Axion-like particle and dark sector searches at BESIII

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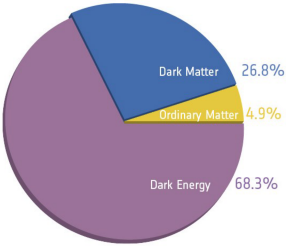
BESIII

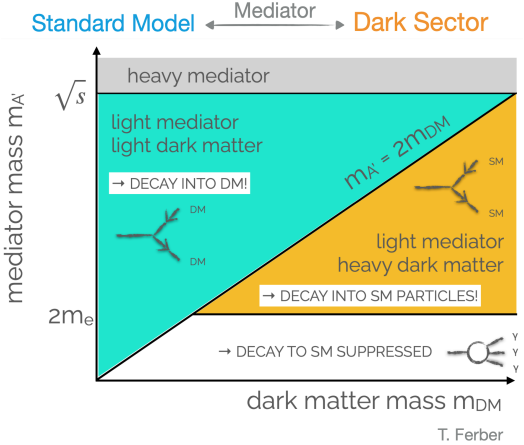
Outline

- Introduction
- BESIII experiment
- Axion-like particle search at BESIII
  - Search for an axion-like particle in radiative J/ψ decays
    - With $\psi(2S)$ data — PLB 838 137698 (2023)
    - With J/ψ data — Preliminary result
- Dark sector searches at BESIII
  - Search for invisible decays of a dark photon — PLB 839, 137785 (2023)
  - Search for a massless dark photon in $\Lambda_c^+ \to p\gamma'$ decay — PRD 106, 072008 (2022)
  - Search for invisible decays of the Λ baryon — PRD 105, L071101(2022)
- Summary

Introdduction

- Existence of dark matter
  - Galaxy rotation curves
  - Gravitational lensing
  - Cosmic microwave background
- Dark matter may interact with Standard Model through "portal" interactions
  - Vector portal (dark photon)
  - Pseudo-scalar portal (axion-like particle)
  - Scalar portal (dark Higgs)
  - Neutrino portal (heavy neutrinos)

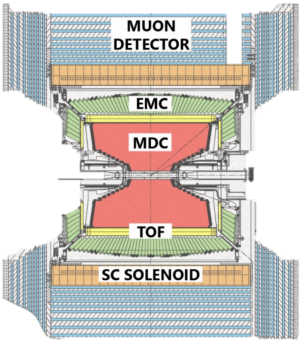


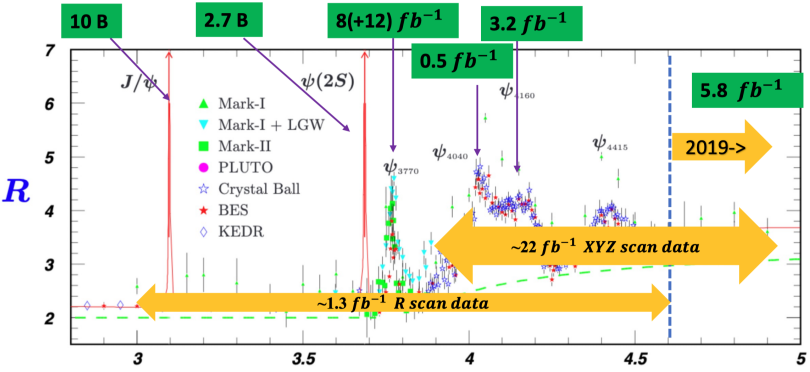


- Not just solving the dark matter puzzle. Could also explain:
  - Astrophysics anomalies: positron excess...
  - The $(g-2)_\mu$ anomaly
  - Strong CP problem, hierarchy problem...

BESIII experiment

- BESIII experiment is a symmetric electron positron collider running at tau-charm region
- BESIII has collected the largest data samples of 10 billion J/ψ, 2.7 billion $\psi(3686)$ on threshold in the world, and 20 fb^{-1} $\psi(3770)$ data samples are comming soon



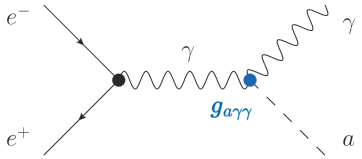


Axion-like particles (ALPs)

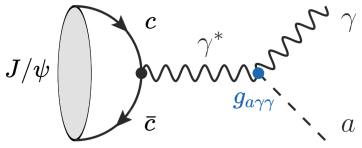
- Pseudo-Goldstone bosons arising from some spontaneously broken global symmetry, addressing the strong CP or hierarchy problems
- Predicted by many BSM theories and proposed as cold dark matter candidates
- The ALP-photon coupling $g_{a\gamma\gamma}$ is mostly discussed $\rightarrow$ ALP decays to two photons
- Independent mass and coupling bounded by experiments $\rightarrow$ $m_a \sim O(\text{GeV})$ mainly from electron-positron colliders

Phys. Lett. B 753, 482 (2016)

- Non-resonant ALP production

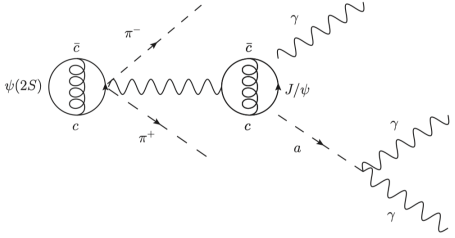


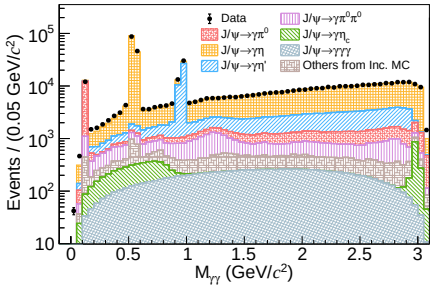
- Resonant ALP production



J. High Energy Phys. 06, 091 (2019)

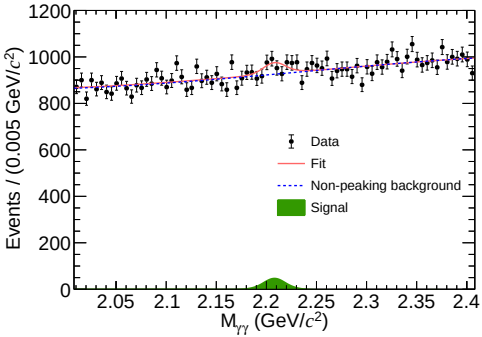
- Data samples: 2.7B $\psi(3686)$ events
- Search for $J/\psi \to \gamma a, a \to \gamma\gamma$ with $\psi(3686) \to \pi^+\pi^- J/\psi$ decays
  - ALP has a negligible width and lifetime in the search region $0.165 \leq m_a \leq 2.84$ GeV/c^2, decay width $\Gamma_a = g^2_{a\gamma\gamma} m_a^3/64\pi$
  - $\psi(3686)$ decay $\to$ preclude the pollution from non-resonant production
    avoid large QED background $e^+e^- \to \gamma\gamma(\gamma)$
  - Three $\gamma\gamma$ combinations per event, perform unbinned maximum-likelihood fits on $M_{\gamma\gamma}$
  - Exclude mass intervals around π^0, η, η' peaks when extracting the signal

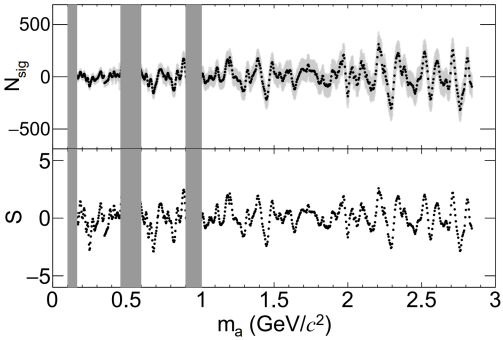




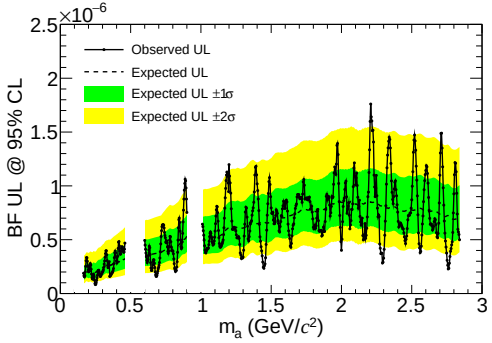
- Perform unbinned maximum likelihood fits to the $M_{\gamma\gamma}$ distribution
- Totally, 674 mass hypotheses are probed
- Step size is less than half the signal resolution (σ), $\sigma = 6 \sim 11$ MeV/c^2
- Fit intervals ($35 \sim 90\sigma$) are mass-dependent
- The maximum local significance is 2.6σ among all mass points

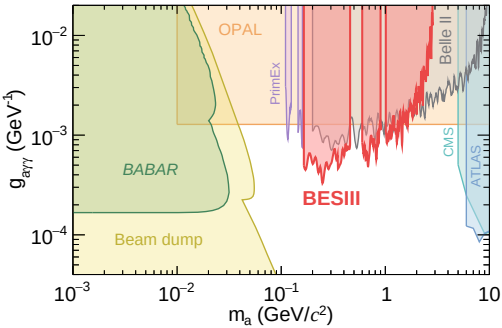
$\mathcal{S} = \text{sign}\,(N_{\text{sig}}) \cdot \sqrt{2 \ln (\mathcal{L}_{\text{max}}/\mathcal{L}_0)}$



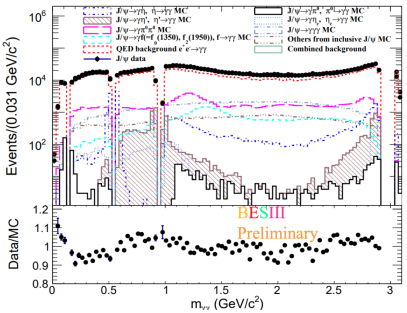


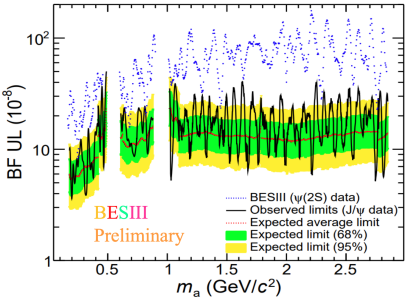
- No significant ALP signal observed
- Upper limit results
  - 95% CL upper limits on $B(J/\psi \to \gamma a)$ are computed using a one-sided frequentist profile-likelihood method Eur. Phys. J. C 71, 1554 (2011)
  - The observed limits range from 8.3×10^{-8} to 1.8×10^{-6} in the search region
  - The exclusion limits on the ALP-photon coupling are the most stringent to date three times better than Belle II result at $m_a \sim 0.25$ GeV/c^2





- Data samples: 10B J/ψ events
- Search for $J/\psi \to \gamma a, a \to \gamma\gamma$ with J/ψ data on threshold
  - Estimate the contribution from non-resonant production, $\sigma_{res} = \frac{N_{J/\psi}}{\mathcal{L}_{J/\psi}} \cdot \mathcal{B}(J/\psi \to \gamma a)$ $\sigma_{non-res}/\sigma_{res} = 0.044$, which is taken as systematic uncertainty
  - Select at three photon candidates in the EMC barrel region
  - Obtain di-photon invariant mass spectrum of all three combinations after vetoing $J/\psi \to \gamma P$ $\left(P = \pi^0, \eta, \eta', \eta_c\right)$ backgrounds
  - The 95% CL upper limits of $B(J/\psi \to \gamma a)$ reach a level of 10^{-7} for full search region



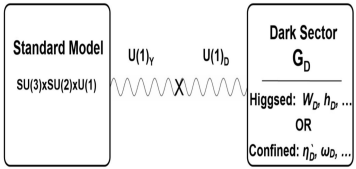


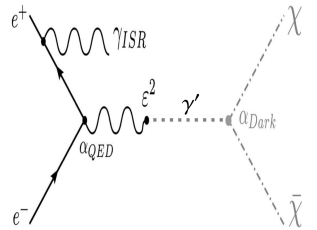
Earlier dark sector searches at BESIII

- Visible dark photon searches
  - $J/\psi \to U\eta/\eta'$ decay PRD 99, 012006 (2019) PRD 99, 012013 (2019)
  - ISR process PLB 774, 252 (2017)
- Searches for fully invisible decays
  - Invisible decays of ω/ϕ mesons PRD 98, 032001 (2018)
  - Invisible decays of η/η' mesons PRD 87, 012009 (2013)
- Other searches with invisible signatures
  - Search for the decay $J/\psi \to \gamma + \text{invisible}$ PRD 101, 112005 (2020)
  - Search for FCNC process with invisibles in $D^0 \to \pi^0\nu\bar{\nu}$ PRD 105, L071102 (2022)

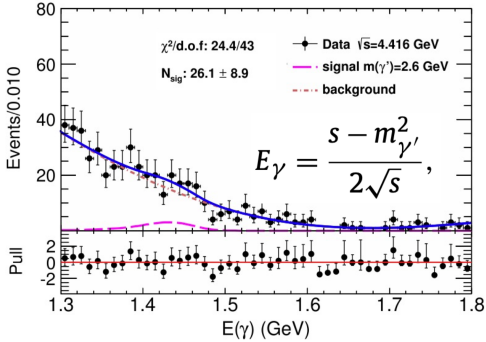
Massive dark photon

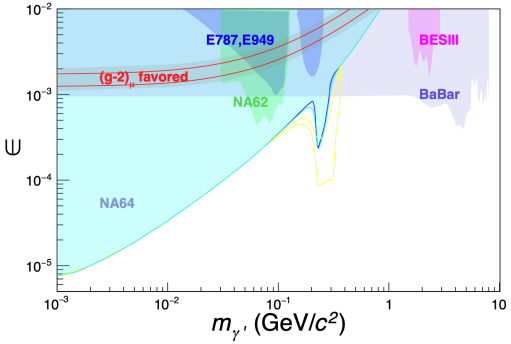
- A spin-one boson associated with a new Abelian gauge symmetry $U(1)_D$ spontaneously broken, massive kind
- Proposed as a force carrier connected to dark matter
- The dark photon couples weakly to a SM photon through kinetic mixing with a mixing parameter $\epsilon \sim 10^{-3}$
- The dark photon (γ') would predominately decay into a pair of DM particles $\gamma' \to \chi\bar{\chi}$ if $m_\chi < m_{\gamma'}/2$
- Search for the dark photon in the radiative annihilation process $e^+e^- \to \gamma\gamma'$, followed by an invisible decay of the γ'





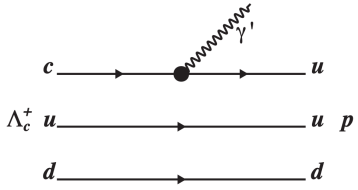
- Data samples: 14.9 fb^{-1} e^+e^- annihilation data at $\sqrt{s} = 4.13 \sim 4.60$ GeV
- Search for single photon signals in $1.3 < \mathrm{E}(\gamma) < 1.8$ GeV corresponding to $1.5 < m_{\gamma'} < 2.9$ GeV
  - Low $E(\gamma)$ region $\rightarrow$ low trigger efficiency & high background level
  - High $E(\gamma)$ region $\rightarrow$ saturation of the EMC electronics
  - A simultaneous likelihood fit on the photon energy spectra is performed to all data sets
  - No obvious signal observed, the 90% CL upper limits of coupling ϵ are $(1.6 - 5.7) \times 10^{-3}$
  - BESIII will produce more competitive results with 20 fb^{-1} data taken at 3.77 GeV in the future



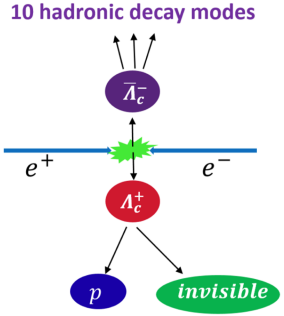


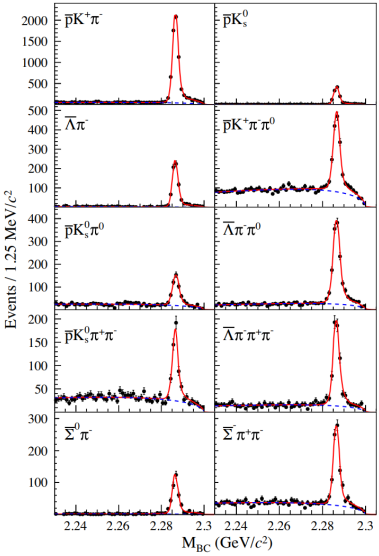
Massless dark photon

- A spin-one boson associated with a new Abelian gauge symmetry $U(1)_D$ unbroken, massless kind
- FCNC process is highly suppressed by the GIM mechanism in the charm sector
  less than 10^{-9} in SM, Phys. Rev. D 98, 030001 (2018)
- A massless dark photon could induce FCNC process through higher dimensional operators,
  allowing $\mathcal{B}(\Lambda_c^+ \to p\gamma')$ up to 1.6×10^{-5}
  Phys. Rev. D 102, 115029 (2020)
- The missing energy due to the dark photon is the feature of the signal processes

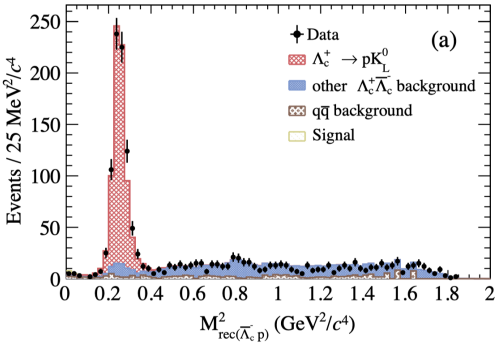


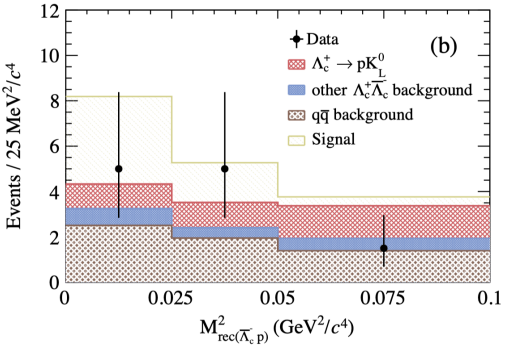
- Data samples: 4.5 fb^{-1} e^+e^- annihilation data at $\sqrt{s} = 4.6 \sim 4.7$ GeV
- Double Tag Method
  - Tag side: reconstruct $\bar{\Lambda}_c^-$ with ten hadronic decay modes. Tag yields: 105244 ± 384
  - Signal side: $\Lambda_c^+ \to p\gamma'$
  - $\mathcal{B}(\Lambda_c^+ \to p\gamma') = \frac{N_{\rm obs} - N_{\rm bkg}}{\sum_{ij} N_{ij}^{\rm ST} \cdot \left(\epsilon_{ij}^{\rm DT}/\epsilon_{ij}^{\rm ST}\right)}$





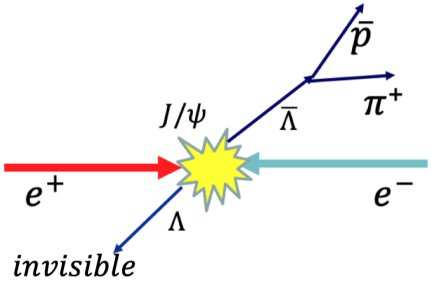
- Search for an invisible signature on the square of the recoil mass spectrum $M^2_{\mathrm{rec}(\bar{\Lambda}_c^- \mathrm{p})}$
  - Signal region is defined as $(0.0, 0.1)\,\mathrm{GeV}^2/c^4$ in the $M^2_{\mathrm{rec}(\bar{\Lambda}_c^- \mathrm{p})}$
  - No significant signal observed, $\mathcal{B}(\Lambda_c^+ \to p\gamma') < 8.0 \times 10^{-5}$ at 90% CL
  - A more stringent constraint is expected with larger Λ_c^+ samples at BESIII

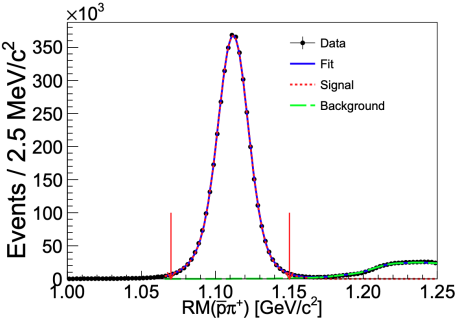




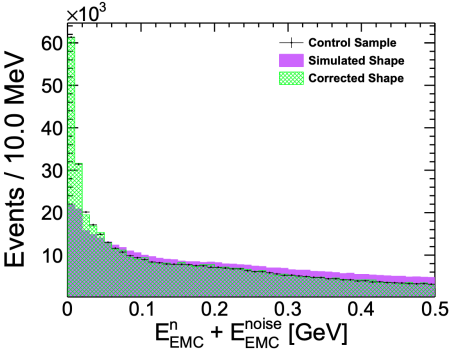
- Dark matter may be represented by baryon matter with invisibles, and many theories suggest a potential correlation between baryon symmetry and dark sector Phys. Rev. D 105, 115005 (2022)
- Discrepancy of neutron lifetime in beam method and the storage methods $\rightarrow \mathcal{B}(n \rightarrow p + X) \approx 99\%$ Phys. Rev. D 99, 035031 (2019)
- Data samples: 10B J/ψ events
- Double Tag Method: reconstruct $\bar{\Lambda}$ with $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ decay

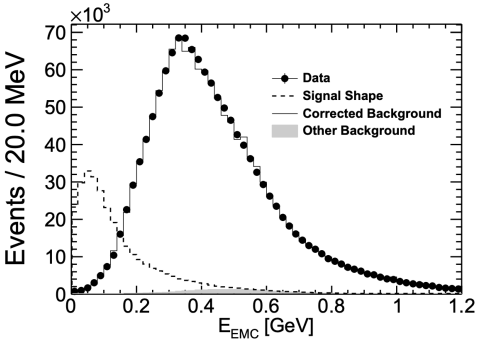
$$\mathcal{B}(\Lambda \rightarrow \text{invisible}) = \frac{N_{\text{sig}}}{N_{\text{tag}} \cdot (\varepsilon_{\text{sig}}/\varepsilon_{\text{tag}})}$$





- Search for signal on total energy in EMC E_{EMC} (not charged tracks)
  - Dominating background: $\Lambda \to n\pi^0$, $E_{\rm EMC} = E^{\pi^0}_{\rm EMC} + E^{n}_{\rm EMC} + E^{\rm noise}_{\rm EMC}$
  - $E^{\pi^0}_{\rm EMC}$: based on the MC simulations
  - $E^{n}_{\rm EMC} + E^{\rm noise}_{\rm EMC}$: based on control sample $J/\psi \to \Lambda\left(n\pi^0\right)\bar{\Lambda}\left(\bar{p}\pi^+\right)$
  - No obvious signal observed, $\mathcal{B}(\Lambda \to \text{invisible}) < 7.4 \times 10^{-5}$ at 90% CL
  - Consistent with the prediction of 4.4×10^{-7} from the mirror model arXiv:2006.10746





Summary

- Dark sectors have become an intriguing idea for understanding dark matter, and also for looking into new physics beyond SM
- BESIII plays an active role in dark sector and axion-like particle search, with many first searches or best limits
  - Search for ALPs with $\psi(2S)$ and J/ψ data (best limits)
  - Search for dark photon invisible decays (competitive results)
  - Search for a massless dark photon in Λ_c^+ decays (first FCNC search of charmed baryon)
  - Search for Λ invisible decays (first search for invisible baryon decays)
- With more data available, more exciting results are coming soon

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