B(J/\psi \rightarrow \gamma \eta^{(\prime)})} = \varepsilon^{2} |F_{J/\psi \eta^{(\prime)}}(m_{\gamma'}^{2})|^{2} \cdot \frac{\Lambda^{3/2}(m_{J/\psi}^{2}, m_{\eta^{(\prime)}}^{2}, m_{\gamma'}^{2})}{\Lambda^{3/2}(m_{J/\psi}^{2}, m_{\eta^{(\prime)}}^{2}, 0)}$$
Branching fraction of $J/\psi \rightarrow \gamma \eta^{(1)}$
Form factor for $J/\psi \rightarrow \gamma^{*} \eta^{(1)}$ transition
evaluated at γ' mass
 $|F_{J/\psi \eta^{(\prime)}}(m_{\gamma'}^{2})|^{2} = \frac{\Lambda^{2}}{\Lambda^{2} - m_{\gamma'}^{2}}$ $\Lambda^{2} = m_{\psi(2S)}$

Event selection and calculation of ε in $e^+e^- \rightarrow \gamma_{ISR}\gamma', \gamma' \rightarrow l^+l^-$ **SESII**

Event selection:
$$e^+e^- \rightarrow \mu^+\mu^-\gamma_{ISR}$$
 and $e^+e^- \rightarrow e^+e^-\gamma_{ISR}$

distance to interaction point	R _{xy} < 1.0 cm R _z < 10.0 cm
acceptance	0.4 rad < θ < π – 0.4 rad
to supress background	PID
# charged tracks	= 2
total charge	= 0
# photons	= 0 (untagged analysis)
missing photon angle	< 0.1 rad or > π – 0.1 rad
1C kinematic fit	χ ² _{1C} < 20

Calculation of ϵ

J. D. Bjorken, R. Essig, P. Schuster, and N. Toro, Phys. Rev., D80, 075018 (2009)

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 A^0 can decays into DM (neutralinos) or SM particles, such as $\mu^+\mu^-$

Phys. Rev. D 81, 075003 (2010)]

Light Higgs boson search via $J/\psi \rightarrow \gamma A^0, A^0 \rightarrow \mu$

Phys. Rev. D 93, 052005 (2016)

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Search for a dark gauge boson decaying to $\gamma \pi^0$ via $J/\psi \rightarrow \gamma \pi^0 \eta'$ **FESI**

Extracted signal yield in the step of 10 MeV/c^2

The significance, $S = \text{sign}(N_{sig})\sqrt{-2lnL_0/L_{max}}$, is observed to be less than 3σ

Search for a dark gauge boson decaying to $\gamma \pi^0$ via $J/\psi \rightarrow \gamma \pi^0 \eta'$ Reliminary

Set the upper limit using the Bayesian approach

Search for a dark gauge boson decaying to $\gamma \pi^0$ via $J/\psi \rightarrow \gamma \pi^0 \eta'$ **FESIM**

Systematic Uncertainties

Source(J/ $\psi \rightarrow$)	${\sf U}'\eta' o\gamma\pi^0\eta'(\%)$
MDC Tracking	2.0
Particle identification	2.0
Photon reconstruction	5.0
5C kinematic fit	0.4
η' mass window	0.2
π^0 mass window	1.1
MC efficiency BESII	I Preliminary 1.0
$\mathcal{B}(\eta' \to \pi^+ \pi^- \eta)$	1.6
$\mathcal{B}(\eta' o \gamma \gamma)$	0.5
$\mathcal{B}(\pi^0 \to \gamma \gamma)$	0.03
Number of J/ψ events	0.54
Veto π^0	1.1
Total	6.0

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