Dark sector and Axion-like particle search at BESIII

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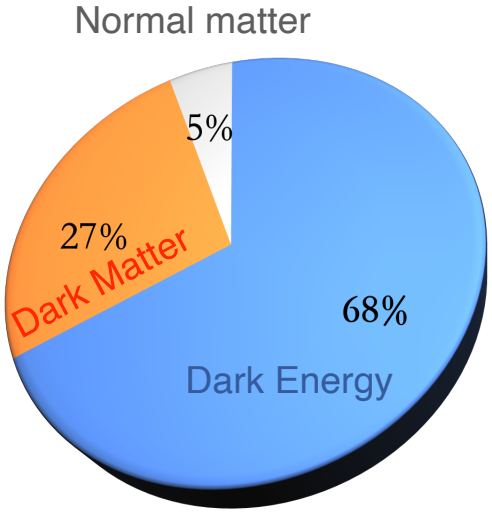
Introduction



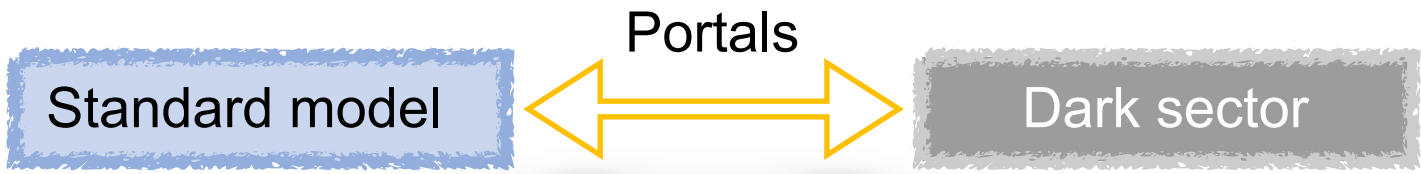
- Standard Model (SM) is incredibly successful, but not complete!
  - SM fails to explain the origin of dark matter (DM) of the universe

New Physics!

- 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)

Dark, but is experimentally accessible!

- High intensity e^+e^- collider experiments, such as BESIII, have the ability to probe dark sector particles and ALPs, benefiting from a well-measured CM energy and a clean environment



Outline

- **Introduction**
- **BEPCII & BESIII**
- **Topics in this talk**
  - **Axion-like particles (ALPs) search**

    Search for an axion-like particle in radiative J/ψ decays

    ✓ Using $\psi(3686)$ data — PLB 838 137698 (2023)

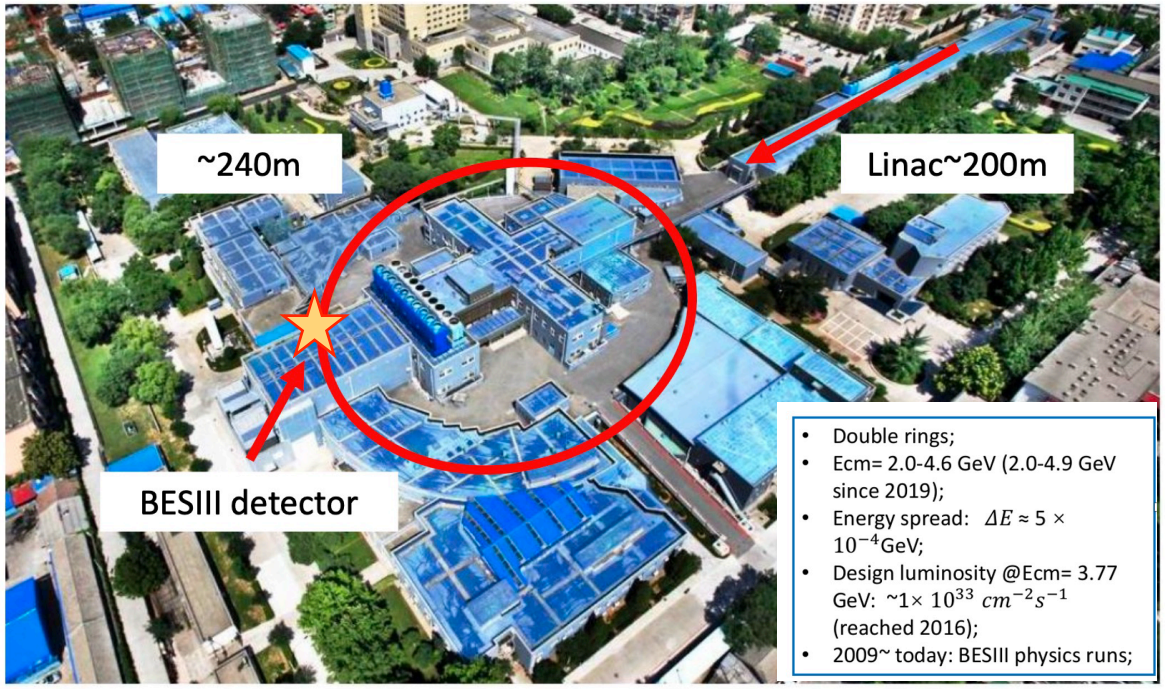
    ✓ Using J/ψ data — Preliminary result
  - **Dark sector search**

    1. Search for massless dark photon in $\Lambda_c^+ \to p\gamma'$ — PRD 105, 106, 072008 (2022)
    2. Search for invisible decays of Λ baryon — PRD 105, L071101(2022)
    3. Search for invisible decays of dark photon — PLB 839, 137785 (2023)
- **Summary**

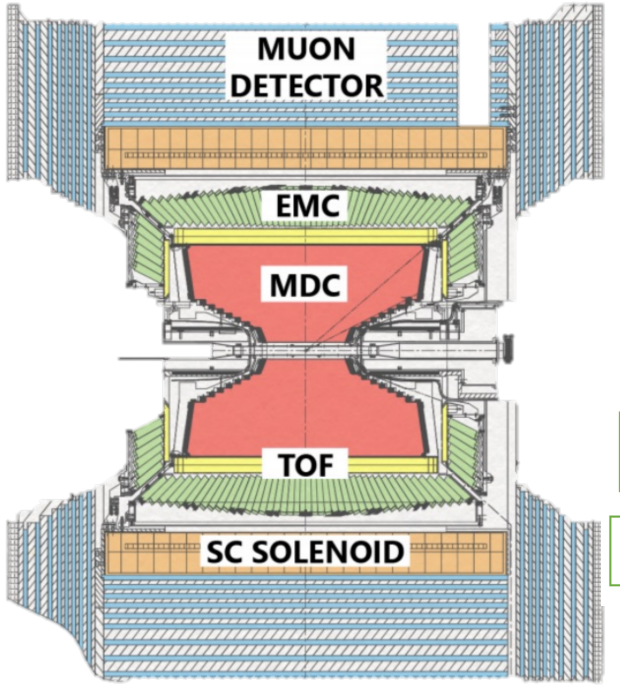
BESIII experiment

- A symmetric electron positron collider running at tau-charm region
  - BEPCII: Electron–positron colliders: accelerate the e^+, e^-
  - BESIII detector : Record the hit positions, momentum , energy of particles.

Beijing Electron–Positron Collider II



Beijing Spectrometer III



Main Drift Chamber
σ_p/p <0.5% (@1GeV) (1T)
σ_{xy} ~120 μm
dE/dx~6%

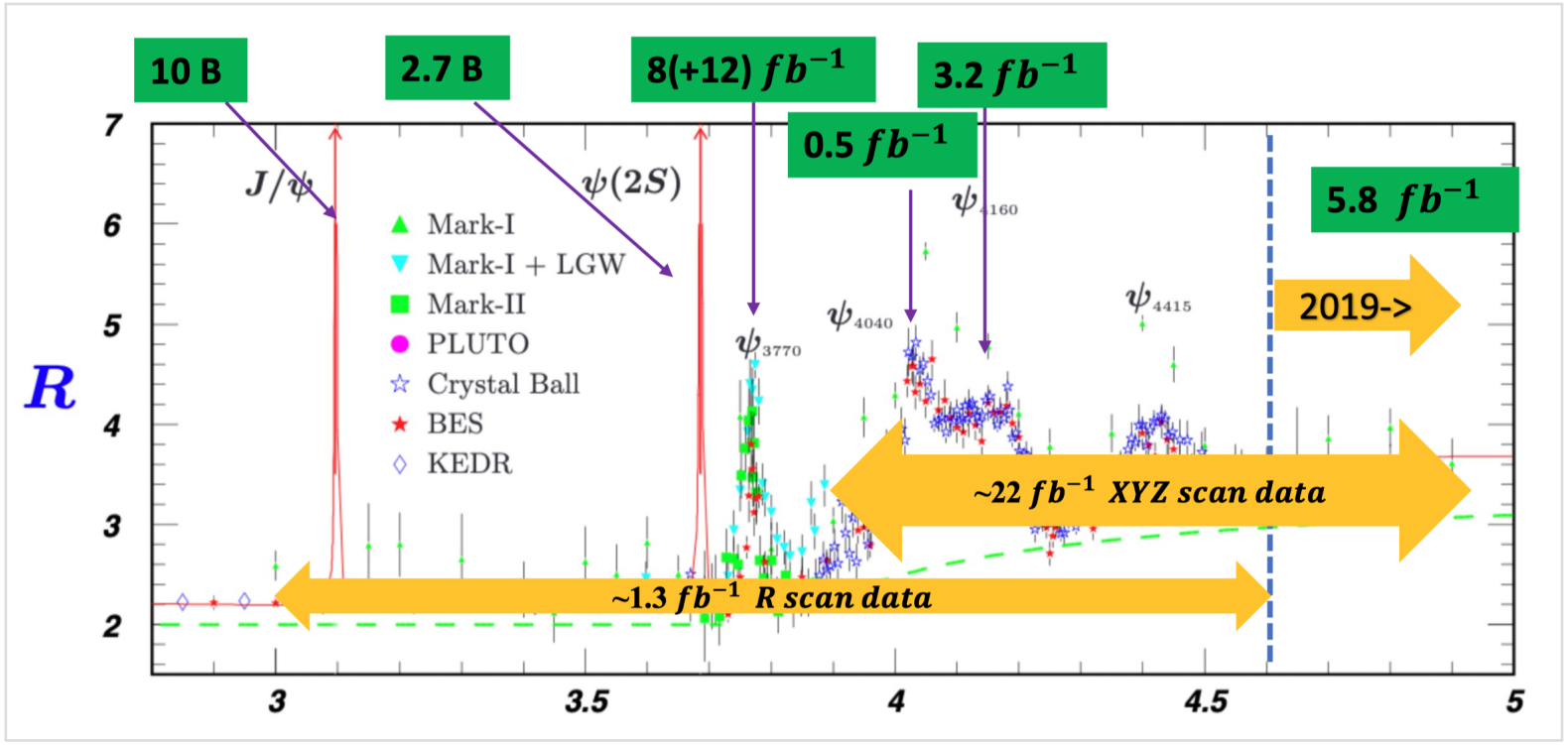
Time Of Flight
$\sigma_t < 68ps$(barrel)
$\sigma_t <$ 60ps (endcap)

Electromagnetic Calorimeter
σ_E/E<2.5%(5%) @1GeV
σ_{xy}~6mm (@1GeV)

Muon Counter
$\sigma_{\text{spatial}} < 2cm$

BESIII Dataset

- World largest data samples in tau-charm region:
  - 10 billion J/ψ, 2.3 billion $\psi(3686)$ on threshold in the world, and 20fb^{-1} $\psi(3770)$ data samples are coming soon
- Ideal environment to study
  - ✓ Charmonium
  - ✓ Charm
  - ✓ Light hadrons
  - ✓ Tau and QCD
  - ✓ New physics



Search for an **axion-like** particle in radiative J/ψ decays

PLB 838 137698 (2023)

Axion-like particles (ALPs)

- Pseudo-scalar particle

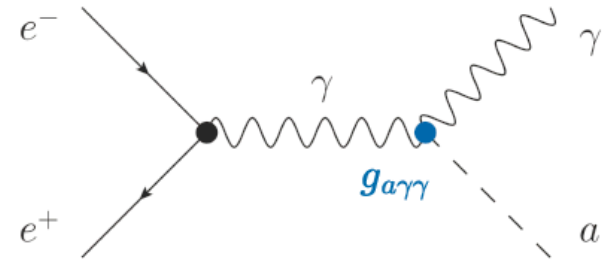
  Phys. Rev. Lett. 40, 223 (1978);
  Phys. Rev. Lett. 40, 279 (1978)

- Introduced by the spontaneous breaking of Peccei-Quinn symmetry to solve the strong CP problem of the QED
- The ALP-photon coupling $g_{a\gamma\gamma}$ is mostly discussed → ALP decays to two photons $(a \to \gamma\gamma)$
- Independent mass and coupling bounded by experiments
  - ☆ Experimental bounds on $g_{a\gamma\gamma}$ with m_a range of $\mathrm{MeV}/c^2 - \mathrm{GeV}/c^2$ mainly from e^+e^- colliders

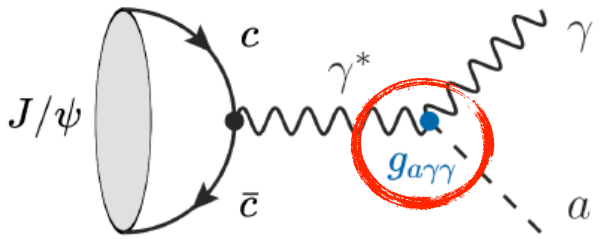
    Phys. Lett. B 753, 482 (2016)
- We search for ALPs decaying into two photons in J/ψ radiative decays via $J/\psi \to \gamma a, a \to \gamma\gamma$ in $0.165 < m_a < 2.84\ \mathrm{GeV}/c^2$

$$\mathcal{B}(J/\psi \to \gamma a) = \frac{m_{J/\psi}^2}{32\pi\alpha_{\mathrm{em}}} g_{a\gamma\gamma}^2 \left(1 - \frac{m_a^2}{m_{J/\psi}^2}\right)^3 \mathcal{B}(J/\psi \to e^+e^-),$$

- Non-resonant ALP production



- Resonant ALP production



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

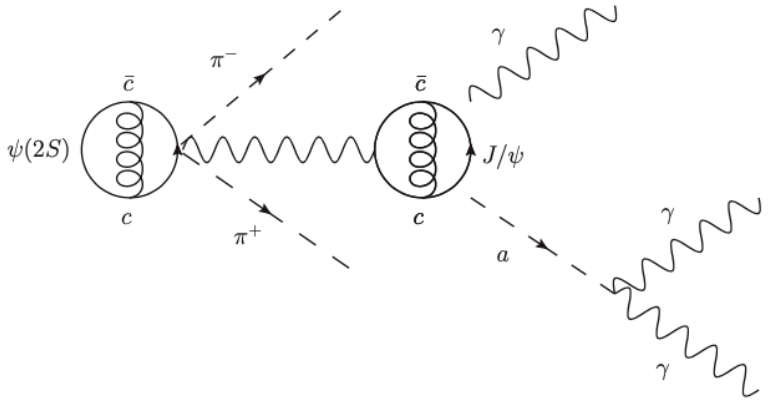
Search for an **axion-like** particle in radiative J/ψ decays

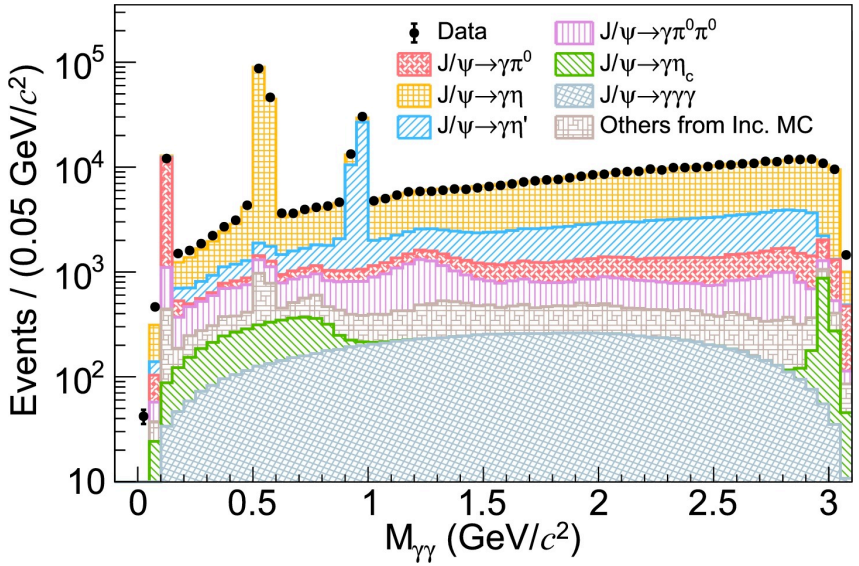
PLB 838 137698 (2023)

- **Data samples**: 2.27 Billion $\psi(3686)$ events
- **Strategy:**

Search for $J/\psi \to \gamma a, a \to \gamma\gamma$ with $\psi(3686) \to \pi^+\pi^- J/\psi$ decays

- Search range: $0.165 < m_a < 2.84$ GeV $/c^2$
- a : negligible lifetime ▸ decay width $\Gamma_a = g^2_{a\gamma\gamma} m_a^3/64\pi$
- $\psi(3686)$ decay
  - ★ 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





Search for an **axion-like** particle in radiative J/ψ decays

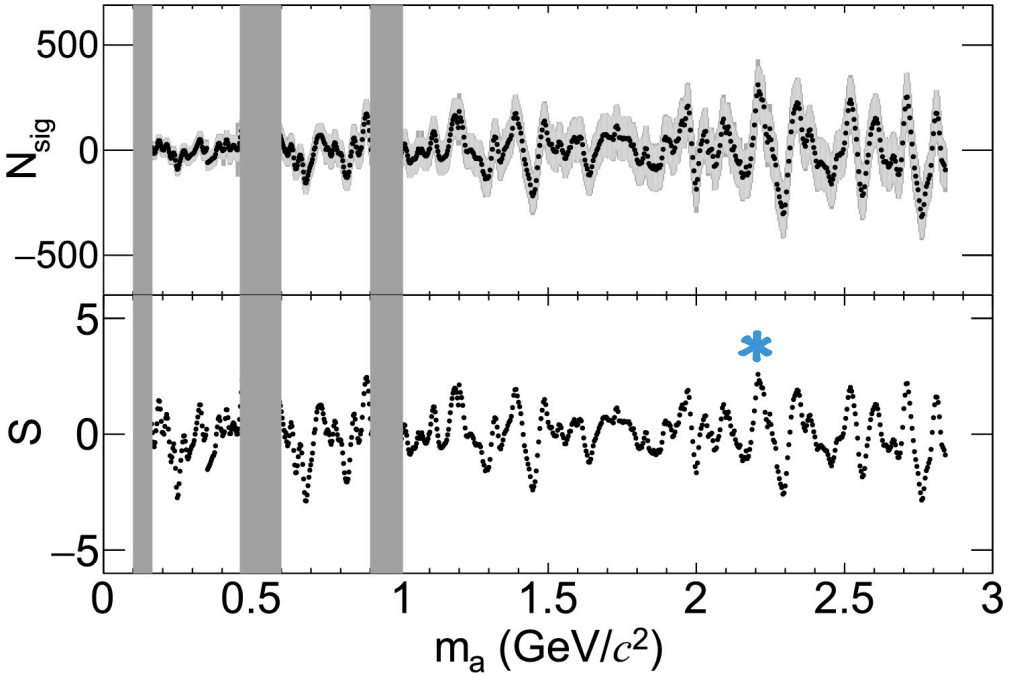
PLB 838 137698 (2023)

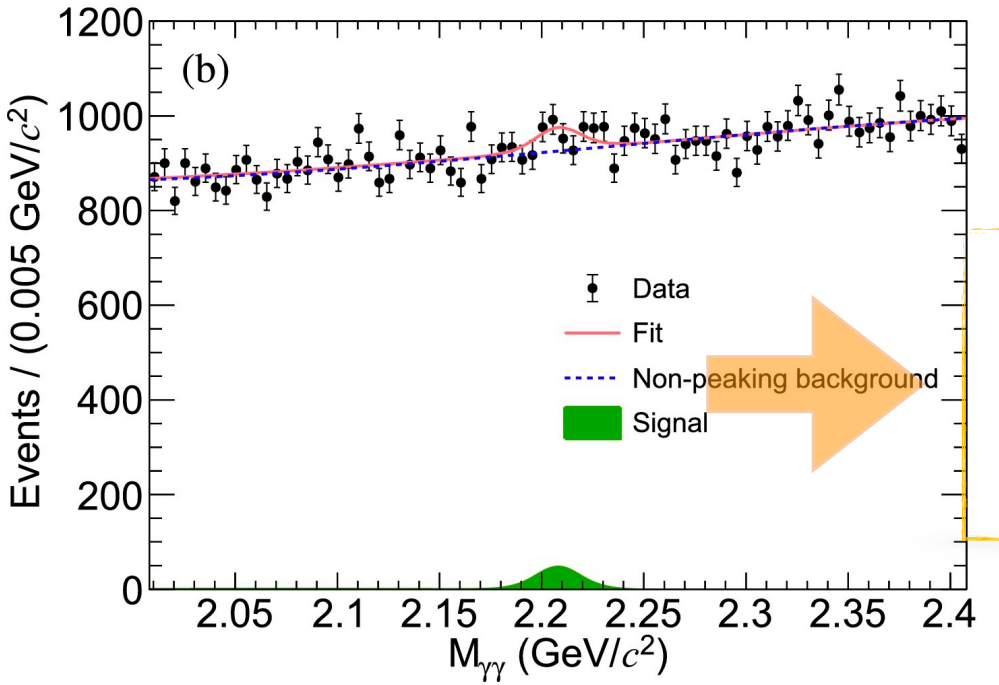
Signal extraction

- A series of 1D unbinned maximum-likelihood fits are performed to $M_{\gamma\gamma}$ distribution
  - Determine the **signal yields** with different **ALP mass** hypotheses.
- Totally, 674 mass hypotheses are probed
  - $m_a = 2.208\text{GeV}/c^2$

The $M_{\gamma\gamma}$ fit intervals for various m_a points.

m_a points (GeV/c^2)	$M_{\gamma\gamma}$ fit intervals (GeV/c^2)
0.165 - 0.35	0.06 - 0.45
0.35 - 0.75	0.25 - 0.85
0.75 - 1.20	0.65 - 1.30
1.20 - 2.84	$(m_a - 0.2)$ - $(m_a + 0.2)$





The maximum local significance are less than 2.6σ among all mass points

Search for an **axion-like** particle in radiative J/ψ decays

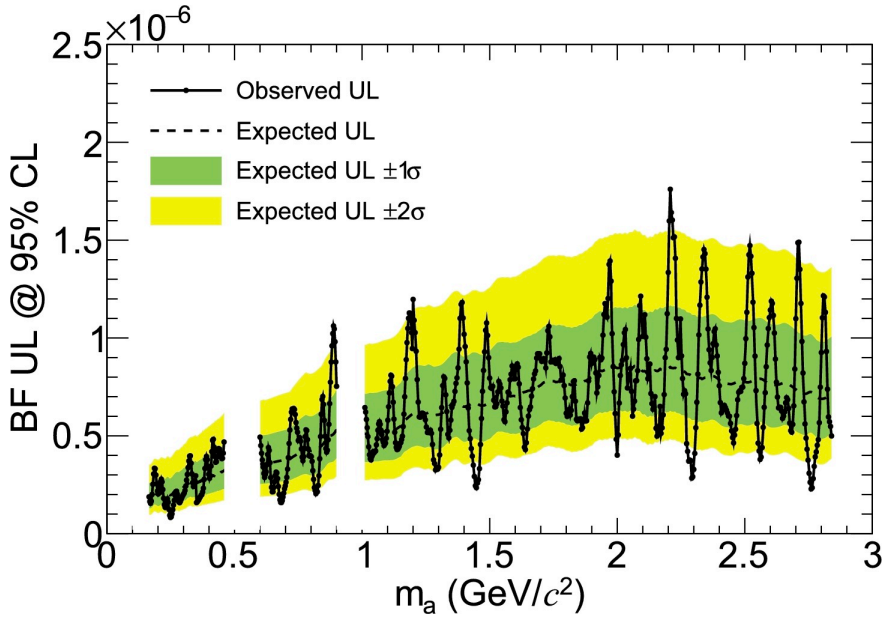
PLB 838 137698 (2023)

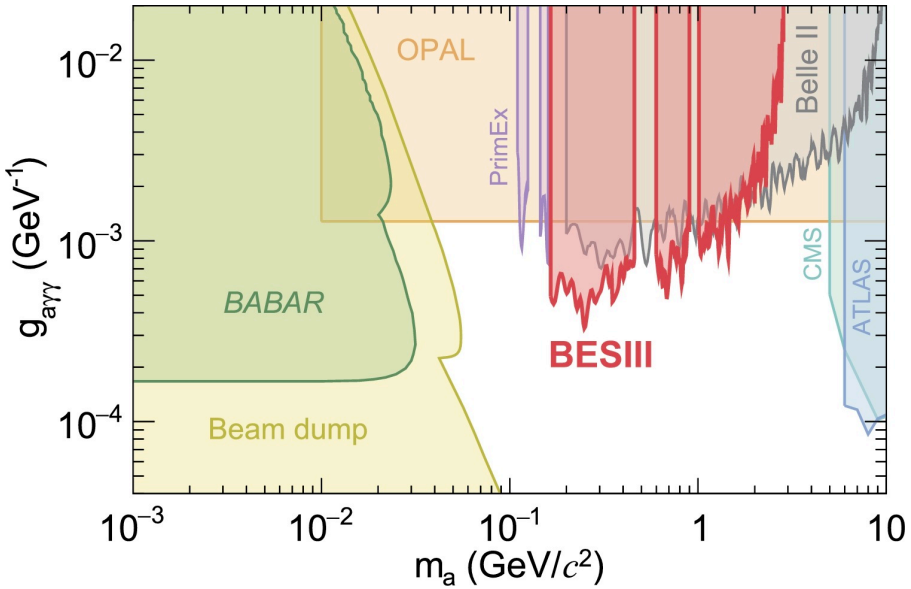
Upper limits

- Since no significant ALP signal is observed, 95% confidence level upper limits on $\mathcal{B}(J/\psi \to \gamma a)$ are computed

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 $0.165 < m_a < 2.84$ GeV $/c^2$
- ★ The exclusion limits on the ALP-photon coupling are the most stringent to date for $0.165 < m_a < 1.468$ GeV $/c^2$





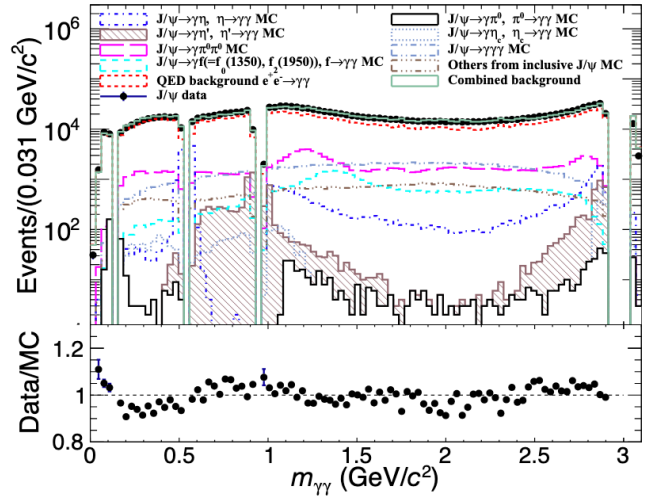
Search for an **axion-like** particle in radiative J/ψ decays

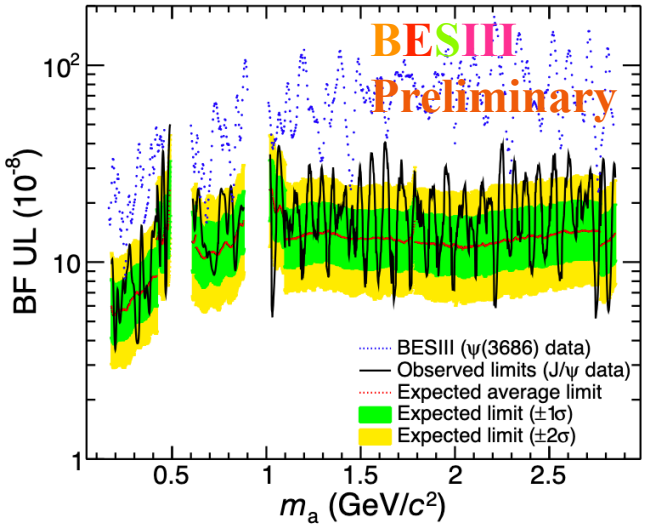
Preliminary result

- **Data samples**: 10B J/ψ events
- **Strategy:**

Search for $J/\psi \to \gamma a, a \to \gamma\gamma$ with J/ψ data on threshold

- The contribution from non-resonant production, $\sigma_{non-res}/\sigma_{res}$, is estimated to be 4.4% (taken as systematic uncertainty)
- Select at least three photon candidates in the EMC barrel region
- Exclude mass intervals around π^0, η, η' peaks when extracting the signal
- ☆ Expected UL
  - ☆ The 95%CL upper limits of $\mathcal{B}(J/\psi \to \gamma a)$ reach a level of 10^{-7} for full search region





Search for massless dark photon in $\Lambda_c^+ \to p\gamma'$

PRD 105, 106, 072008 (2022)

Motivation on Massless dark photon γ'

- spontaneous broken: massive
- Unbroken: massless

- A new force mediated by γ' between the dark sector and the SM is proposed
- The flavor changing neutral current (FCNC) is highly suppressed by the GIM mechanism in the charm sector

  $< 10^{-9}$ in SM, Phys. Rev. D 98, 030001 (2018)

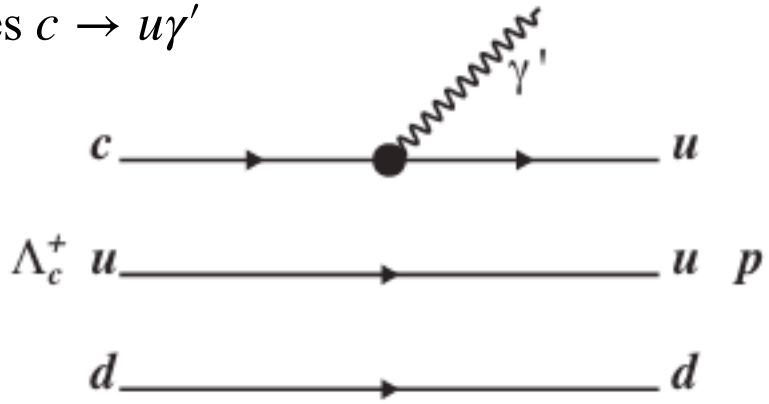
  - ☆ any significant observation would be a hint for the new physics.

- 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)

  within the sensitivity of BESIII experiments!

- The missing energy due to the dark photon is the feature of the signal processes $c \to u\gamma'$

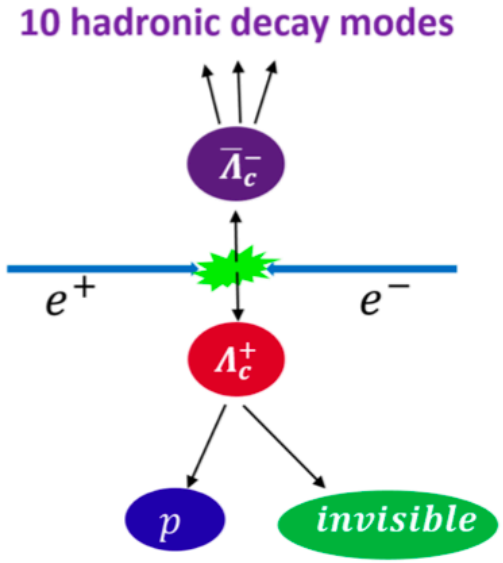


Search for massless dark photon in $\Lambda_c^+ \to p\gamma'$

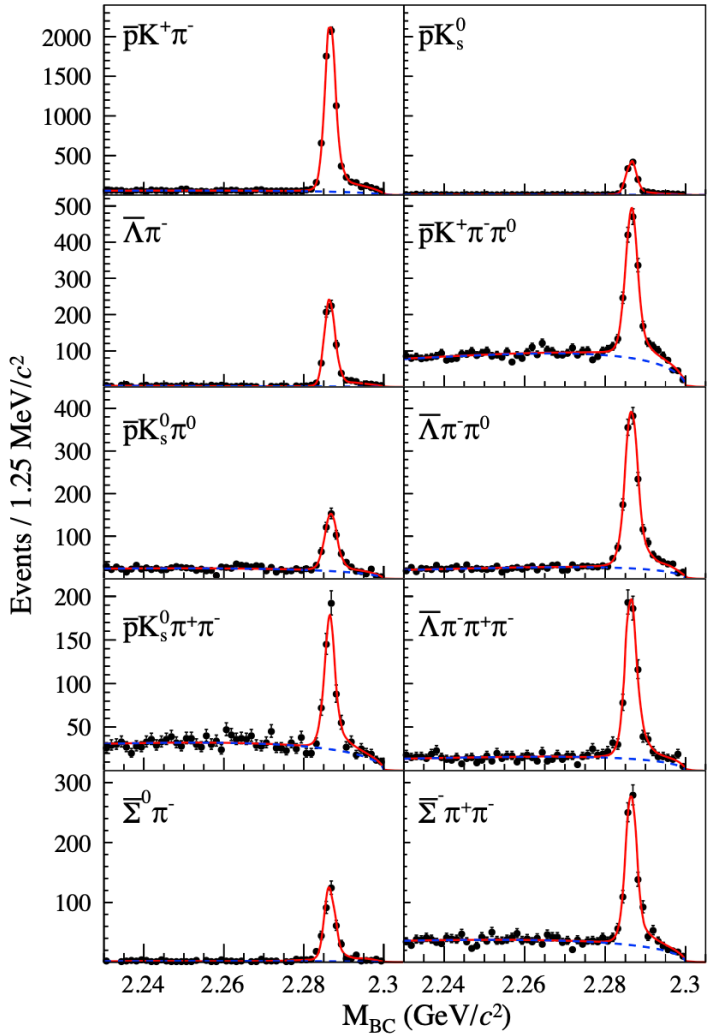
PRD 105, 106, 072008 (2022)

- **Data samples**: 4.5 fb^{-1} e^+e^- annihilation data at $\sqrt{s} = 4.6 \sim 4.7$ GeV
- **Strategy:**
  - The $\Lambda_c^+\bar{\Lambda}_c^-$ are pair produced in $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$
  - Double Tag Method
    - Tag side: reconstruct $\bar{\Lambda}$ with 10 hadronic decay modes. Tag yields: 105244 ± 384
    - Signal side: $\Lambda_c^+ \to p\gamma'$

$$\mathcal{B}(\Lambda_c^+ \to p\gamma') = \frac{N_{\rm obs} - N_{\rm bkg}}{\sum_{ij} N_{ij}^{\rm ST} \cdot (\epsilon_{ij}^{\rm DT}/\epsilon_{ij}^{\rm ST})},$$



$\bar{\Lambda}_c \to$ 10 hadronic decays



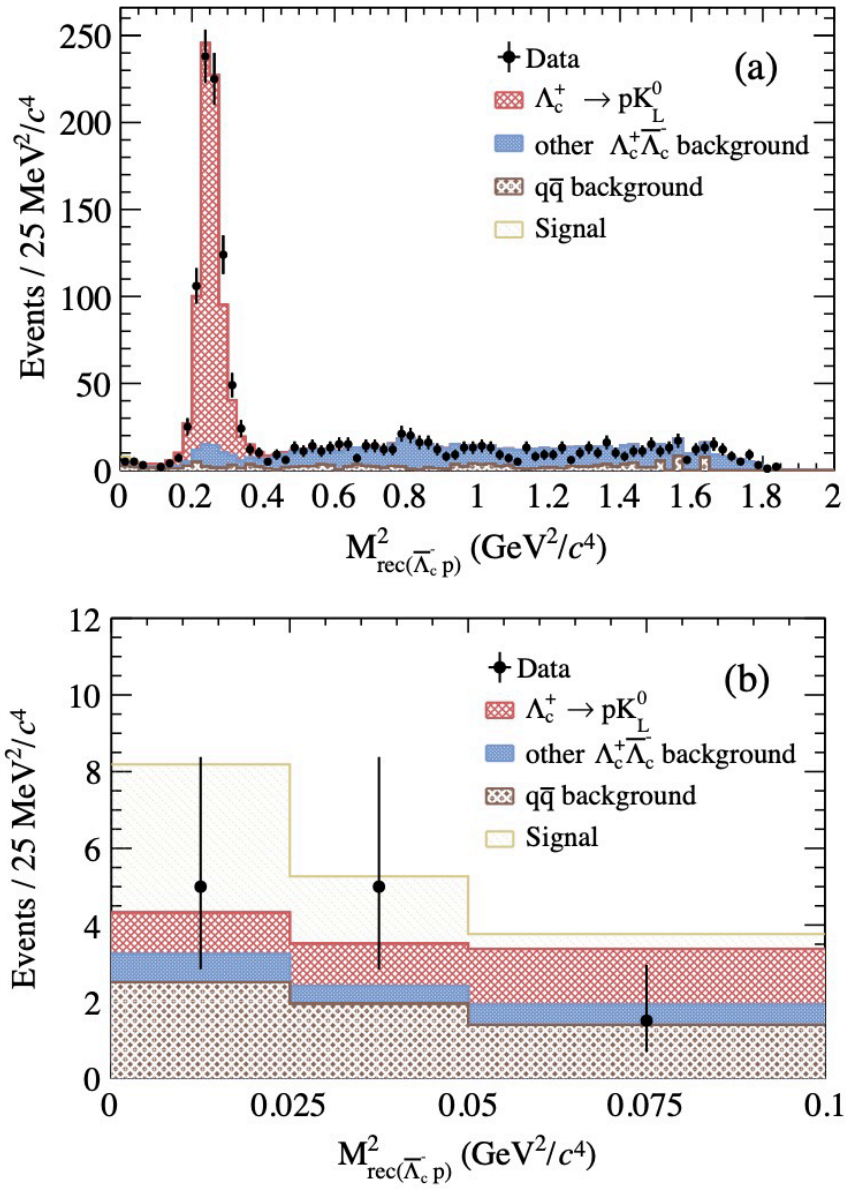
Search for massless dark photon in $\Lambda_c^+ \to p\gamma'$

PRD 105, 106, 072008 (2022)

Signal extraction

- Search for an invisible signature on the square of the recoil mass spectrum $M^2_{\mathrm{rec}(\bar{\Lambda}_c^- p)}$
- Signal region is defined as (0.0, 0.1) GeV^2/c^4 in the $M^2_{\mathrm{rec}(\bar{\Lambda}_c^- p)}$
- 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

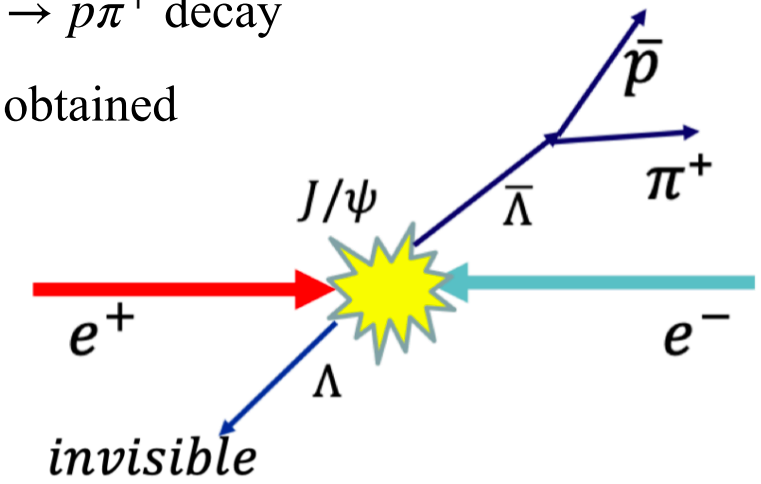


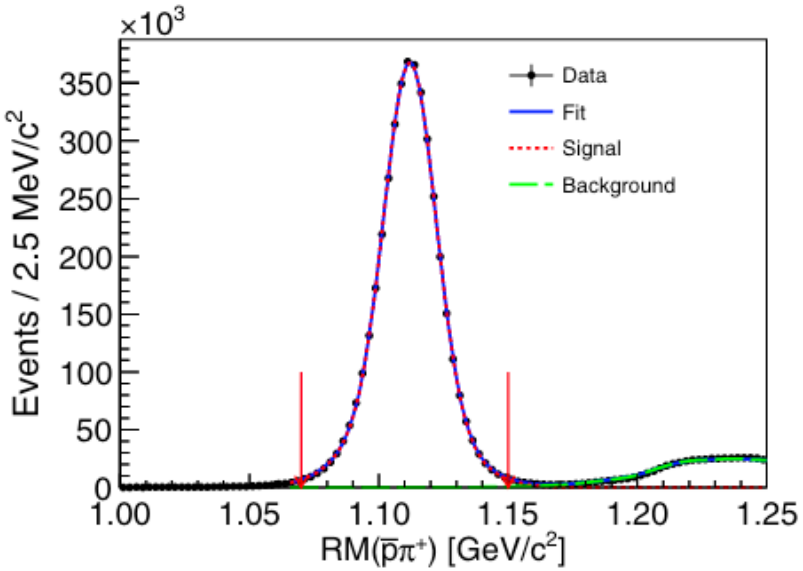
Search for invisible decays of the Λ baryon

PRD 105, L071101(2022)

- **Motivation**
  - 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 → $B(n \to p + X) \approx 99\%$ Phys. Rev. D 99, 035031 (2019)
- **Data samples:** 10B J/ψ events
- **Method:** Double tag method
  - Tag side: reconstruct $\bar{\Lambda}$ with $\bar{\Lambda} \to \bar{p}\pi^+$ decay
    - 4 Million tag $\bar{\Lambda}$ events are obtained
  - Signal side: $\Lambda \to$ invisible

$$\mathcal{B}(\Lambda \to \text{invisible}) = \frac{N_{sig}}{N_{tag} \times (\epsilon_{sig}/\epsilon_{tag})}$$





Search for invisible decays of the Λ baryon

PRD 105, L071101(2022)

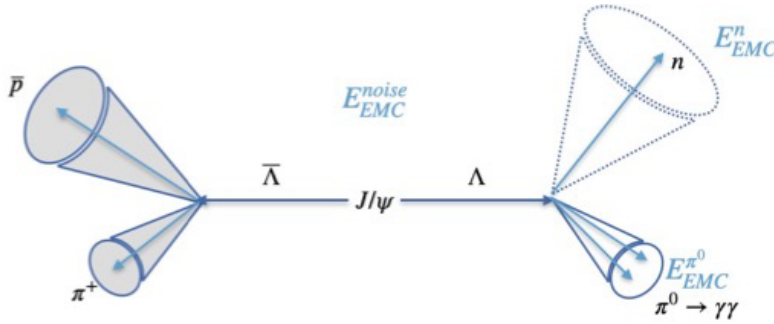
Signal extraction

- Search for signal on total energy deposited in EMC → E_{EMC} (not charged tracks);
- Dominating background: $\Lambda \to n\pi^0$
- E_{EMC} divided into three parts

$$E_{\rm EMC} = E^{\pi^0}_{\rm EMC} + E^{n}_{\rm EMC} + E^{\rm noise}_{\rm EMC},$$

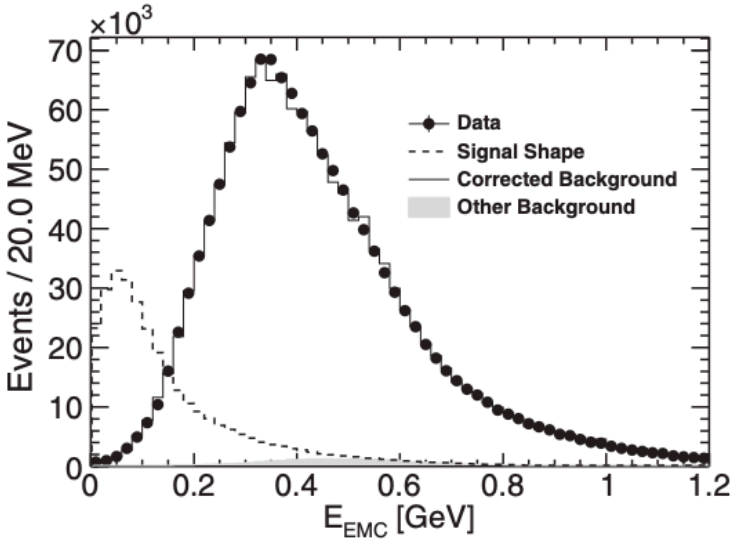
  - ☆ $E^{\pi^0}_{EMC}$: based on the MC simulations
  - ☆ $E^{n}_{EMC} + E^{\rm noise}_{EMC}$: based on control sample $J/\psi \to \Lambda(n\pi^0)\bar{\Lambda}(\bar{p}\pi^0)$

Electromagnetic Calorimeter
σ_E/E<2.5%(5%) @1GeV
σ_{xy}~6mm (@1GeV)



Upper limits

- No obvious signal observed
  - ☆ $\mathcal{B}(\Lambda \to \text{invisible}) < 7.4 \times 10^{-5}$ at 90% CL arXiv:2006.10746
- ✓ Consistent with the prediction of 4.4×10^{-7} from the mirror model
- ✓ The first search of invisible decays of baryons

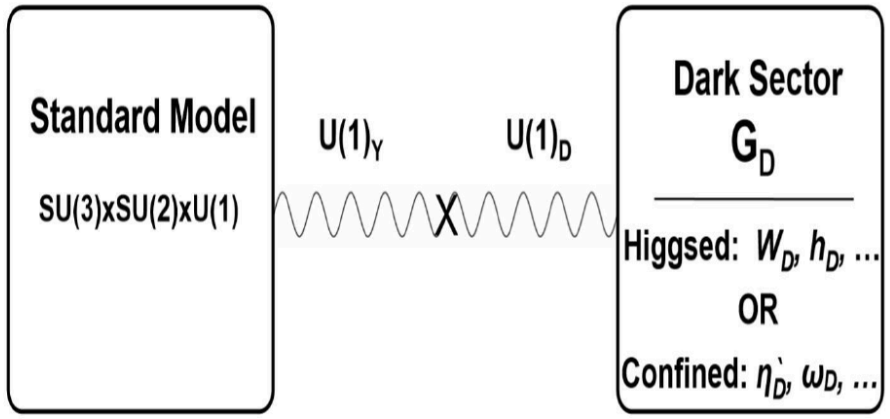


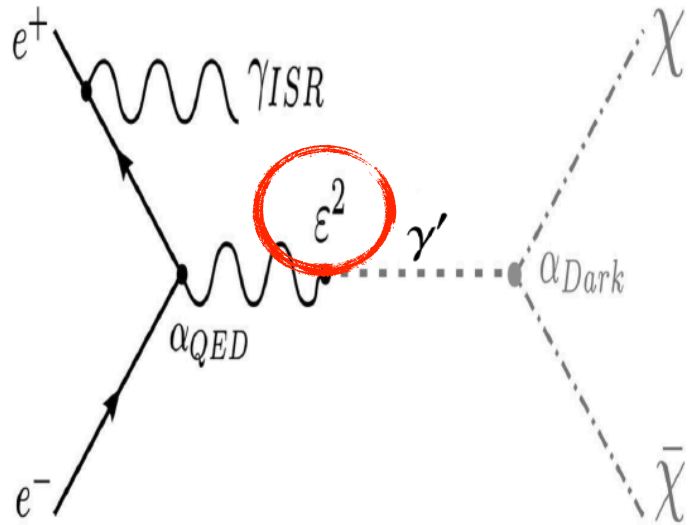
Search for invisible decays of dark photon

PLB 839, 137785 (2023)

- **Motivation on Massive dark photon γ'**
  - γ' couples weakly to a SM photon γ through kinetic mixing with a mixing parameter $\epsilon \sim 10^{-3}$

    γ' with mass in the GeV range
  - Search for the dark photon in the radiative annihilation process $e^+e^- \to \gamma\gamma'$, $\gamma' \to$ invisible decay of the γ'





★**dark photon γ'**

- spontaneous broken: massive
- Unbroken: massless

Search for invisible decays of dark photon

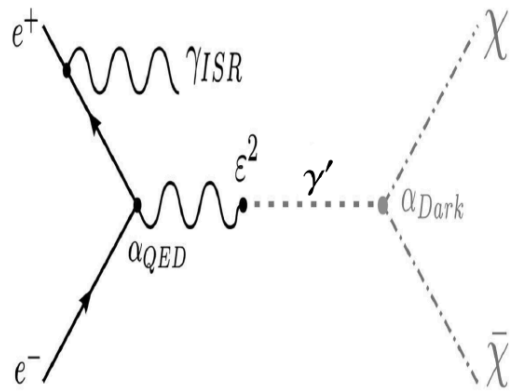
PLB 839, 137785 (2023)

- **Data samples**:
  - 14.9 fb^{-1} e^+e^- annihilation data at $\sqrt{s} = 4.13 \sim 4.60$ GeV
- **Strategy:**

  Search for single photon signals in $1.3 < E(\gamma) < 1.8$ GeV

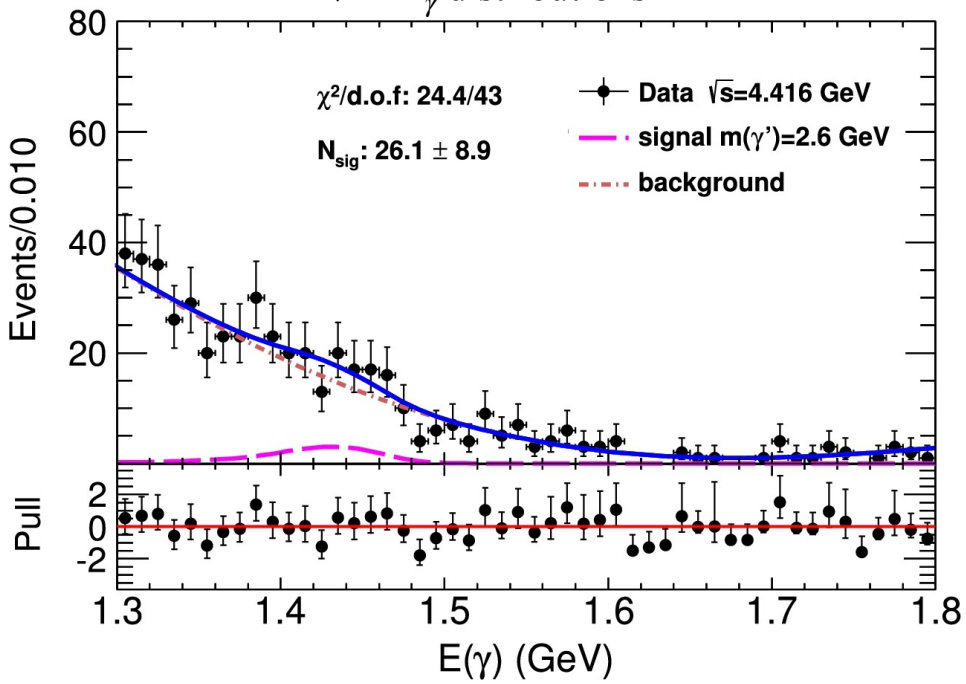
  corresponding to $1.5 < m_{\gamma'} < 2.9$ GeV

$$E_\gamma = \frac{s - m_{\gamma'}^2}{2\sqrt{s}},$$



- **Signal extraction**
  - A simultaneous maximum likelihood fit to the photon energy spectra E_γ is performed to all data sets
  - No obvious signal, the maximum global significance is determined to be **2.2σ**

◆ E_γ distributions



Search for invisible decays of dark photon

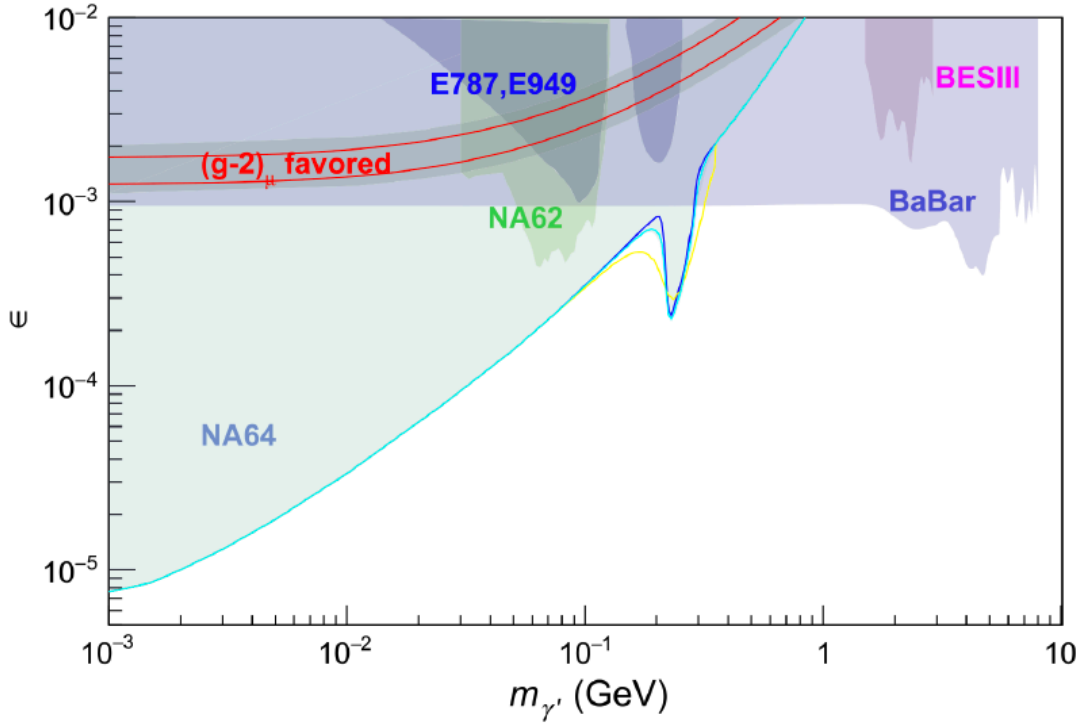
PLB 839, 137785 (2023)

Upper limits

- We set an upper limit on the coupling ϵ at the 90% confidence level (C.L.) using Bayesian method
- The 90% C.L. upper limits of coupling ϵ are $(1.6 - 5.7) \times 10^{-3}$, depending on $m_{\gamma'}$ between 1.5 and 2.9 GeV

✓ Consistent with what already excluded by BaBar PRL 119 (2017) 131804

- BESIII will produce more competitive results with 20 fb^{-1} data taken at 3.77 GeV in the future



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
  - **ALPs search**
    - ☆ Search for ALPs with $\psi(3686)$ and J/ψ data (best limits)
  - **Dark sector search**
    - ☆ Search for a massless dark photon in Λ_c^+ decays $\Lambda_c^+ \to p\gamma'$ (first FCNC search of charmed baryon))
    - ☆ Search for $\Lambda \to$ invisible: (first search for invisible baryon decays)
    - ☆ Search for dark photon invisible decay $e^+e^- \to \gamma\gamma'$(competitive results)
- With more data available, more exciting results are coming soon

The future is bright!