# Dark sector and Axion-like particle search at BESIII

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The 29th international Workshop On Weak Interactions and Neutrinos

# Outline

✓ Introduction

✓ BEPCII & BESIII

✓ Topics in this talk:

- Dark sector search
  1. Search for invisible decays of dark photon — PLB 839, 137785 (2023)
  2. Search for a CP-odd light Higgs boson in $J/\psi \to \gamma A^0$ — PRD 105, 012008 (2022)
  3. Search for invisible decays of $\Lambda$ baryon — PRD 105, L071101(2022)
  4. Search for massless dark photon in $\Lambda_c^+ \to p\gamma'$ — PRD 105, 106, 072008 (2022)

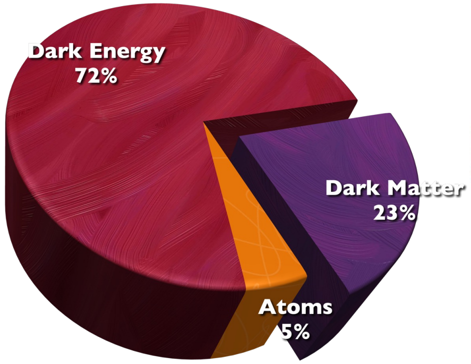
- Axion-like particles (ALPs) search
  1. Search for an axion-like particle in radiative J/ψ decays — PLB 838 137698 (2023)

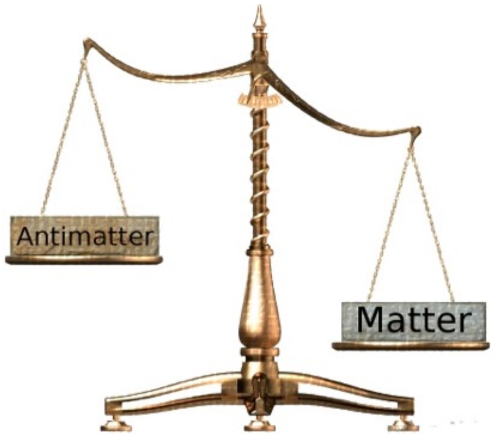
✓ Summary

# Introduction

✓ The SM still leaves many questions unanswered:

- The quest for dark matter
- Matter-antimatter asymmetry
- Several anomaly : astrophysical anomalies, $(g-2)_\mu \ldots$




✓ Several BSM physics include new degrees of freedom that do not interact with the SM directly. Such DOFs constitute the so-called "Dark Sector". The DM particles can couple to the SM via a portal.

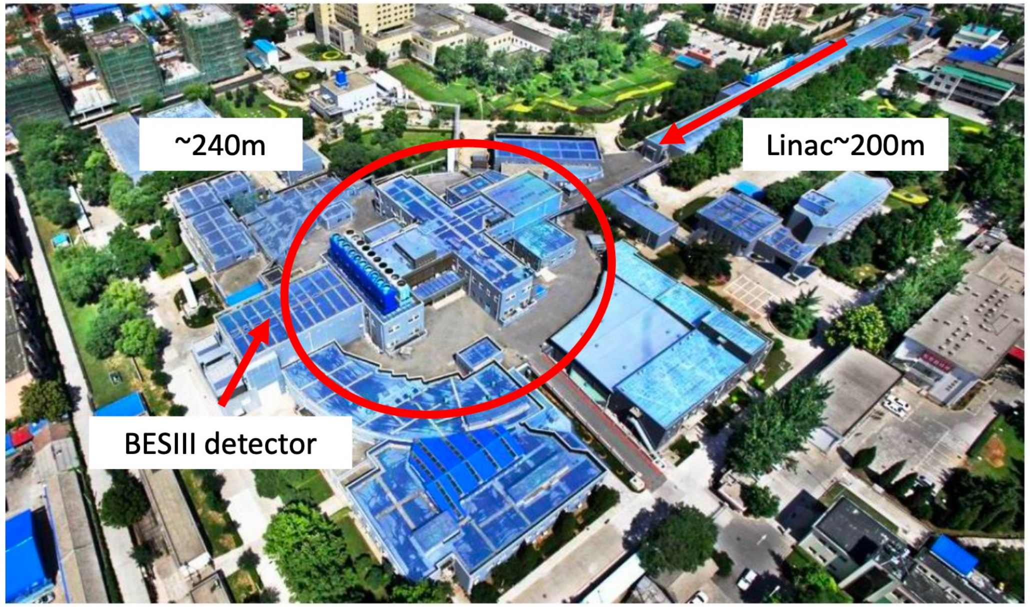
✓ Axion-like particles (ALPs) arise from some spontaneously broken global symmetry, addressing the strong CP or hierarchy problems PRL 115, 38, 1440 (1977), 221801 (2015)

✓ $e^+e^-$ collision experiments have the ability to probe dark matter particles and ALPs, benefiting from a well-measured CM energy and a clean environment

**Standard model** — Portal — Dark Sector

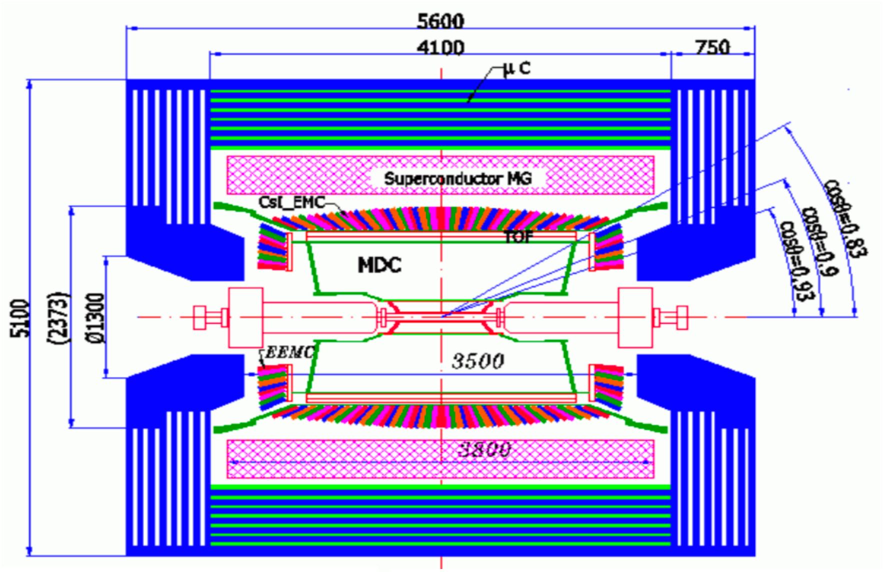
# BEPCII & BESIII

## Beijing Electron Positron Collider II




- Double rings;
- Ecm= 2.0-4.6 GeV (2.0-4.9 GeV since 2019);
- Energy spread: $\Delta E \approx 5 \times 10^{-4}$GeV;
- Design luminosity @Ecm= 3.77 GeV: ~$1\times 10^{33}\ cm^{-2}s^{-1}$
  Reached in 2016;
- 2009~ today: BESIII physics runs;

## Beijing Spectrometer III



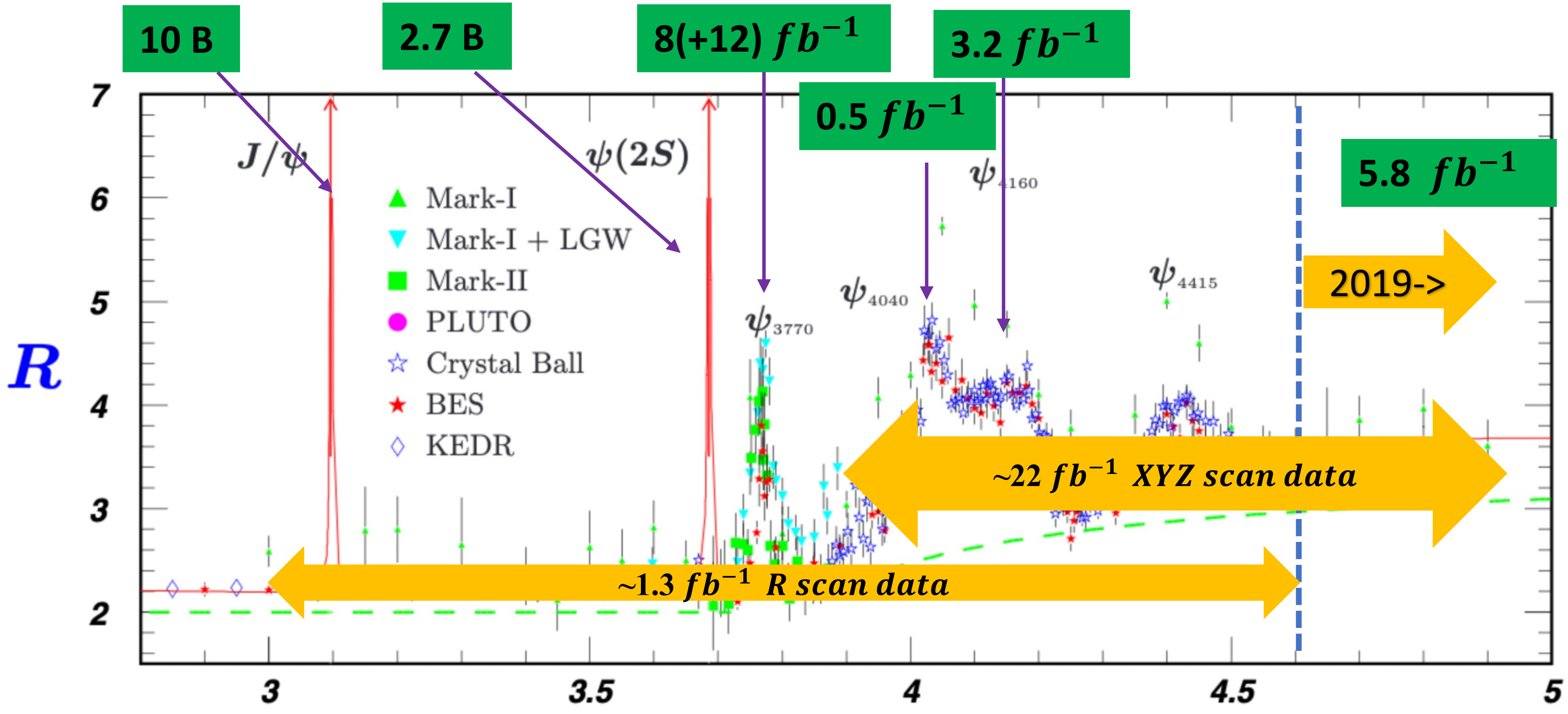

**Main Drift Chamber**
$\sigma_p/p$ <0.5% (@1GeV) (1T)
$\sigma_{xy}$ ~120 $\mu m$
$dE/dx$~6%

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

**Electromagnetic Calorimeter**
$\sigma_E/E$<2.5%(5%) @1GeV
$\sigma_{xy}$~6$mm$ (@1GeV)

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

# Data samples at BESIII

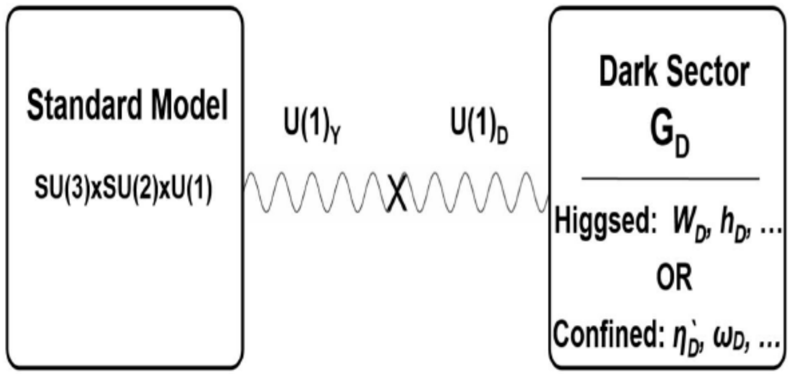


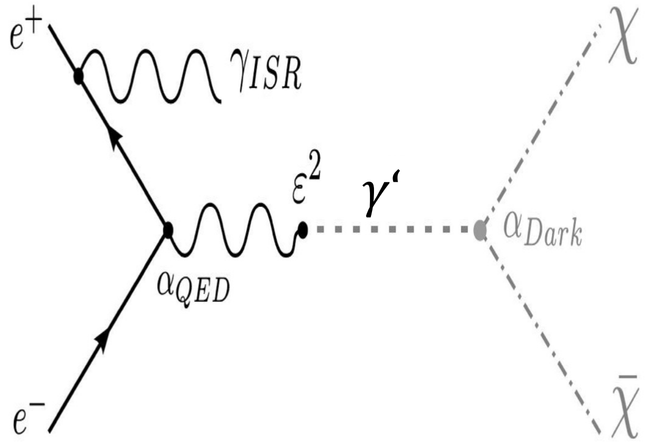

- ✓ Largest $e^+e^-$ annihilation data sets in $\tau - c$ energy region
- ✓ World largest: 10-B $J/\psi$, 2.7-B $\psi'$, coming 20 $fb^{-1}$ $\psi''$ data samples. Chin. Phys. C 44, 040001

PLB 839, 137785 (2023)

# Search for invisible decays of dark photon

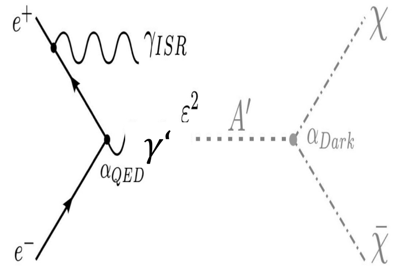
- ✓ **Motivation:** The dark sectors may contain new light weakly-coupled particles, particles well below the Weak-scale that interact only feebly with ordinary matter
- ✓ A new forces mediated by new abelian U(1) gauge bosons $\gamma'$ ( dark photon ) that couple very weakly to a SM photon through "Kinetic mixing" ($\varepsilon$)
- ✓ We perform a search for a dark photon in the radiative annihilation process $e^+e^- \to \gamma\gamma'$, followed by an invisible decay of the $\gamma'$



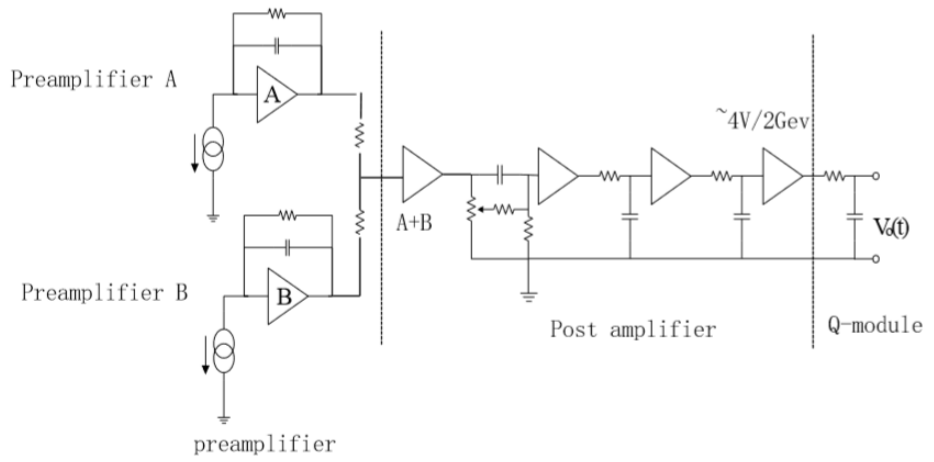



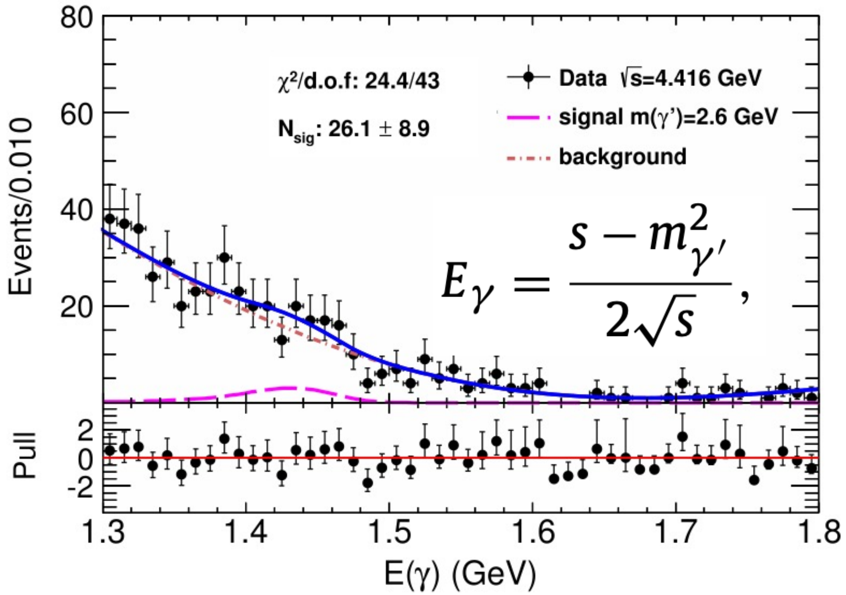
PLB 839, 137785 (2023)

# Search for invisible decays of dark photon




- ✓ **Data sample :** 14.9 $fb^{-1}$ $e^+e^-$ annihilation data at $\sqrt{s} = 4.13 - 4.60$ GeV
- ✓ Search for single photon signals, usually huge background from Digamma process
- ✓ Dark photon are search in 1.3 < E($\gamma$) < 1.8 GeV corresponding to 1.5 < $m_{\gamma'}$< 2.9 GeV
  - Low E($\gamma$) region -> Low trigger efficiency & high bkg. level / High region ->saturation of the EMC electronics
  - A simultaneous maximum likelihood fit to the photon energy spectra is performed to all data sets
  - No obvious signal, the maximum global significance, is determined to be 2.2σ

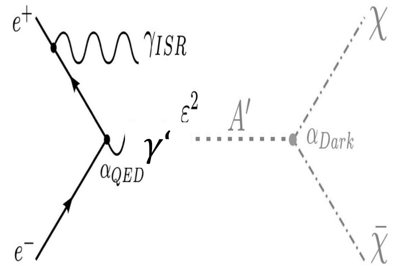



$$E_\gamma = \frac{s - m_{\gamma'}^2}{2\sqrt{s}},$$

PLB 839, 137785 (2023)

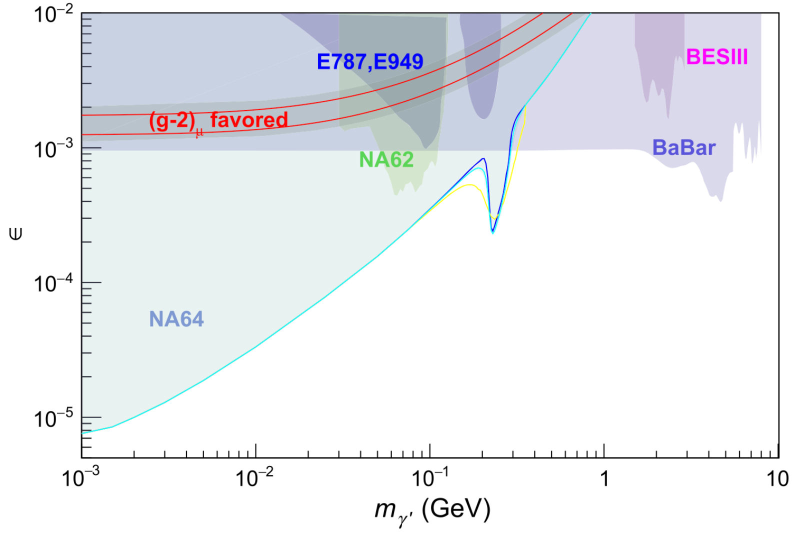
# Search for invisible decays of dark photon




✓ **Upper limits:**

- We set an upper limit on coupling ε at the 90% confidence level (C.L.) using Bayesian method
- The 90% C.L. upper limits of coupling ε are $(1.6 - 5.7)\times10^{-3}$, depending on $m_{\gamma'}$ between 1.5 and 2.9 GeV
- Our exclusion limits are consistent with what already excluded by BaBar PRL 119 (2017) 131804
- BESIII will produce more competitive results with the coming 17 $\text{fb}^{-1}$ data taken at 3.77 GeV

$$\sigma(e^+e^- \to \gamma\gamma') = \frac{2\pi\alpha^2}{s}\epsilon^2(1-x)\left(\left(1+\frac{2x}{(1-x)^2}\right)\Theta - 2\cos\theta_c\right)$$



PRD 105, 012008 (2022)

# Search for a CP-odd light Higgs boson in $J/\psi \to \gamma A^0$

✓ **Motivation:** The next-to-minimal supersymmetric Standard Model (NMSSM), extend the Higgs sector to include additional Higgs fields, containing a total of three CP-even, two CP-odd and two charged Higgs bosons

✓ The mass of the lightest Higgs boson, $A^0$, may be smaller than twice the mass of the charmed quark, thus making it accessible via $J/\psi \to \gamma A^0$

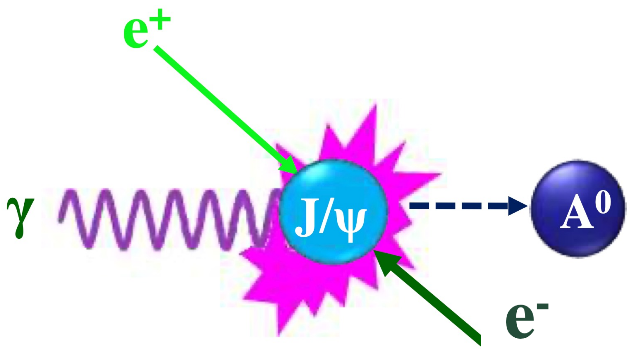
✓ We perform the search for di-muon decays of a CP-odd light Higgs boson in radiative decays of $J/\psi$

PRL 39, 1304 (1977)

$$\frac{\mathcal{B}(V \to \gamma A^0)}{\mathcal{B}(V \to l^+ l^-)} = \frac{G_F m_q^2 g_q^2 C_{\rm QCD}}{\sqrt{2}\pi\alpha}\left(1 - \frac{m_{A^0}^2}{m_V^2}\right),$$

$$g_c = \cos\theta_A / \tan\beta$$

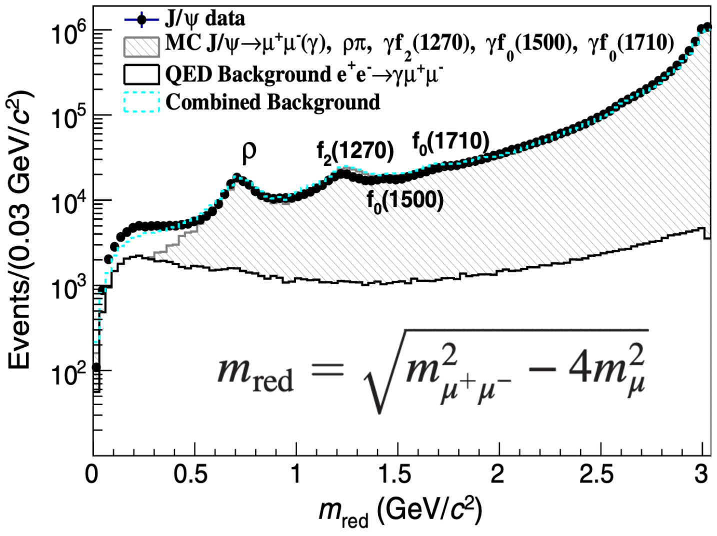
$$g_b = \cos\theta_A \tan\beta$$

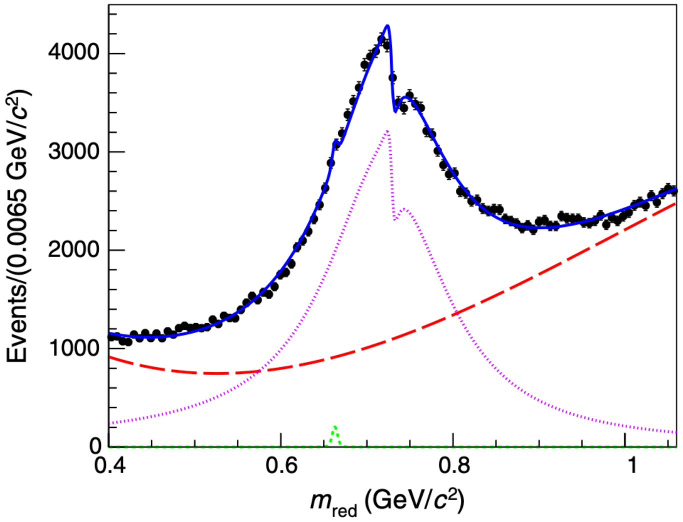


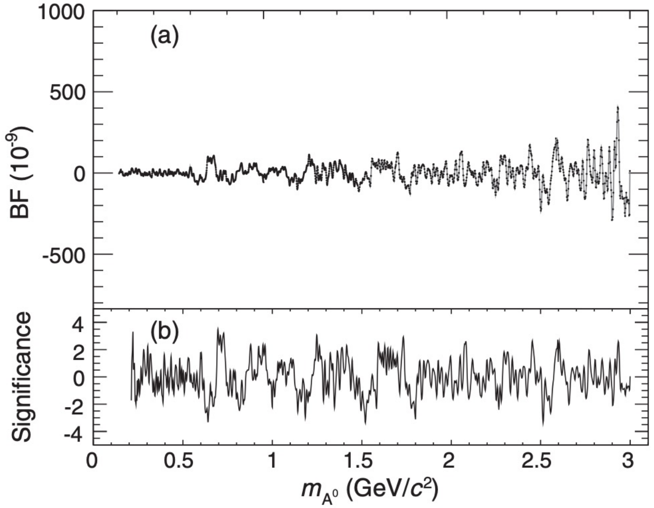
PRD 105, 012008 (2022)

# Search for a CP-odd light Higgs boson in $J/\psi \to \gamma A^0$

- ✓ **Data sample:** 9B J/ψ events
- ✓ The signal of $A^0$ is determined in mass range of $0.212 \leq m_{A^0} \leq 3.0$ GeV/$c^2$ by performing a series of unbinned extended maximum likelihood fits to the reduced mass
  - Peaking backgrounds of $J/\psi \to \gamma f$ are fixed
  - The largest local significance value is 3.5σ at $m_{A^0}$ =0.696 GeV/$c^2$, global significance value is at the level of 1σ



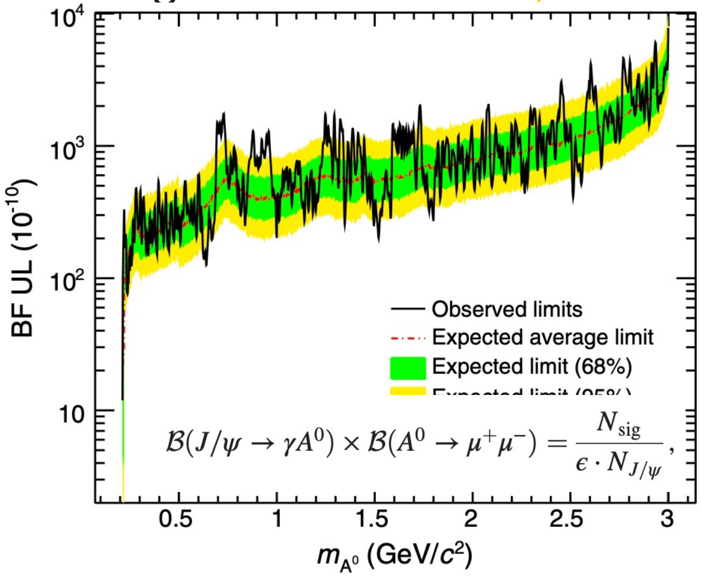



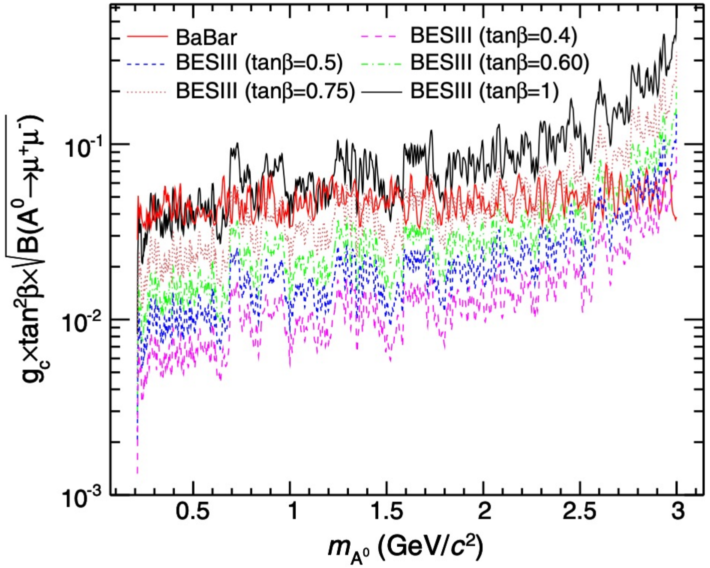
PRD 105, 012008 (2022)

# Search for a CP-odd light Higgs boson in $J/\psi \rightarrow \gamma A^0$

**Upper limit:**

- ✓ Set 90% CL upper limits on the branching fractions using a Bayesian method
- ✓ The ULs range in (1.2 - 778.0) $\times 10^{-9}$ for in mass range of $0.212 \leq m_{A^0} \leq 3.0$ GeV/$c^2$
- ✓ Upper limits on the effective Yukawa coupling $g_c \times tan^2\beta \times \sqrt{\mathcal{B}(A^0 \rightarrow \mu^+\mu^-)}$ are computed.
- ✓ The results is better than the BABAR for $m_{A^0} \leq 0.7$ GeV/$c^2$ for tanβ=1. The result is lower than the prediction at the threshold 0.212GeV, and thus constrains the parameter space of the NP models, including NMSSM PRL 95, 041801



PRD 105, L071101(2022)

# Search for invisible decays of the Λ baryon

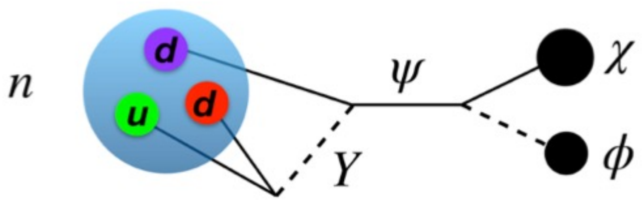
✓ **Motivation:** Dark matter may be represented by baryon matter with invisibles, and many theories suggest a potential correlation between baryon symmetry and dark sector

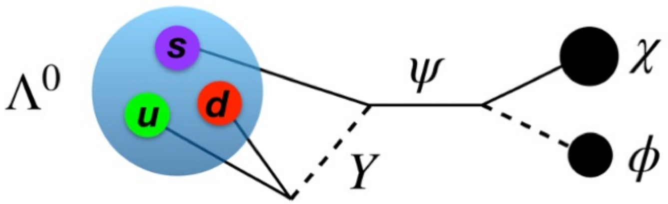
*Phys. Rev. D 105, 115005*

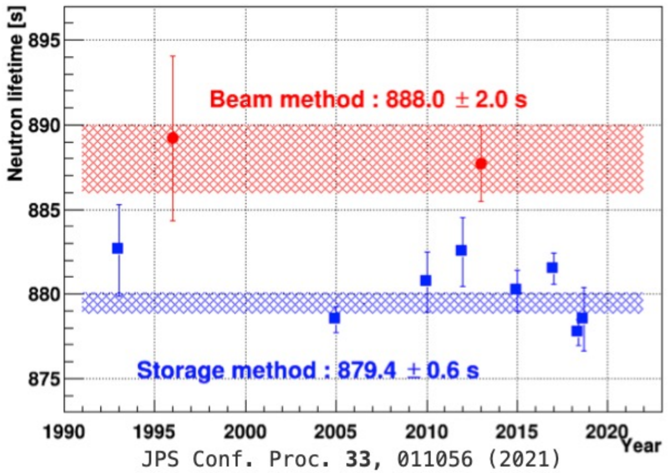
✓ Discrepancy of neutron lifetime in beam method and the storage methods (4.1σ)

$$\tau_n^{beam} = \frac{\tau_n}{\mathcal{B}(n \to p + X)} > \tau_n^{bottle} \Rightarrow \mathcal{B}(n \to p + X) \approx 99\%$$

can be explained by 1% of the neutron decay into dark matter



JPS Conf. Proc. 33, 011056 (2021)

*Phys. Rev. D* 99, 035031

✓ The first study of invisible baryon decays ($\Lambda \to invisible$)

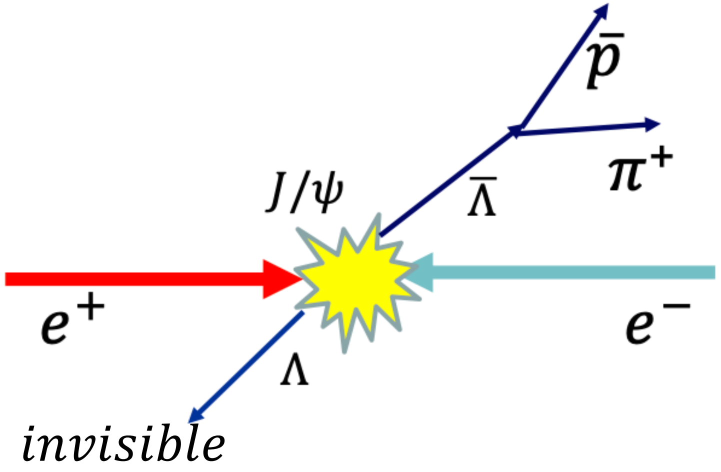
PRD 105, L071101(2022)

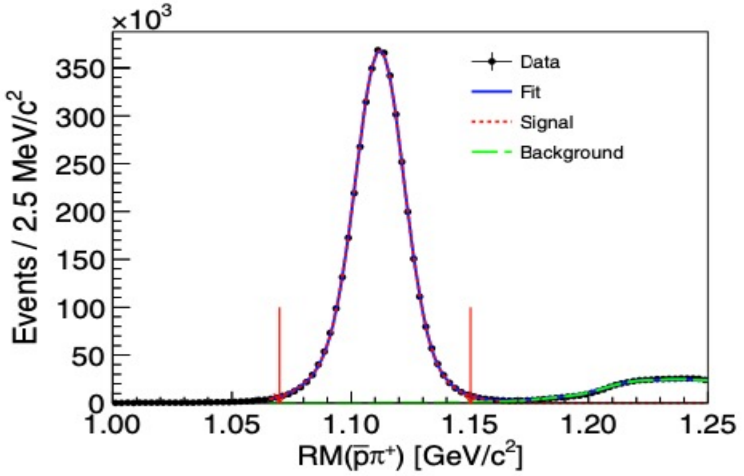
# Search for invisible decays of the Λ baryon

- ✓ **Data sample:** 10B $J/\psi$ events
- ✓ **Analysis strategy:**
  - $J/\psi \to \Lambda\bar{\Lambda}$ provide a clean environment for Λ invisible decay
  - Double Tag Method:
    - ➢ Tag side: $\bar{\Lambda}$ is tagged by $\bar{\Lambda} \to \bar{p}\pi^+$, 4.1M Λ events
    - ➢ Signal side: Λ decays invisibly

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

- ✓ The $\bar{\Lambda}$ invisible decay is not pursued, because the dominant background from $\bar{\Lambda} \to \bar{n}\pi^0$ is hard to estimate and simulate



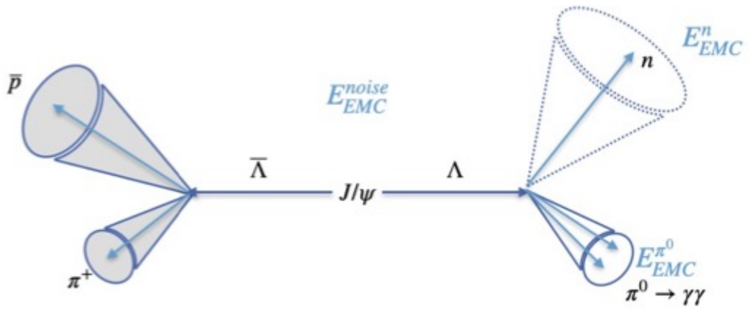



PRD 105, L071101(2022)

# Search for invisible decays of the Λ baryon

- ✓ **Signal extraction :** Search for signal on total energy in EMC $E_{EMC}$ (not charged tracks);
  - Dominating background: $\Lambda \to n\pi^0$

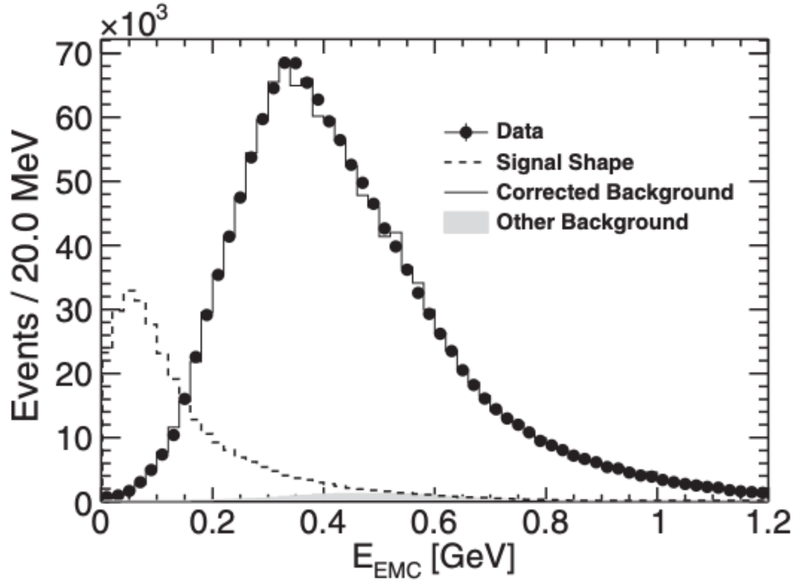
$$E_{\mathrm{EMC}} = E_{\mathrm{EMC}}^{\pi^0} + E_{\mathrm{EMC}}^{n} + E_{\mathrm{EMC}}^{\mathrm{noise}},$$




  - $E_{EMC}^{\pi^0}$: Based on the MC simulations
  - $E_{EMC}^{n}$+ $E_{EMC}^{noise}$: Based on control sample $J/\psi \to \Lambda(n\pi^0)\bar{\Lambda}(\bar{p}\pi^+)$;

- ✓ The corrected $\mathrm{E_{EMC}}$ for $\Lambda \to \mathrm{n}\pi^0$ is derived by combining $\mathrm{E_{EMC}^{\pi^0}}$ with a random value of the sum of $\mathrm{E_{EMC}^{n}}$+ $\mathrm{E_{EMC}^{noise}}$

- ✓ No obvious signals are observed



PRD 105, L071101(2022)

# Search for invisible decays of the Λ baryon

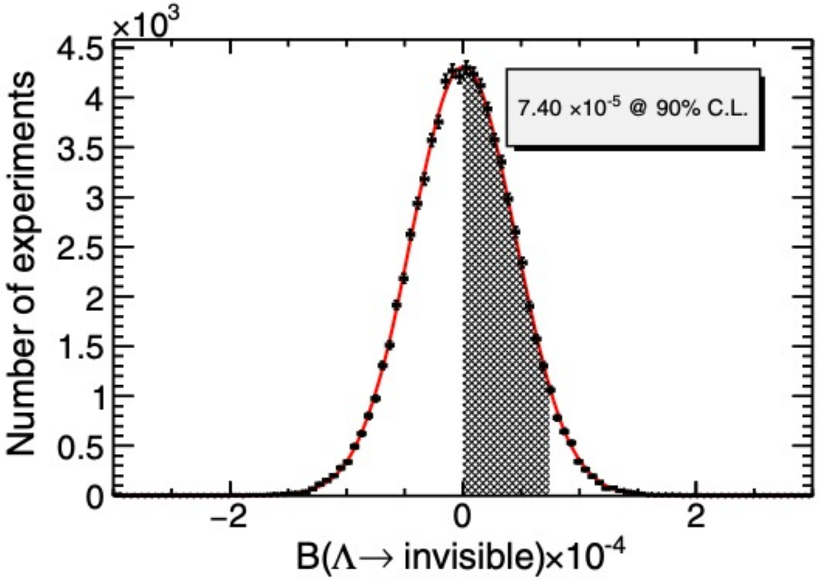
✓ **Upper limit ：**

A modified frequentist approach is adopted to estimate the UL

Eur. Phys. J. C 71, 1554 (2011)

- $\mathcal{B}(\Lambda \rightarrow invisible) < 7.4 \times 10^{-5}$ at 90% C.L.
- The UL is consistent with the prediction of $4.4 \times 10^{-7}$

  arXiv:2006.10746
- This result sheds light on the neutron lifetime measurement puzzle and helps to constrain dark sector models related to the baryon asymmetry



PRD 106 072008 (2022)

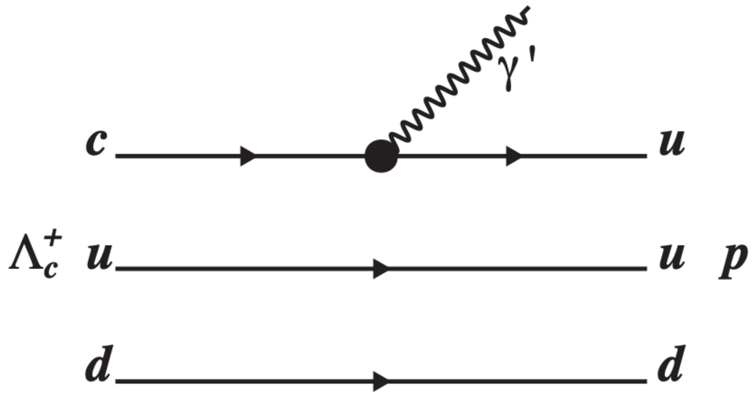
# Search for massless dark photon in $\Lambda_c^+ \to p\gamma'$

✓ **Motivation**：

- The FCNC is suppressed in SM, any significant observation would be a hint for the new physics.
- Minimal supersymmetric SM and the two-Higgs-doublet model predict the BFs of the same FCNC decays to be two to three orders of magnitude larger.

  Phys. Lett. 119B, 136 (1982)

- we concentrate on FCNC effects arising from the dark photon with the c and u quarks, where the missing energy due to the dark photon is the feature of the signal processes



PRD 106 072008 (2022)

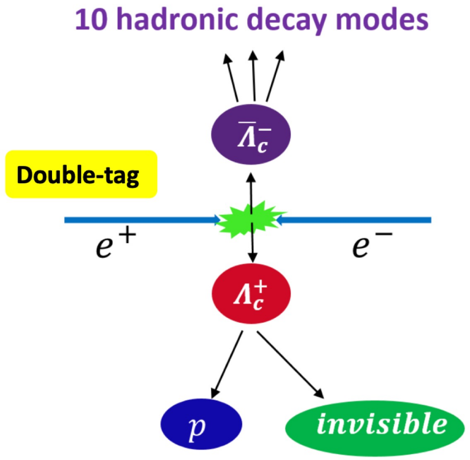
# Search for massless dark photon in $\Lambda_c^+ \to p\gamma'$

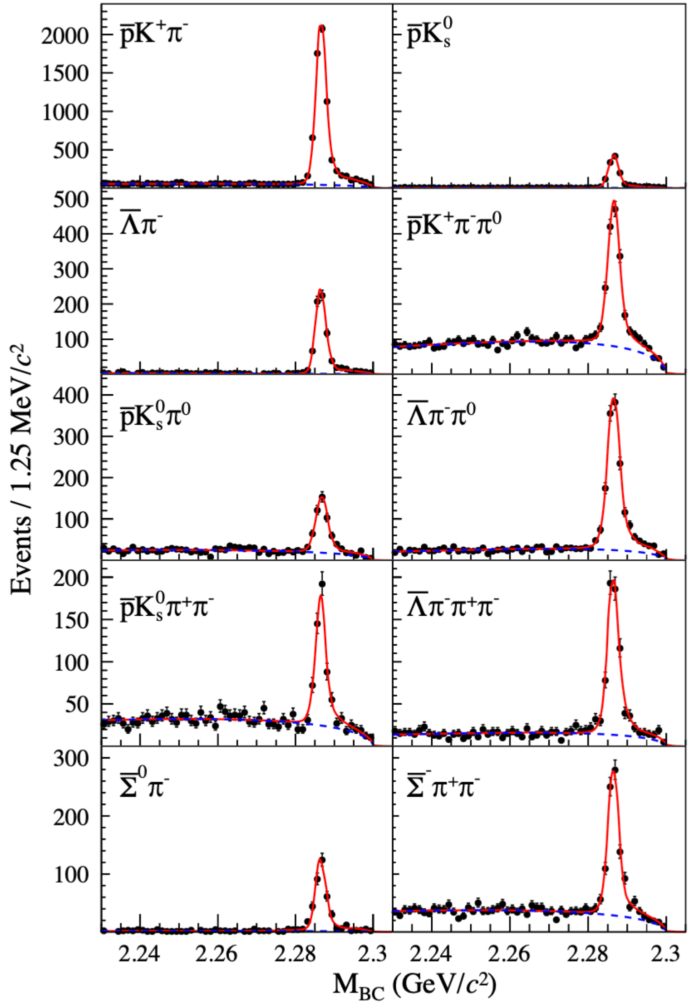
✓ **Data sample** : $4.5\ fb^{-1}$ $e^+e^-$ annihilation data at $\sqrt{s} = 4.6 - 4.7$ GeV

✓ **Analysis strategy:**

- The $\Lambda_c^+\overline{\Lambda}_c^-$ are pair produced in $\boldsymbol{e^+e^-} \to \Lambda_c^+\overline{\Lambda}_c^-$
- Double Tag Method:
  - ➢ Single-tag : $\overline{\Lambda}_c^-$ reconstructed with ten hadronic decay modes
    yields: 105244±384
  - ➢ Signal side: $\Lambda_c^+ \to p\gamma'$

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



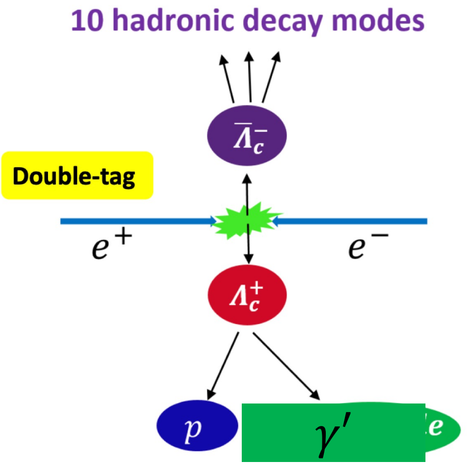



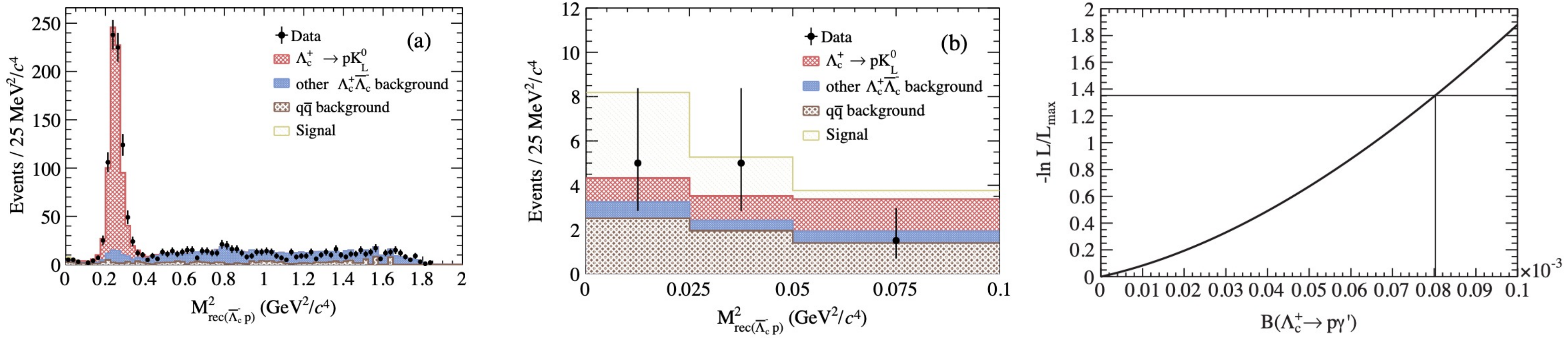
PRD 106 072008 (2022)

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

- ✓ The signal is searched on the  the square of the recoil mass spectrum $M^2_{rec(\bar{\Lambda}_c^- p)}$
- ✓ Background components:
  - From continuum hadron production $e^+e^- \to q\bar{q}$
  - From $\boldsymbol{e^+e^-} \to \Lambda_c^+\bar{\Lambda}_c^-$ process
- ✓ The **upper limit** is $\mathcal{B}(\Lambda_c^+ \to p\gamma') < 8.0{\times}10^{-5}$ at 90% confidence level

  Theory prediction: $1.6{\times}10^{-5}$- $9.1{\times}10^{-6}$ PRD 102, 115029 (2020)



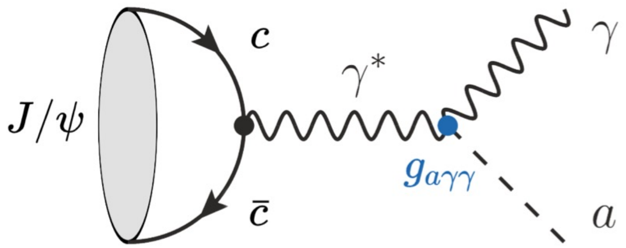



PLB 838 137698 (2023)

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

✓ **Axion-like particles** (ALPs)

- Pseudo-Goldstone bosons arising from some spontaneously broken global symmetry addressing the strong *CP* or hierarchy problems. Also proposed as cold DM candidates
  Phys. Rev. Lett. 115, 221801 (2015).




- The ALP-photon coupling $g_{a\gamma\gamma}$ is mostly discussed → ALP decays to two photons

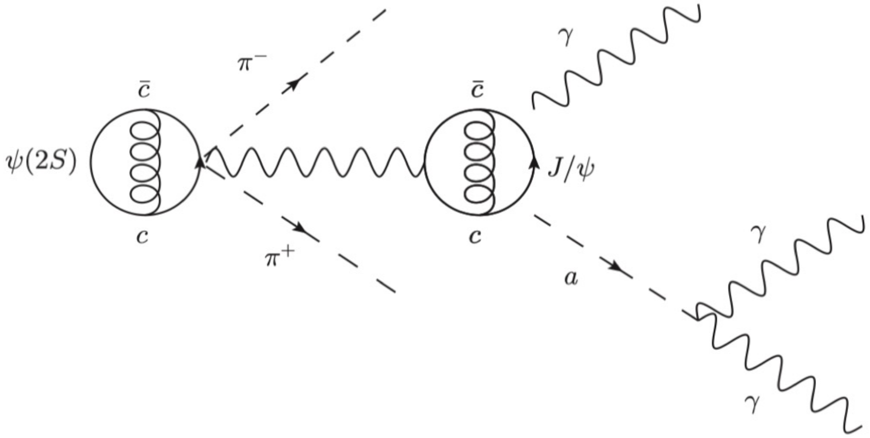
- Independent mass and coupling bounded by experiments → $m_a$~ O(GeV) mainly from electron-positron colliders Phys. Lett. B 753 (2016) 482

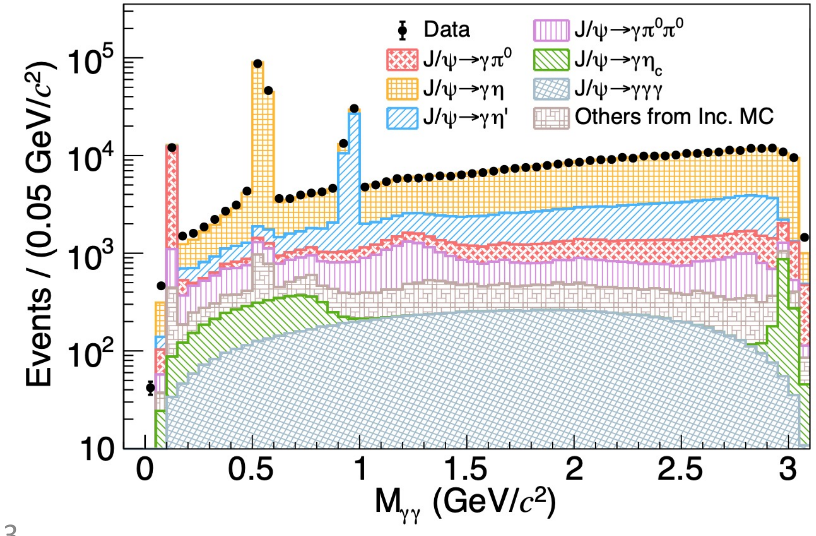
- We search for ALPs decaying into two photons in J/ψ radiative decays via $J/\psi \to \gamma a, a \to \gamma\gamma$

PLB 838 137698 (2023)

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

- ✓ **Data sample**: 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
  - $a$ has negligible decay width and lifetime
  - $\psi(3686)$ decay -> preclude the pollution from non-resonant production and avoid QED background
  - Blind analysis strategy
  - Three $\gamma\gamma$ combinations per event, exclude intervals around $\pi^0$, η, η′ peaks



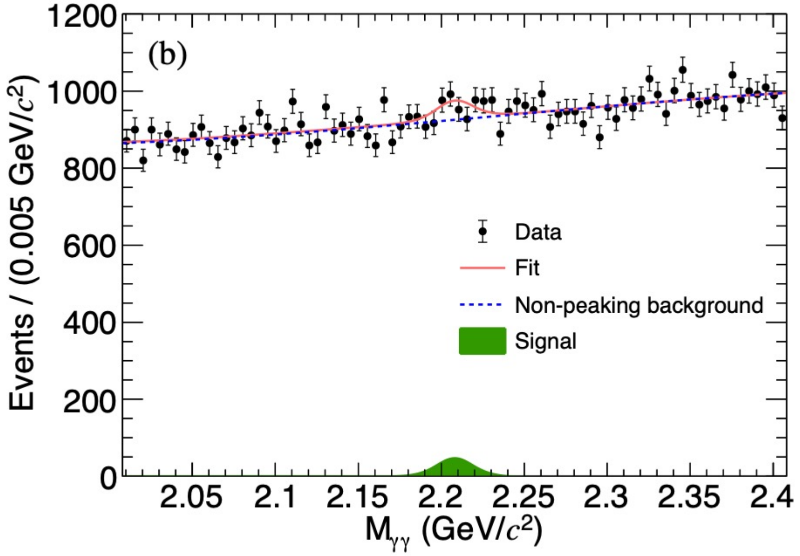



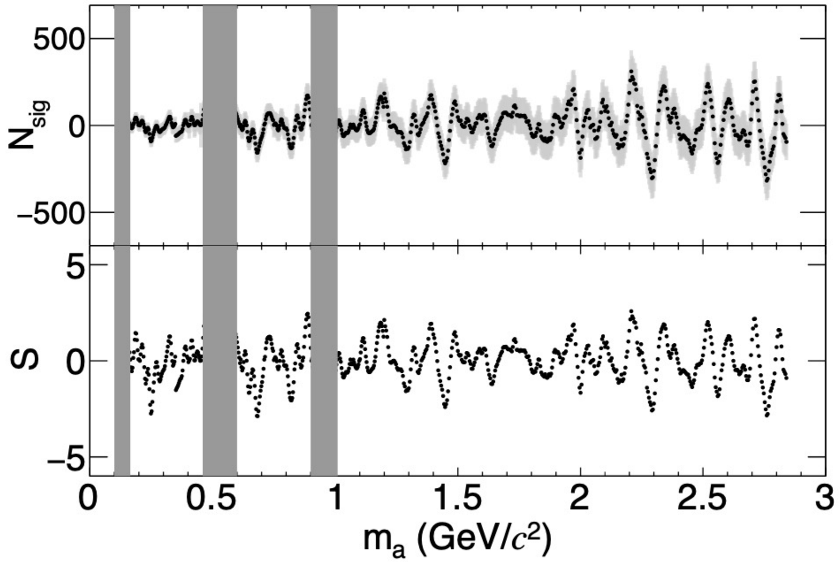
PLB 838 137698 (2023)

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

## ✓ Signal extraction

- A series of unbinned maximum-likelihood fits are performed to the $M(\gamma\gamma)$ to determine the in the mass range of $0.165 \leq m_a \leq 2.84\ \mathrm{GeV}/c^2$.
- Totally, 674 mass hypotheses are probed
- Fit intervals (35 ~ 90σ) are mass-dependent
- The local significance are less than $2.6\sigma$ for all mass point



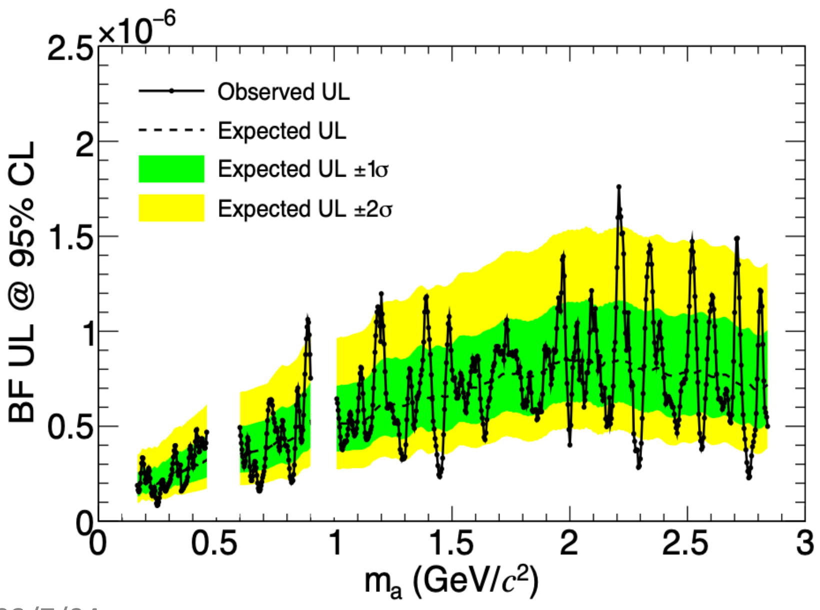



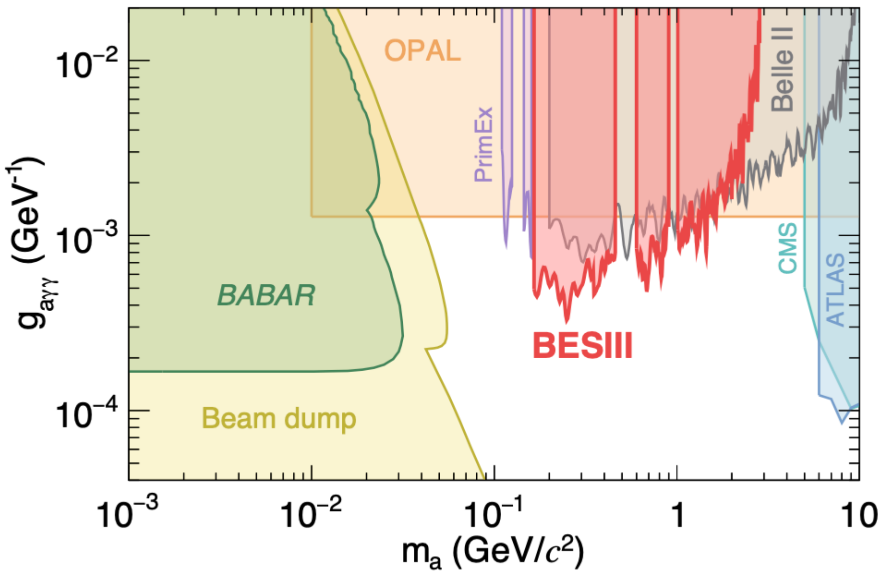
PLB 838 137698 (2023)

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

✓ **Upper limits**

- 95% confidence level upper limits on B($J/\psi \rightarrow \gamma a$) are determined a one-sided frequentist profile-likelihood method Eur. Phys. J. C 71, 1554 (2011)
- The observed limits range from $8.3 \times 10^{-8}$ to $1.8 \times 10^{-6}$ in $0.165 \leq m_a \leq 2.84$ GeV/$c^2$
- The exclusion limits on the ALP-photon coupling are the most stringent to date



# Summary

✓ The recent result about dark sector and Axion-like particle search at BESIII are presented:

- Dark sector search
  - ➢ $e^+e^- \to \gamma\gamma'$ : 90% UL on coupling ε are (1.6 - 5.7)×$10^{-3} for\ m_{\gamma'}$ in 1.5 and 2.9 GeV
  - ➢ $J/\psi \to \gamma A^0$: ULs on BFs are (1.2 - 778.0) $\times 10^{-9}$ for in mass range of 0.212 ≤ $m_{A^0}$≤ 3.0 GeV/$c^2$
  - ➢ $\Lambda \to invisible$: ULs on BF $\mathcal{B}(\Lambda \to invisible)$< 7.4$\times 10^{-5}$
  - ➢ $\Lambda_c^+ \to p\gamma'$: ULs on BF $\mathcal{B}(\Lambda_c^+ \to p\gamma') < 8.0\times 10^{-5}$

- ALPs search
  - ➢ $J/\psi \to \gamma a, a \to \gamma\gamma$: ULs on BFs are 8.3 × $10^{-8}$to 1.8 × $10^{-6}$ in 0.165 ≤ $m_a$ ≤ 2.84 GeV/$c^2$

✓ More data will be available, more sensitive results is ongoing and coming soon

The future is bright!