Exotic searches (visible decay) at BESIII

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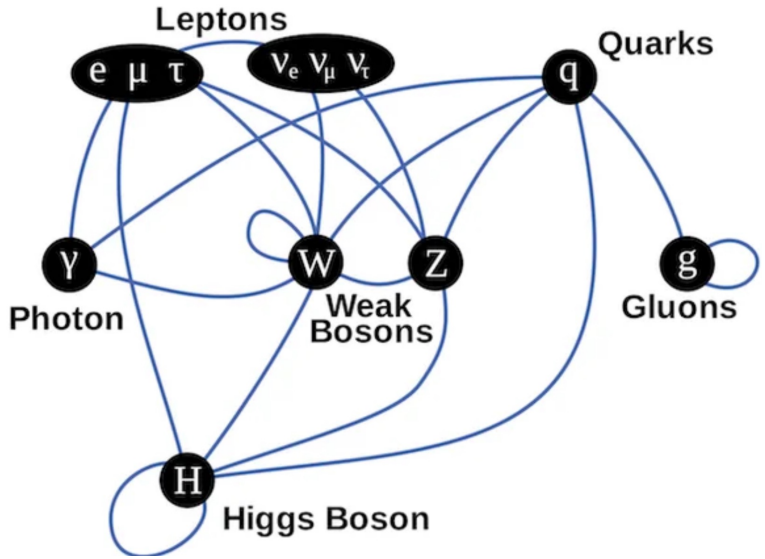
2023年BESIII新物理研讨会

The Standard Model and Beyond



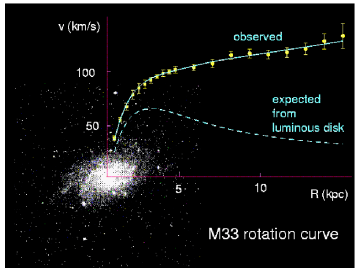
- The standard model of particle physics is an extremely successful theory of fundamental interactions

- "Particle physics is at a crossroads"
  1. Theory motivations: such as Hierarchy problem(s), origin of SM symmetries, particle mass hierarchies, too many free parameters .....

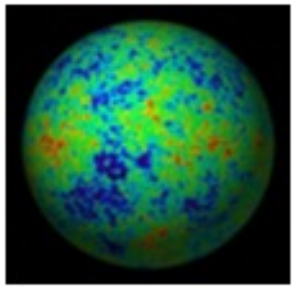
  2. Experimental `issues': strong CP problem, neutrino oscillations, dark matter, dark energy, matter-antimatter asymmetric, decays of bottom-quark hadrons ....

Motivation of "dark sector"

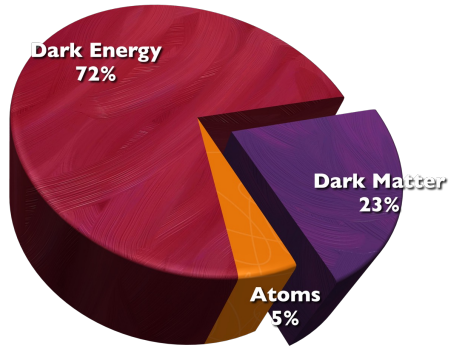
The presence of cold DM



Rotation curves



CMB



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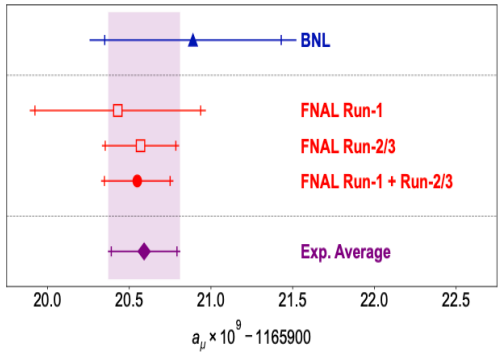
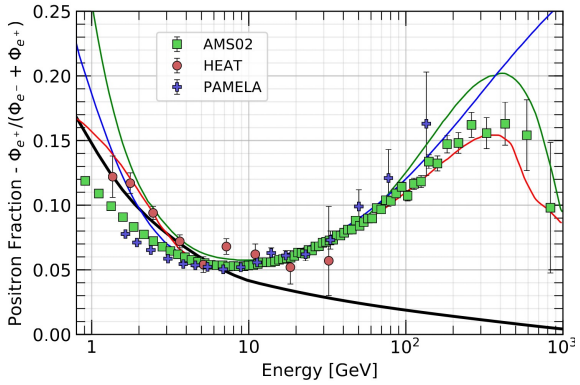
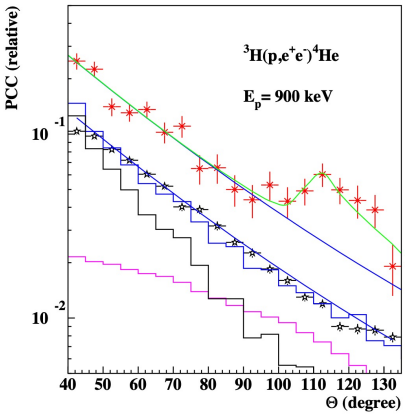
Anomalies







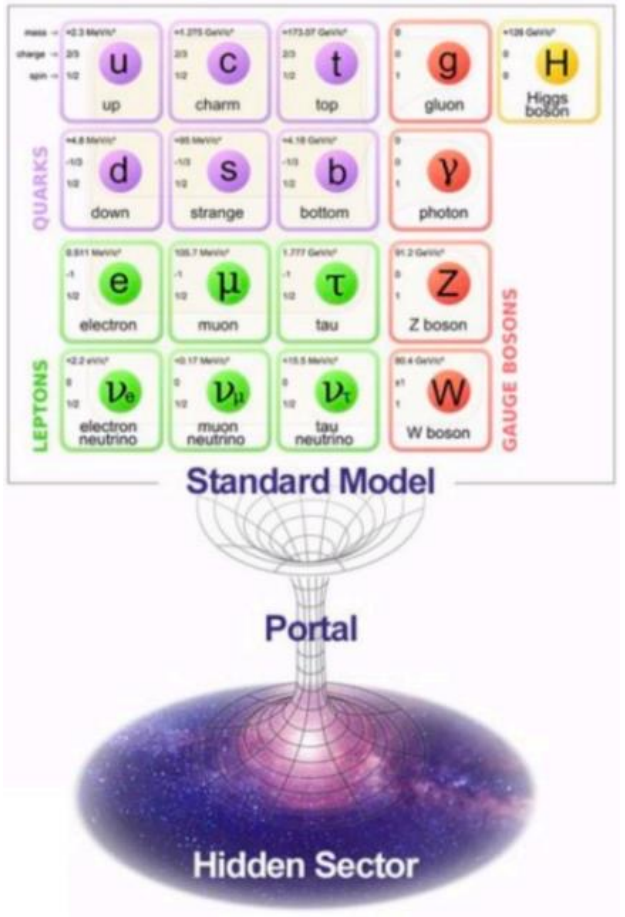
...

- Its existence provides a strong hint that there may be a dark sector, consisting of particles do not interact with the known strong, weak, or electromagnetic forces

“Portals” between Standard Model and dark sector

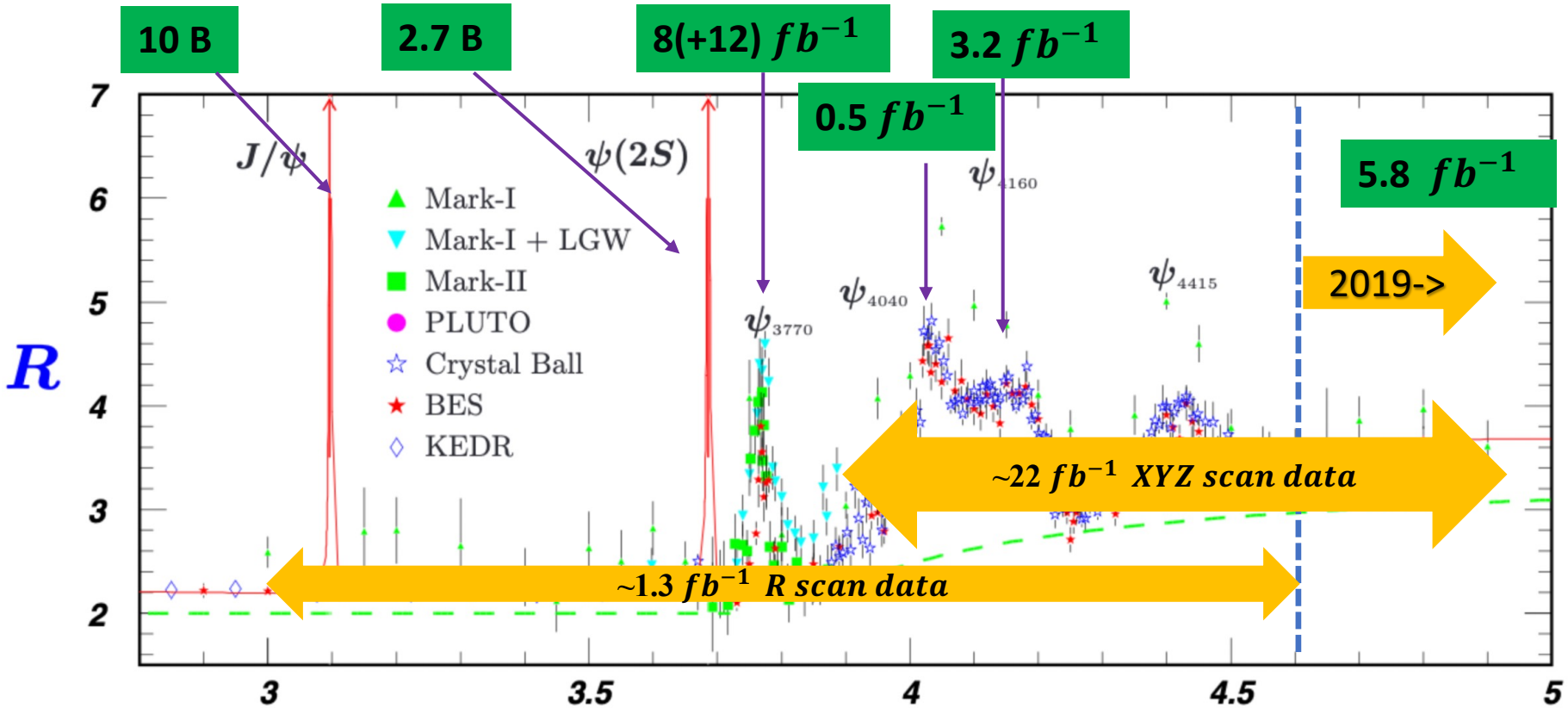
- ✓ Dark sectors typically include one or more mediator particles coupled to the SM via a portal

Portal	Particles	Operator(s)
“Vector”	Dark photons	$-\frac{\epsilon}{2\cos\theta_W}B_{\mu\nu}F'^{\mu\nu}$
“Axion”	Pseudoscalars	$\frac{a}{f_a}F_{\mu\nu}\widetilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i\mu\nu}\widetilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
“Higgs”	Dark scalars	$(\mu S+\lambda S^2)H^\dagger H$
“Neutrino”	Sterile neutrinos	$y_N L H N$



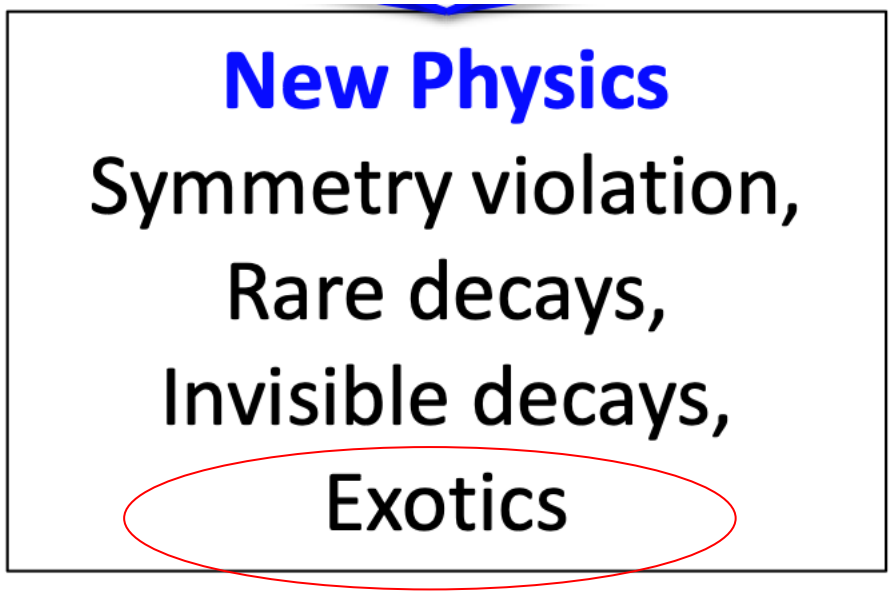
- ✓ These new particles can be accessible by high intensity e^+e^- collider experiments, such as BESIII experiment, if their masses are in the MeV-GeV range

Data samples at BESIII



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

Exotic searches at BESIII



- We focus on the visible decay of (dark photon, light higgs, axion-like particles) searches in this talk

- Electron-positron colliders are suitable for exotic via either the

  direct production or decays of hadrons

Topics in this talk

- A review of the exotic visible decay at BESIII

  ✓ Dark photon (γ') search:
  1. via $J/\psi \to \gamma' \eta,\ \gamma' \to e^+e^-$
  2. via $J/\psi \to \gamma' \eta',\ \gamma' \to e^+e^-$
  3. via $e^+e^- \to \gamma' \gamma_{ISR},\ \gamma' \to l^+l^-$

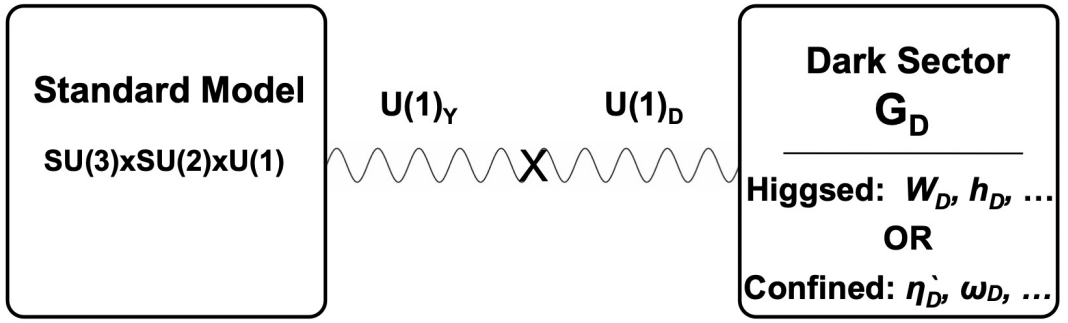
  ✓ Light Higgs boson (A^0) search:
  1. via $J/\psi \to \gamma A^0,\ A^0 \to \mu^+\mu^-$

  ✓ Axion-like particle (a) search:
  1. Search for axion-like particles using $\psi(2S)$ data
  2. Search for axion-like particles using J/ψ data

An introduction to the “dark photon”

- As a “Portals” between Standard Model and dark sector, the dark photon field V_μ couples to the SM photon A_μ via kinetic mixing:

$$\epsilon e A'_\mu J^\mu_{\mathrm{EM}}$$



PRD80 015003

- ε values in the 10^{-12} – 10^{-3} range have been predicted in the literature

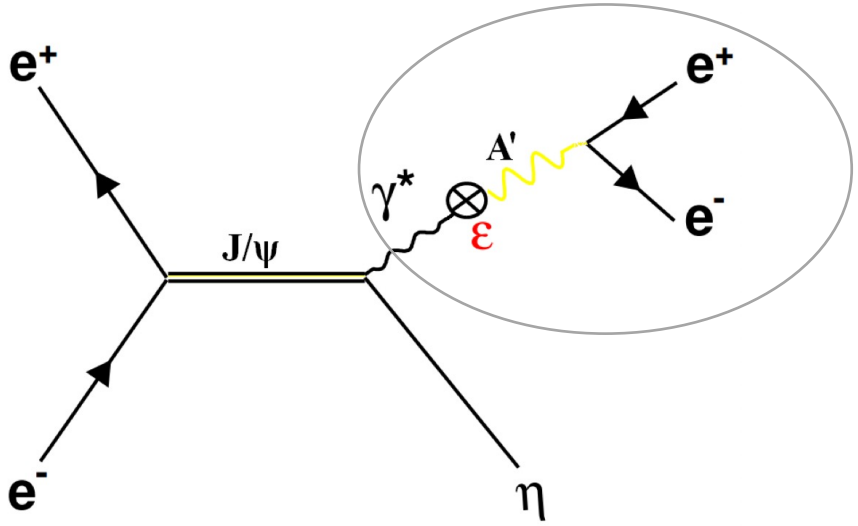
- A MeV-GeV scale dark photon could explain the features of astrophysical observations, and the anomaly of $(g-2)_\mu$……

I: Dark photon search via $J/\psi \to \gamma'\eta, \gamma' \to e^+e^-$

PRD99, 012006 (2019)

- Data: 1310.6 $\pm$ 7.0 $\times 10^6$ J/ψ events

- Search for dark photon via electromagnetic dalitz decay, where $\epsilon = \alpha'/\alpha$ and α' is the fine structure constant in the dark sector



- η Reconstruction: $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$

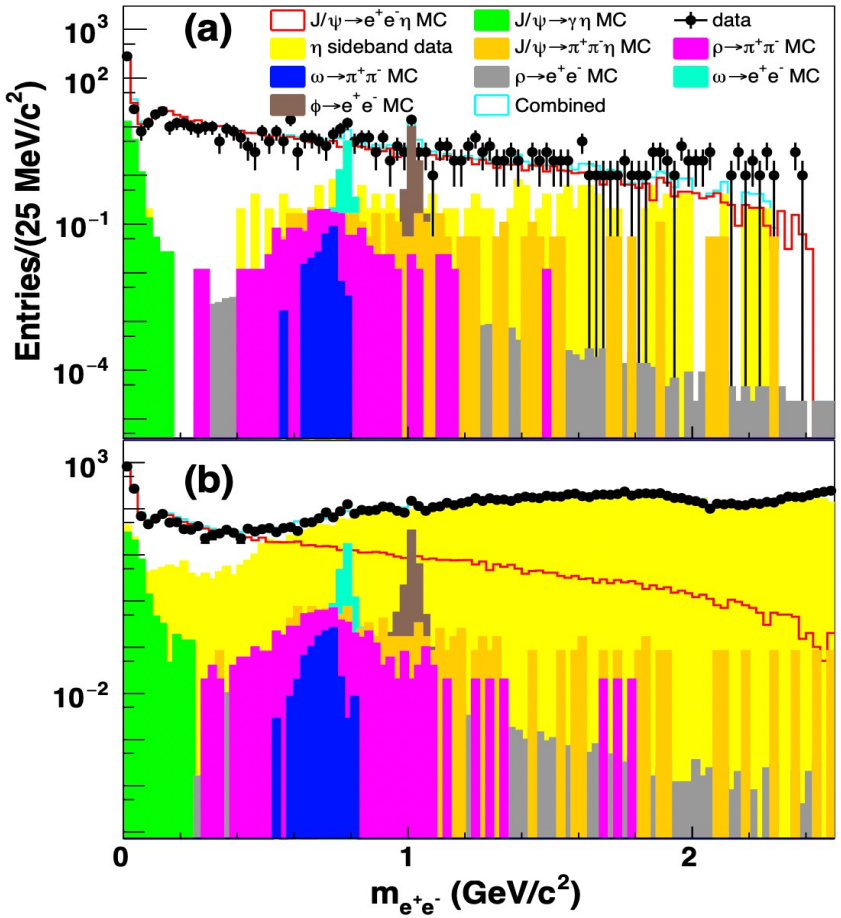
- Event selection:
  1. Two /four charged tracks with zero net charge;
  2. PID algorithm is performed to identify electron;
  3. Suppression of gamma conversion events;
  4. $\eta \to \gamma\gamma$ mode: | cos θ_{helix}| < 0.9 ($e^+e^- \to \gamma e^+e^-$) ;
  5. …

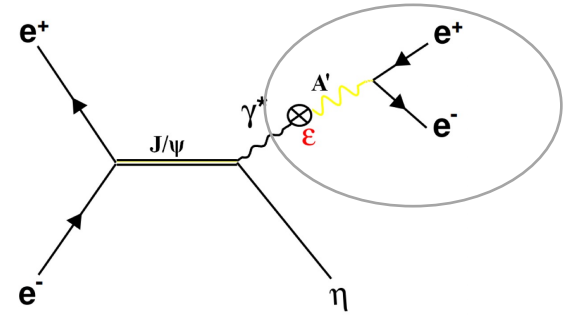
I: Dark photon search via $J/\psi \to \gamma'\eta, \gamma' \to e^+e^-$

PRD 99, 012006 (2019)

✓ m(e^+e^-) and η signal:

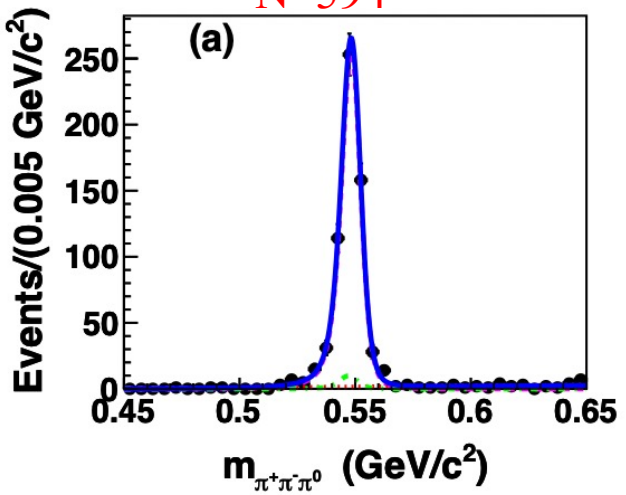
within the η signal region





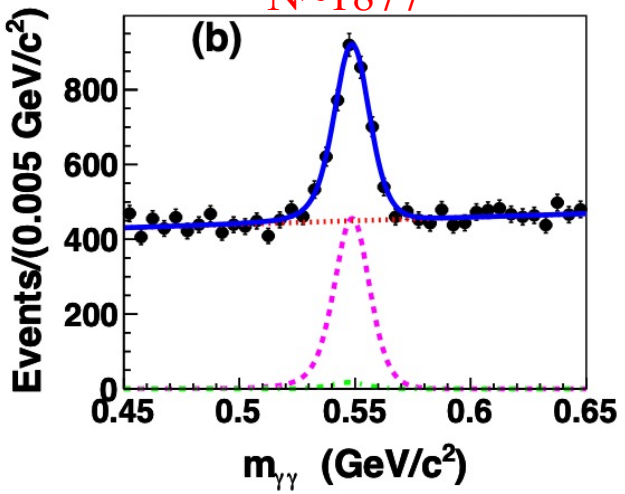
$\eta \to \pi^+\pi^-\pi^0$

N~594



$\eta \to \gamma\gamma$

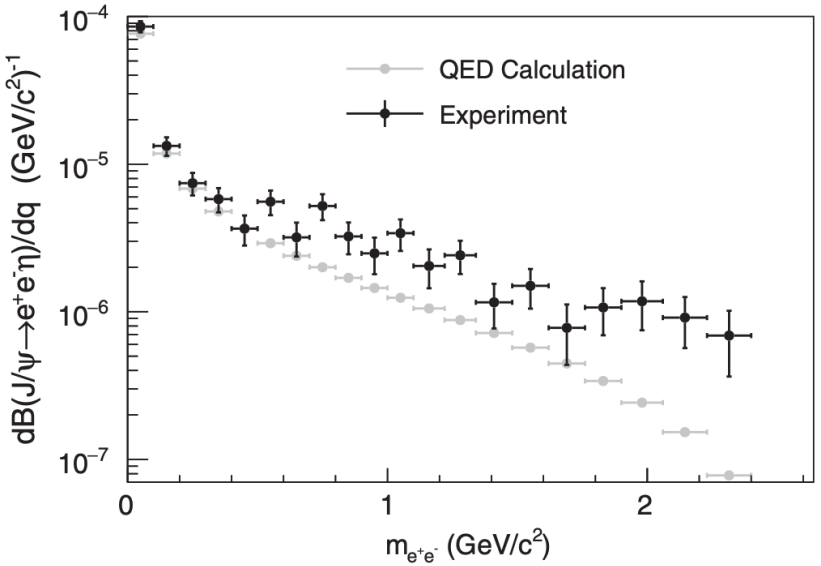
N~1877

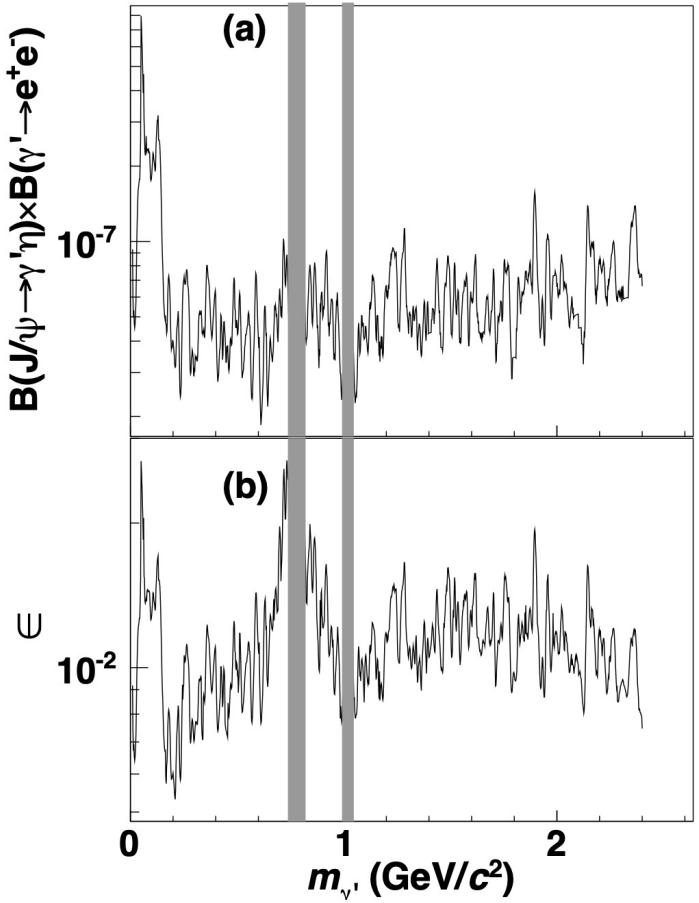


I: Dark photon search via $J/\psi \to \gamma'\eta, \gamma' \to e^+e^-$

PRD 99, 012006 (2019)

- ✓ Search for dark photon signa m(e^+e^-) :
  - Exclude the ω and ϕ mass regions for the γ' searches
  - The 90% CL upper limits on ε vary in range of 10^{-2} - 10^{-3} in 0.01<m(e^+e^-) <2.4 GeV



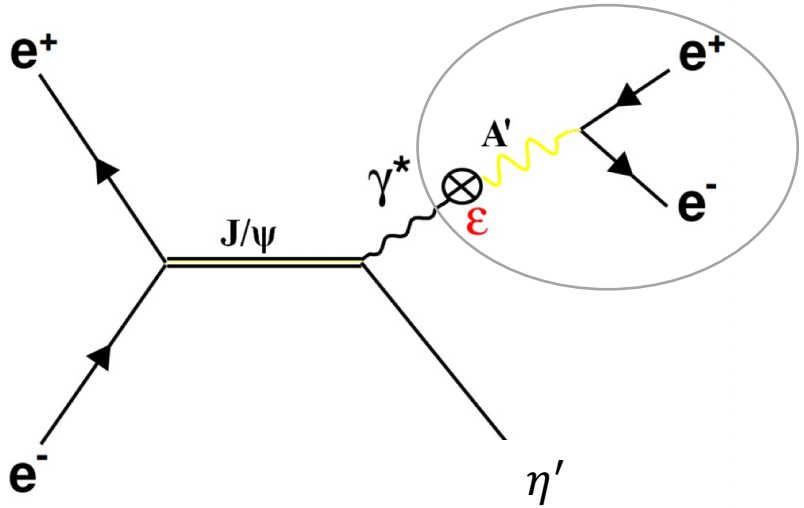


$\mathcal{B}$ ($\gamma' \to e^+e^-$) from
PRD 79, 115008 (2009)
JHEP 0907, 051 (2009)

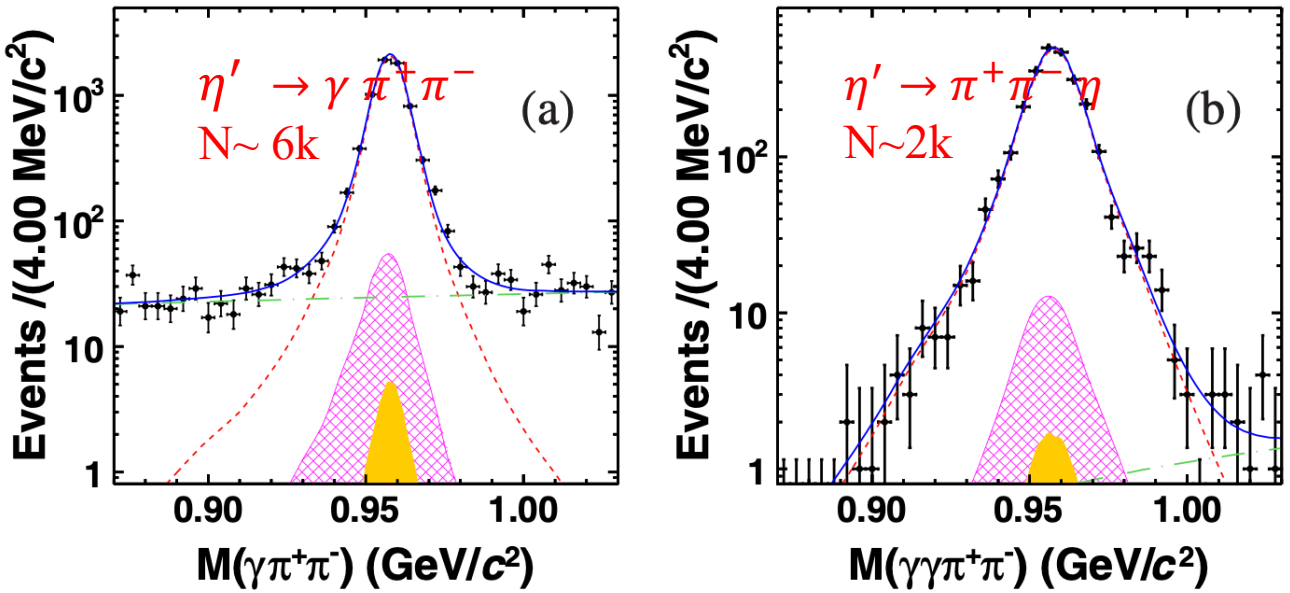
II: Dark photon search via $J/\psi \to \gamma'\eta', \gamma' \to e^+e^-$

PRD 99, 012013 (2019)

- **Data:** 1310.6 $\pm$ 7.0 $\times$ 10^6 J/ψ events;
- **The event selection** criteria is similar *to* $J/\psi \to \gamma'\eta$ work
- η' **Reconstruction:** $\eta' \to \gamma\ \pi^+\pi^-$ and $\eta' \to \pi^+\pi^-\ \eta$



Signal of η'

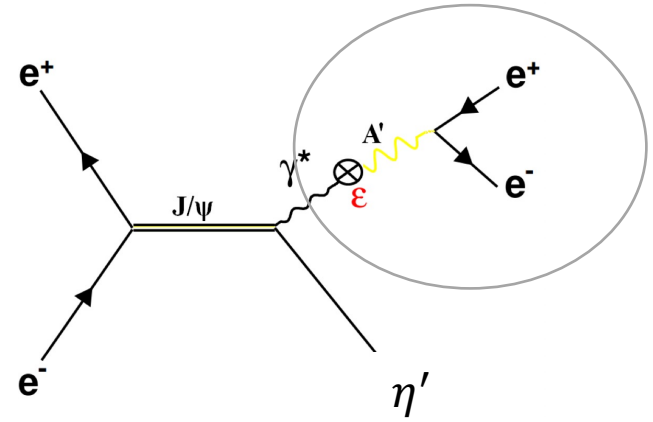


II: Dark photon search via $J/\psi \to \gamma'\eta', \gamma' \to e^+e^-$

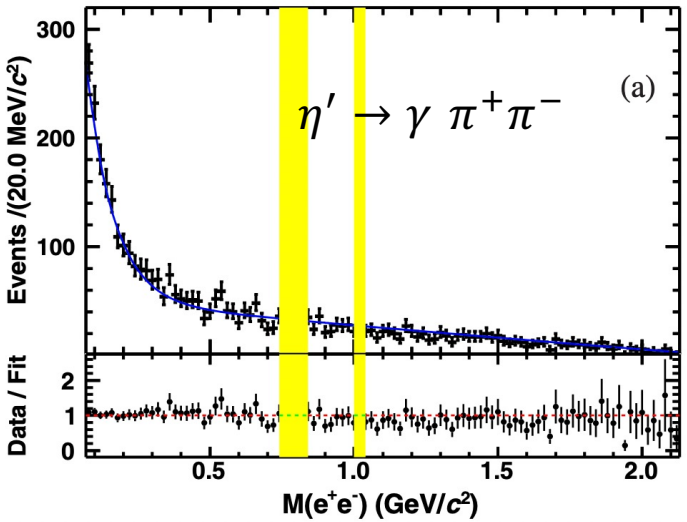
PRD 99, 012013 (2019)

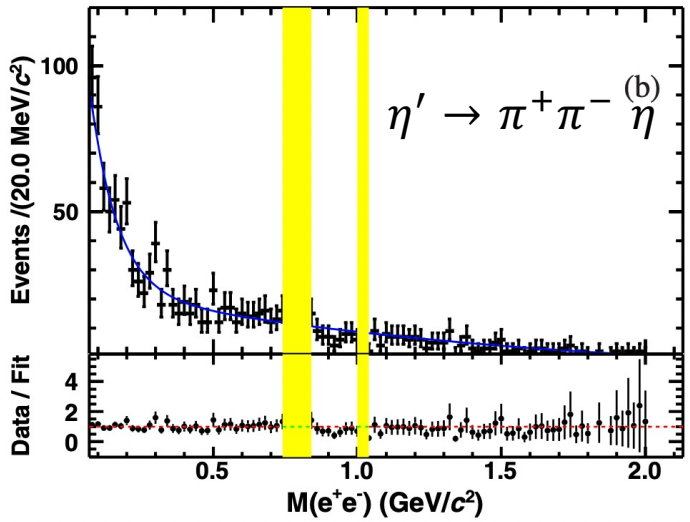
✓ **Search for the dark photon signal :**

1. The dark photon is searched for by looking for a narrow resonance peaking in 0.07<m(e^+e^-) <2.13 GeV
2. Peaking background region (ω, ϕ) are excluded



within the η' signal region





- The corresponding global significance is less than 1σ

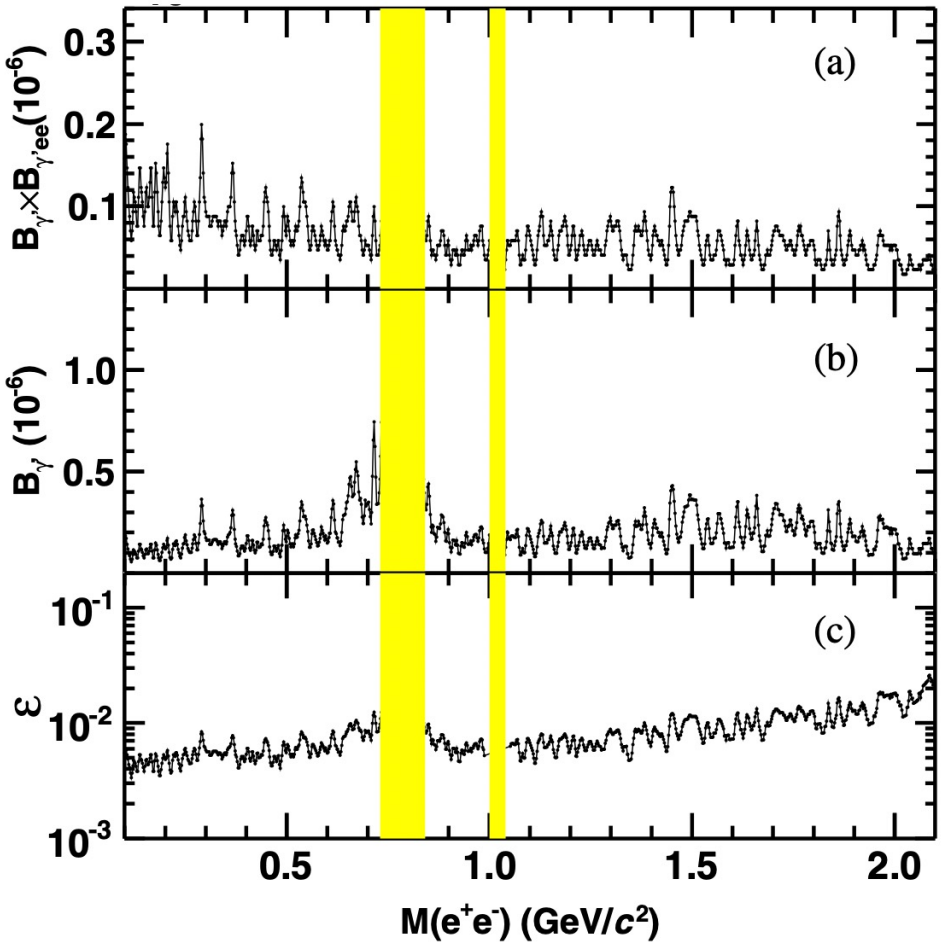
  PRD 93, 052005 (2016)

- No significant dark photon signal!!!

II: Dark photon search via $J/\psi \to \gamma'\eta', \gamma' \to e^+e^-$

PRD 99, 012013 (2019)

✓ **Dark photon search result :**



$$\frac{\mathcal{B}(J/\psi \to \eta'\gamma')}{\mathcal{B}(J/\psi \to \eta'\gamma)} = \varepsilon^2 |F(m^2_{\gamma'})|^2 \frac{\lambda^{3/2}(m^2_{J/\psi}, m^2_{\eta'}, m^2_{\gamma'})}{\lambda^{3/2}(m^2_{J/\psi}, m^2_{\eta'}, 0)},$$

- The 90% CL upper limits on ε vary in range of 3.4×10^{-3} - 2.6×10^{-2} in 0.07<m(e^+e^-) <2.13 GeV

  $\mathcal{B}\ (\gamma' \to e^+e^-)$ from

  PRD 79, 115008 (2009)

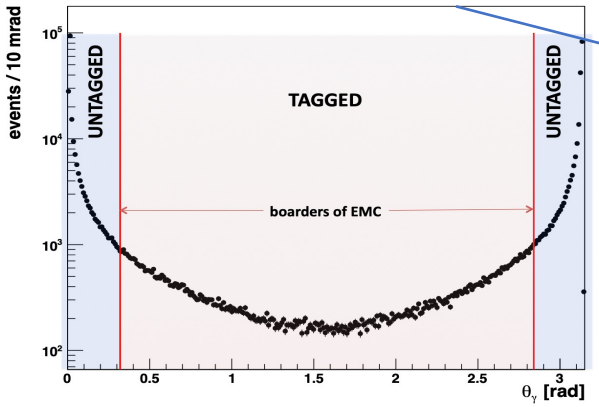
  JHEP 0907, 051 (2009)
- Worse than existing stringent experimental results

III: Dark photon search via $e^+e^- \to \gamma'\gamma_{ISR}, \gamma' \to l^+l^-$

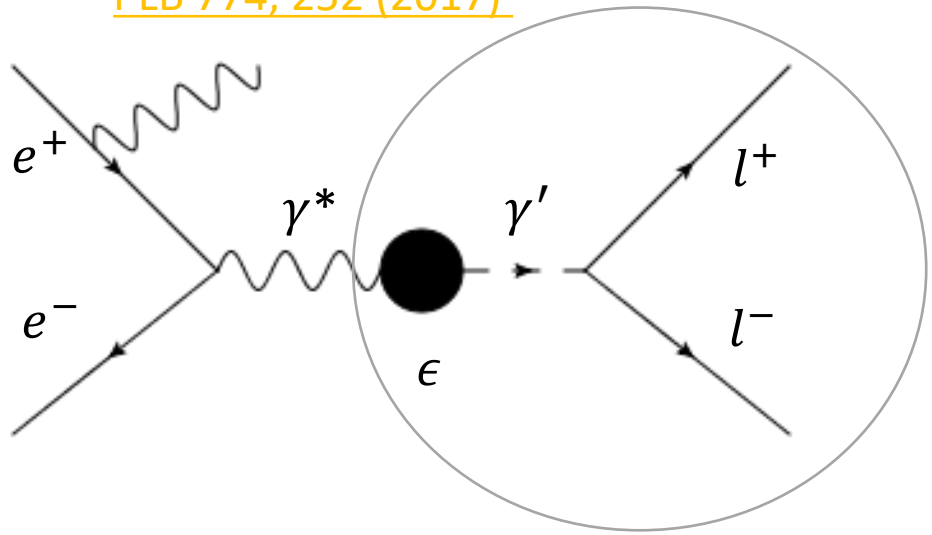
PLB 774, 252(2017)

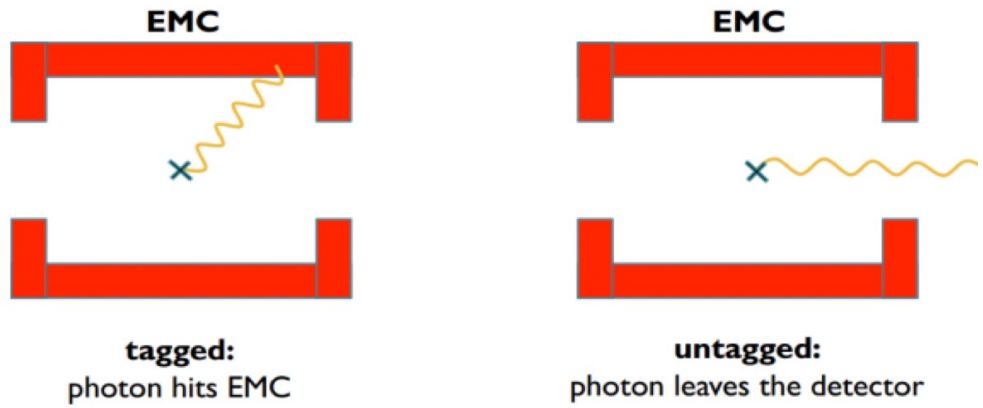
- **Data:** 2.93fb^{-1} data taken at $\sqrt{s}$ = 3.773 GeV
- Both of $e^+e^- \to \gamma_{ISR}\ e^+e^-$ and $\gamma_{ISR}\ \mu^+\mu^-$ are studied
- **Event selection:**
  1. Two charged tracks with zero net charge;
  2. Tracks are required to be $0.4 < \theta < \pi - 0.4$;
  3. Pt of each tracks above 300 MeV/c;
  4. PID for muon : P(μ)>P(e); Electron: E/p>0.8c;
  5. Use an untagged photon ISR photon method to increase statistics ;
  6. 1C fit ….;

Polar angle of leading order ISR photon.



PLB 774, 252 (2017)

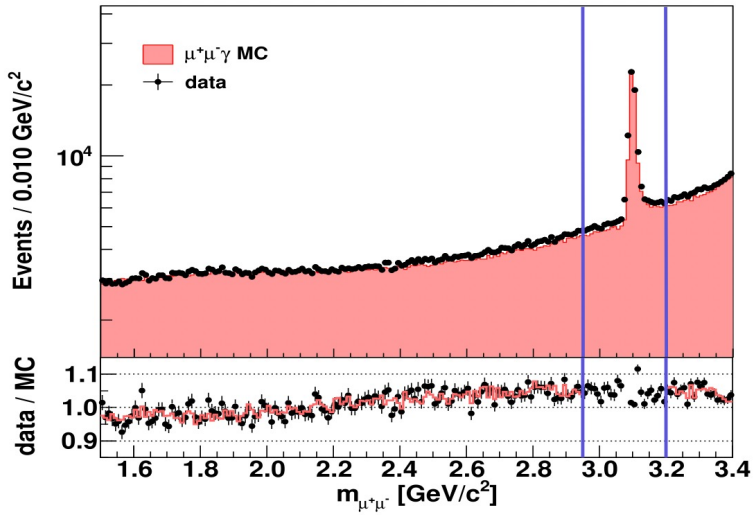


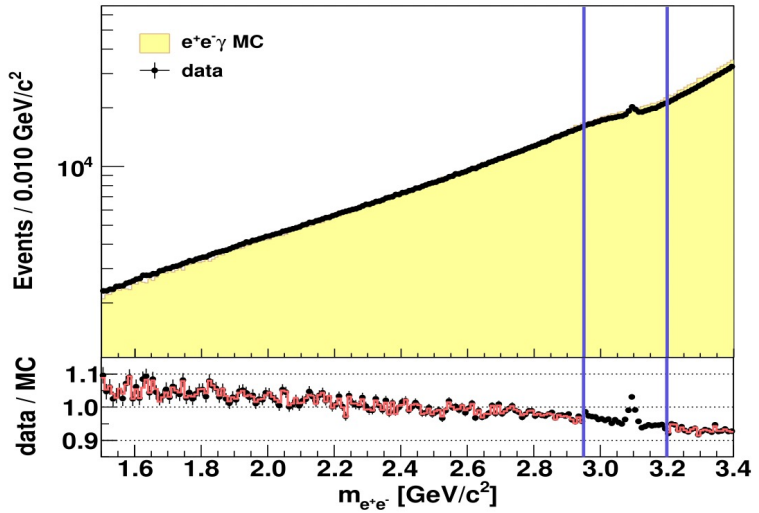


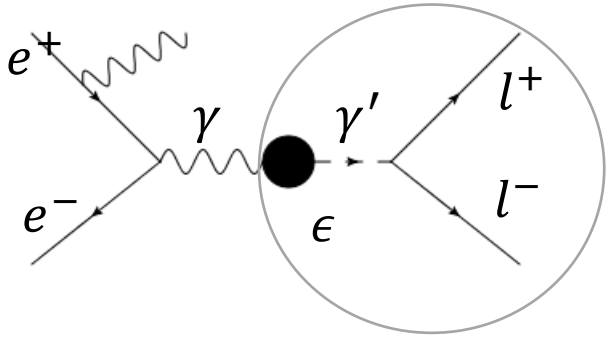
III: Dark photon search via $e^+e^- \to \gamma'\gamma_{ISR}, \gamma' \to l^+l^-$

PLB 774, 252(2017)

✓ **m(e^+e^-) and m($\mu^+\mu^-$) distributions:**







- Dominant QED backgrounds: $e^+e^- \to \gamma_{ISR}\ l^+l^-$
- Below 1.5 GeV/c^2 the $\pi^+\pi^-\gamma_{ISR}$ cross section with muon misidentification dominates the m($\mu^+\mu^-$) spectrum. Above 3.4 GeV/c 2 the hadronic $q\bar{q}$ process can not be suppressed sufficiently by the χ^2_{1c} requirement
- The mass range around the narrow J/ψ resonance between 2.95 and 3.2 GeV/c^2 is excluded

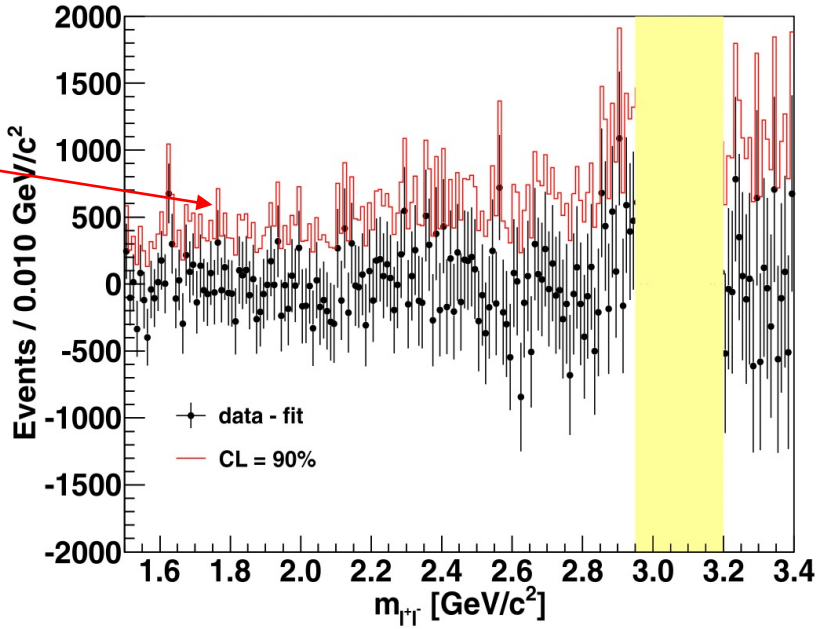
III: Dark photon search via $e^+e^- \to \gamma'\gamma_{ISR}, \gamma' \to l^+l^-$

PLB 774, 252(2017)

✓ **Search for A narrow structure in m(l^+l^-) spectrum:**

- The combined differences between the γ_{ISR} e^+e^- and γ_{ISR} $\mu^+\mu^-$ event yields, and their respective fit results

90% CL
Upper Limit



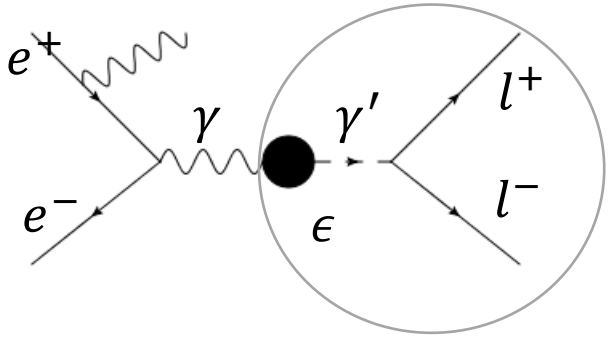
- The observed statistical significances are less than 3σ everywhere in the explored region

III: Dark photon search via $e^+e^- \to \gamma'\gamma_{ISR}, \gamma' \to l^+l^-$

PLB 774, 252(2017)

✓ **Calculation of mixing strength ε :**

$$\frac{\sigma_i(e^+e^- \to \gamma'\gamma_{ISR} \to l^+l^-\gamma_{ISR})}{\sigma_i(e^+e^- \to \gamma^*\gamma_{ISR} \to l^+l^-\gamma_{ISR})} = \frac{3\pi \cdot \varepsilon^2 \cdot m_{\gamma'}}{2N_f^{l^+l^-}\alpha \cdot \delta_m^{l^+l^-}},$$



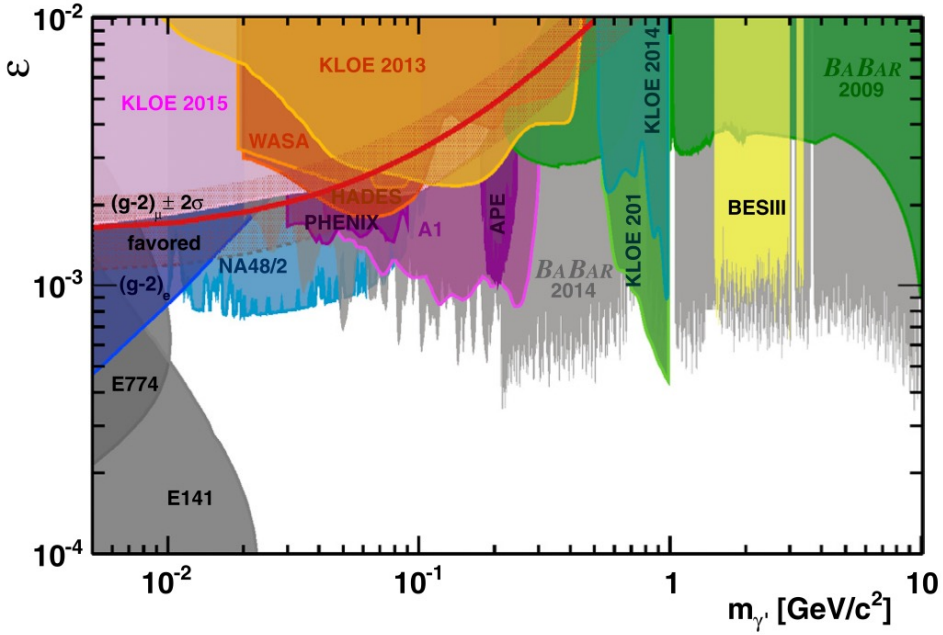
$$N_f^{l^+l^-} = \Gamma_{tot}/\Gamma_{ll}$$

$$\Gamma_{ll} = \frac{\alpha\varepsilon^2}{3m_{\gamma'}^2}(m_{\gamma'}^2 + 2m_l^2)\sqrt{m_{\gamma'}^2 - 4m_l^2}$$

$$\Gamma_{tot} = \Gamma_{ee} + \Gamma_{\mu\mu} \cdot (1 + R(\sqrt{s})) ,$$

PRD 80 (2009) 075018

Phys. Rev. D 88 (2013) 015032.



- This is a competitive limit (10^{-4} - 10^{-3}) in this dark photon mass range

- BESIII 2.93 fb^{-1} ~ Babar 514 fb^{-1}

An introduction to the light higgs boson

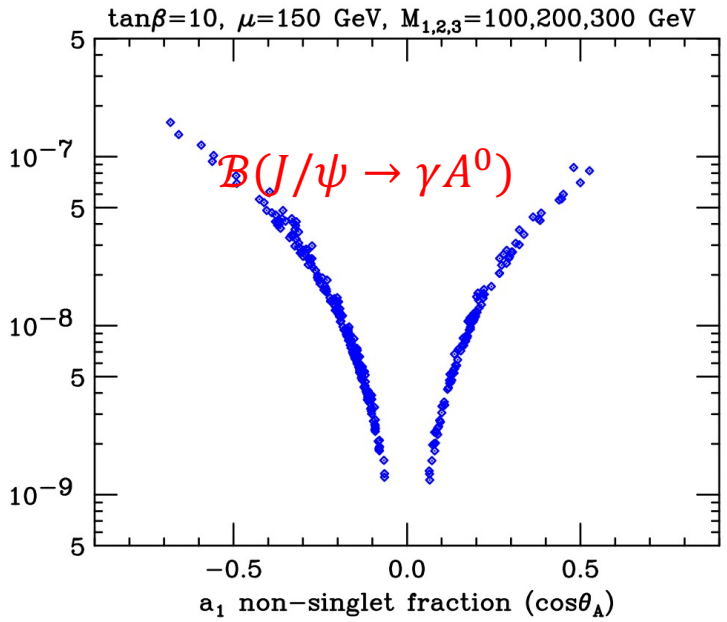
- A light Higgs boson is predicted by many extensions of Standard Model, such as Next-to-Minimal Supersymmetric Standard Model (NMSSM) PRL 95 041801 PRD 76, 051105
- NMSSM contains a total of three CP-even, two CP-odd and two charged Higgs bosons, which can alleviate the so-called "litte hierarchy problem" Phys. Lett. B 710, 460
- The lightest state of the A_0 is defined as:

$$A_0 = \cos\theta_A A_{MSSM} + \sin\theta_A A_S$$

Non-singlet Singlet

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

$$g_c = \cos\theta_A / \tan\beta \quad (q = c)$$



- If m(A_0) is smaller than two charmed quark, $J/\psi \to \gamma A^0$ is accessible

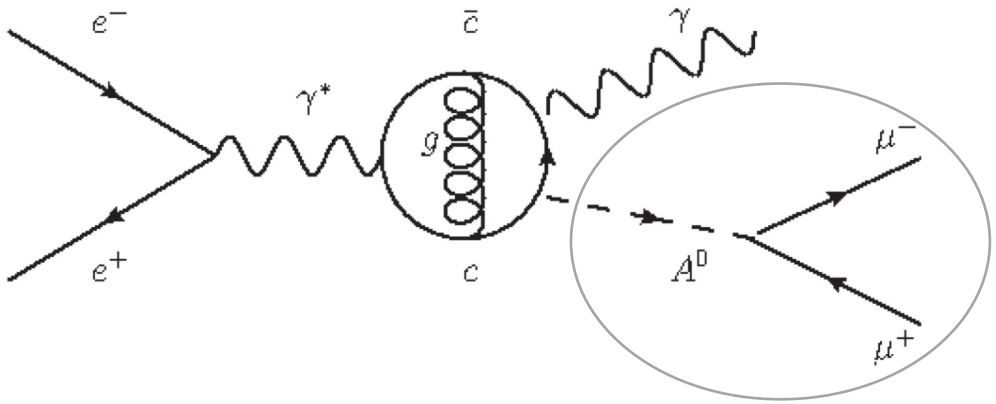
eConf C070805 19

I: Light Higgs boson search via $J/\psi \to \gamma A^0,\ A^0 \to \mu^+\mu^-$

PRD 105, 012008(2022)

- **Data:** 9 billion J/ψ events
- $\mathcal{B}(J/\psi \to \gamma A^0)$ is predicted to be in $10^{-9} - 10^{-7}$

PRD 76, 051105



- **Event selection:**
  1. Two charged tracks with zero net charge;
  2. E_{EMC} /P <0.9c, 0.1<E_{EMC}<0.3 GeV;
  3. MUC information to identify muon track;
  4. 4C kinematic fit;
  5. Reject fake photon by requiring m($\mu^+\mu^-$)<3.04 GeV/c^2;
  6. …

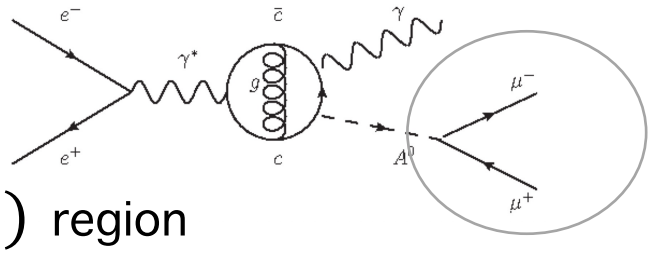
$$\frac{\mathcal{B}(V \to \gamma A^0)}{\mathcal{B}(V \to l^+l^-)} = \frac{G_F m_q^2 g_q^2 C_{\mathrm{QCD}}}{\sqrt{2}\pi\alpha}\left(1 - \frac{m_{A^0}^2}{m_V^2}\right),$$

I: Light Higgs boson search via $J/\psi \to \gamma A^0,\ A^0 \to \mu^+\mu^-$

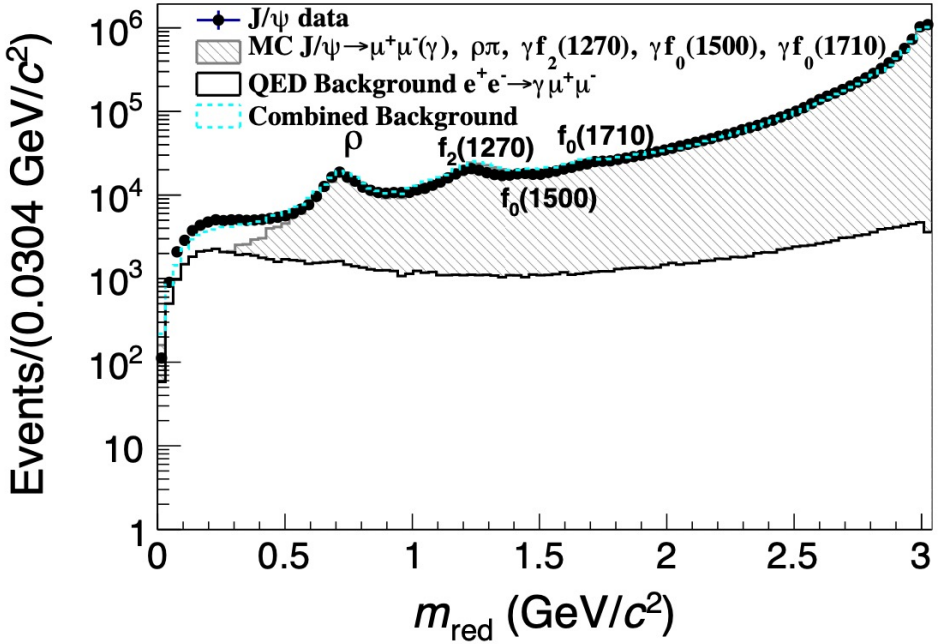
PRD 105, 012008(2022)

✓ m_{red} **distribution:**

$$m_{\rm red} = \sqrt{m^2_{\mu^+\mu^-} - 4m^2_{\mu}},$$



m_{red} is used to model the non-peaking background across the entire $m(A_0)$ region more easily



- The background is dominated by:

  $e^+e^- \to \gamma\mu^+\mu^-, J/\psi \to (\gamma)\mu^+\mu^-$

  Several peaking background:

  $J/\psi \to \rho/\omega\ \pi;$

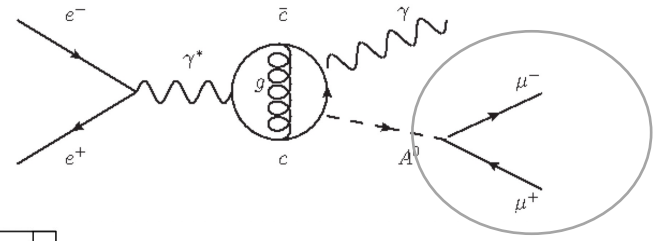
  $J/\psi \to \gamma f_2(1270)/f_0(1500)/f_0(1710);$

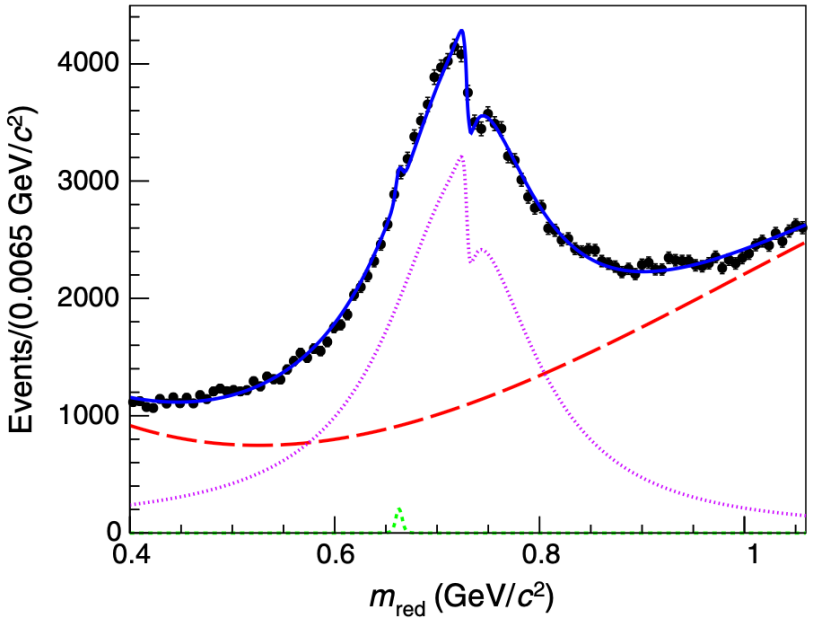
I: Light Higgs boson search via $J/\psi \to \gamma A^0,\ A^0 \to \mu^+\mu^-$

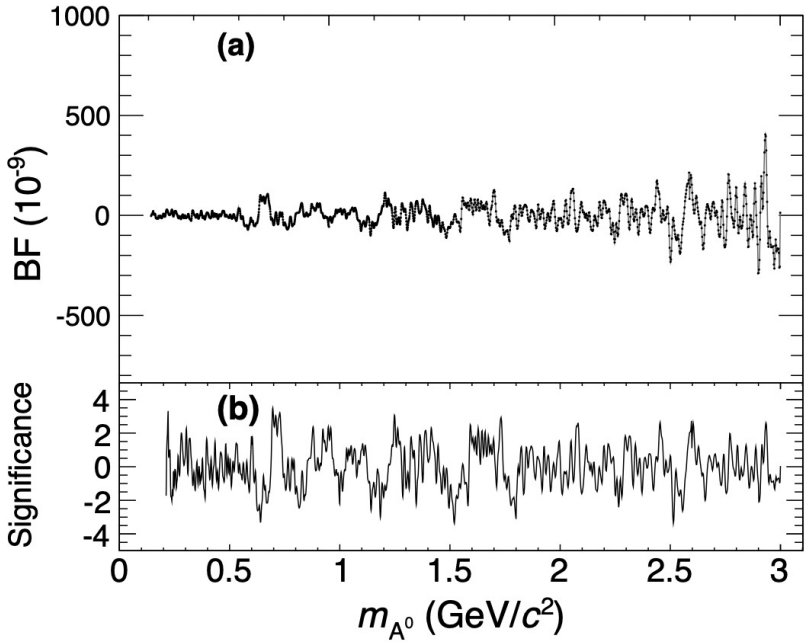
PRD 105, 012008(2022)

✓ **A_0 Search:**

A series of one-dimensional unbinned extended maximum likelihood fits to the m_{red} distribution







- The largest local significance is 3.5σ at m(A_0)= 0.696 GeV/c^2 The corresponding global significance is 1σ.

I: Light Higgs boson search via $J/\psi \to \gamma A^0,\ A^0 \to \mu^+\mu^-$

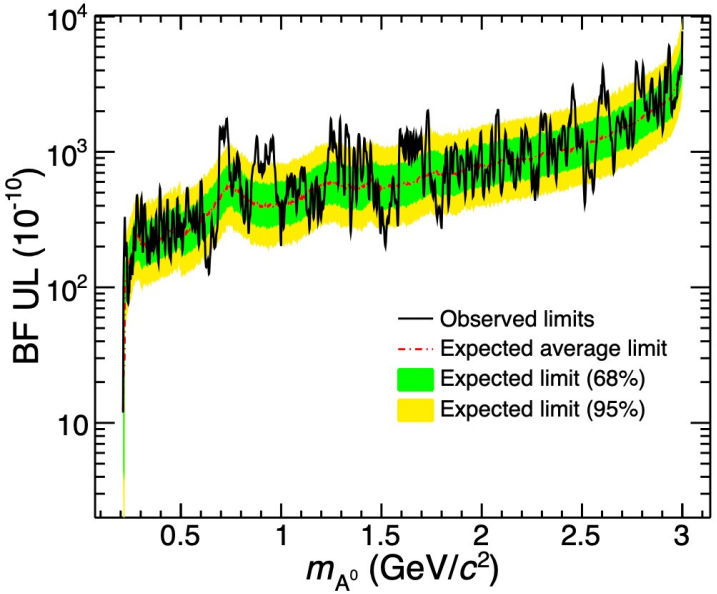
PRD 105, 012008(2022)

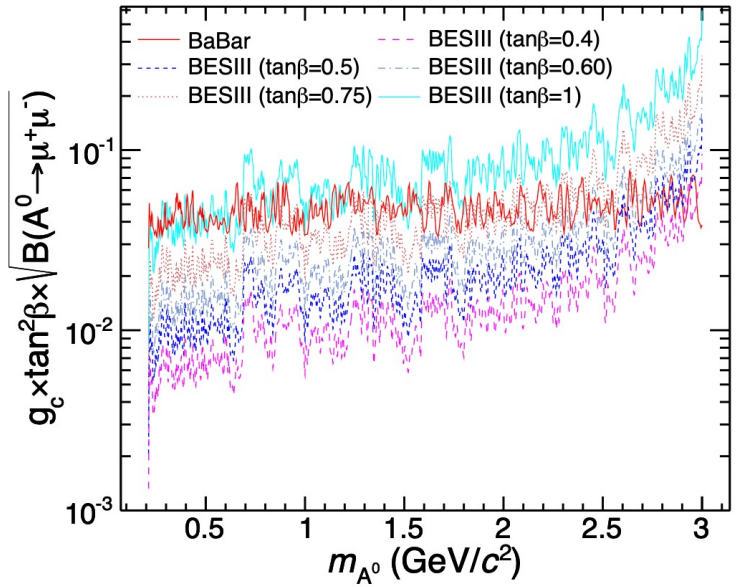
✓ **Result of light higgs search:**

- 90% C.L. upper limits of $\mathcal{B}(J/\psi \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-)$ is $(1.2 - 778.0) \times 10^{-9}$

  lower than the theoretical prediction at the threshold

- This result has an improvement by a factor of 6-7 over the previous BESIII measurement





$$g_b(=g_c\tan^2\beta) \times \sqrt{\mathcal{B}(A^0 \to \mu^+\mu^-)}$$

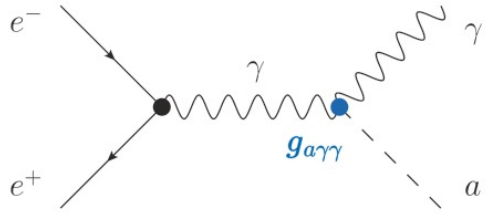
- The is slightly better than the BaBar measurement in the low-mass region for tan β = 1.0

Axion-like particles in radiative J/ψ decays

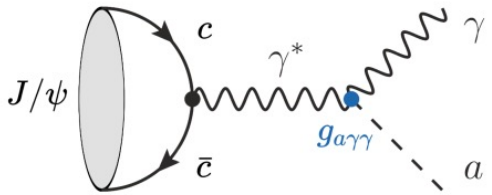
✓ **Axion-like particles** (ALPs)

- 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

Non-resonant ALP production



Resonant ALP production



I: Search for an axion-like particle using $\psi(3686)$ data

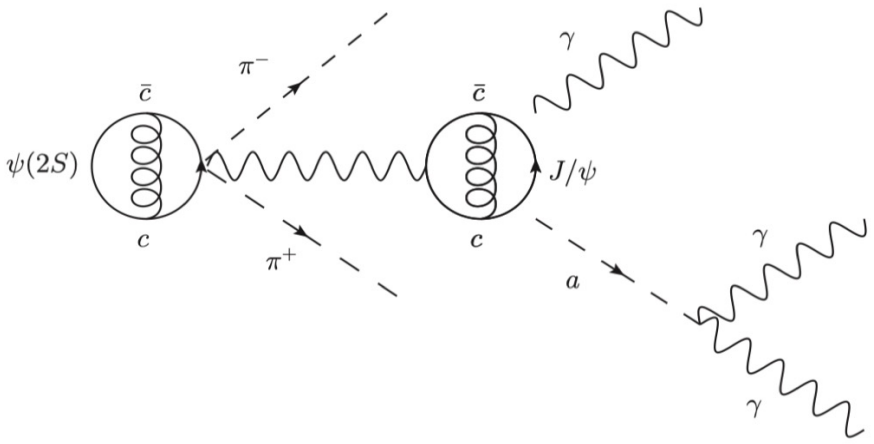
PLB 838, 137698(2023)

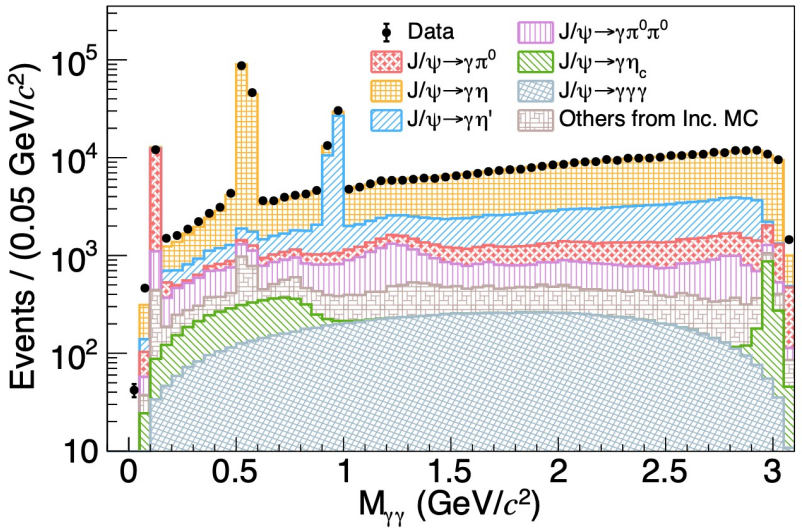
- **Data sample :** 2.7B $\psi(3686)$ events

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

✓ 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 in $0.165 \leq m_a \leq 2.84$ GeV/c^2
- $\psi(3686)$ decay -> preclude the pollution from non-resonant production and avoid QED background
- Three $\gamma\gamma$ combinations per event, exclude intervals around π^0, η, η′ peaks



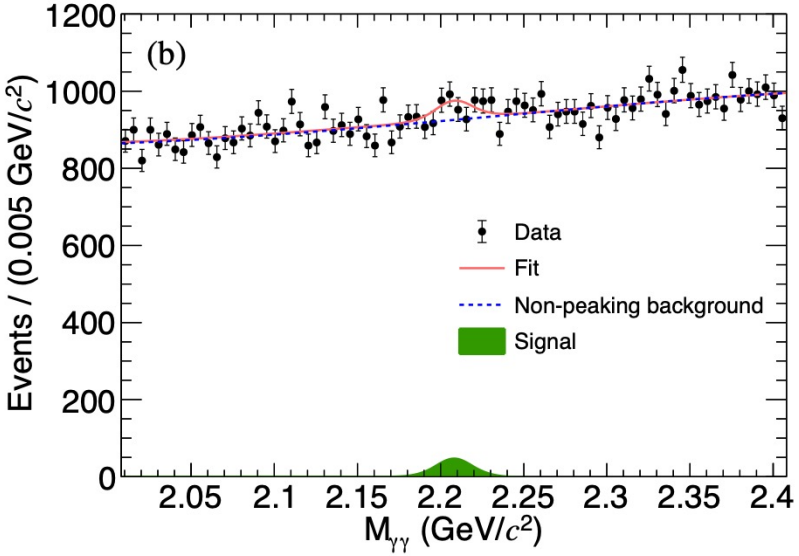


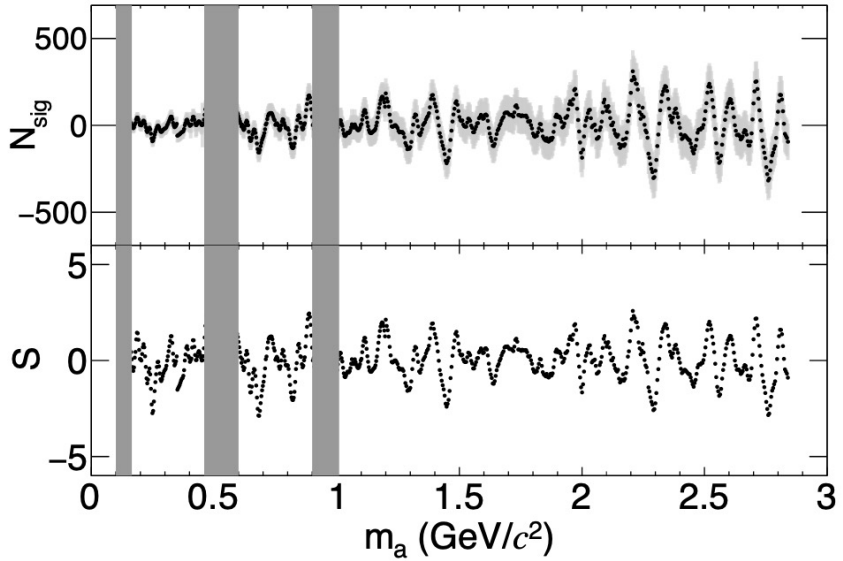
I: Search for an axion-like particle using $\psi(3686)$ data

PLB 838, 137698(2023)

✓ Signal extraction

- Fits are performed to the $\mathrm{M}(\gamma\gamma)$ to determine the in the mass range of $0.165 \leq m_a \leq 2.84$ GeV/c^2.
- Totally, 674 mass hypotheses are probed, exclude intervals around π^0, η, η′ peaks
- The local significance are less than 2.6σ for all mass point





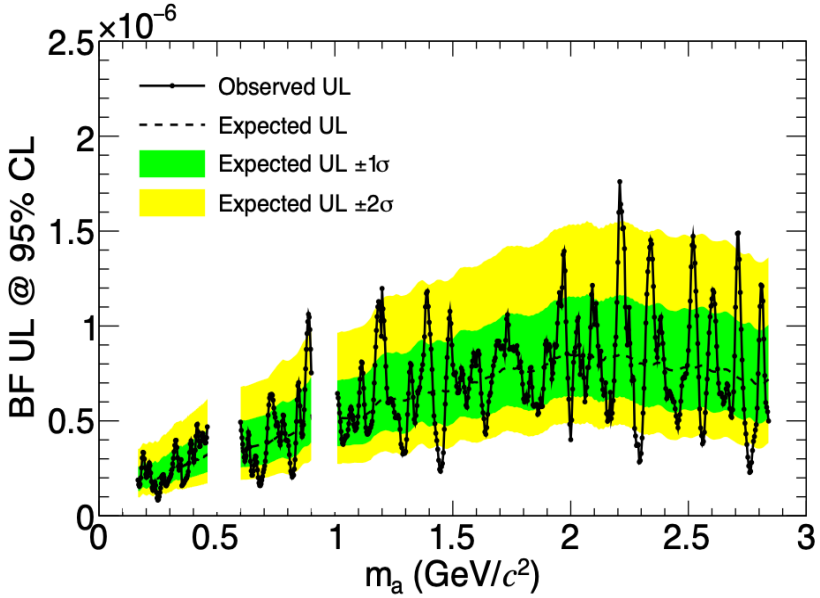
I: Search for an axion-like particle using $\psi(3686)$ data

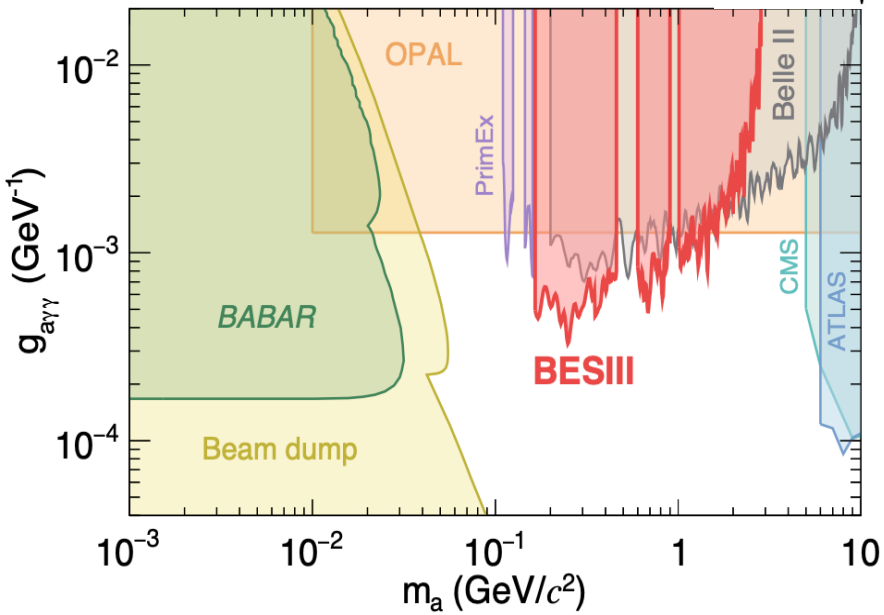
PLB 838, 137698(2023)

✓ **Upper limits**

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

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





II: Search for an axion-like particle using J/ψ data

BESIII preliminary

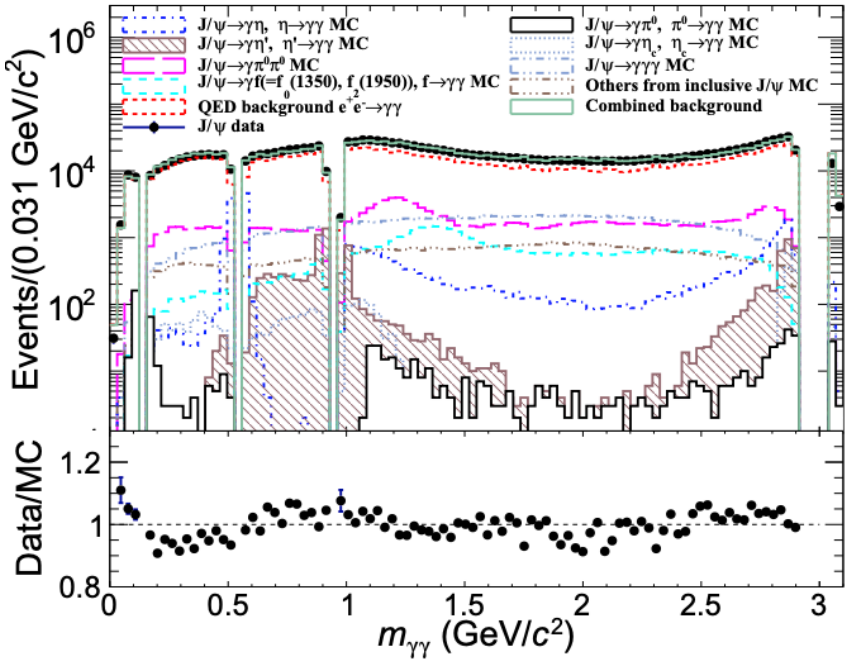
✓ **Data sample :** 10B J/ψ events

✓ Exclusion limits can be further improved using 10 billion of BESIII J/ψ data

✓ Search for $J/\psi \to \gamma a, a \to \gamma\gamma$ decays

$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha.(\hbar.c)^2}{24}\left(1-\frac{m_a^2}{s}\right)^3$$

- Expected pollution of ALP-Strahlung process $e^+e^- \to \gamma a$ is 4.4% (sys.err)
- Select at three photon candidates in the EMC barrel region
- Three $\gamma\gamma$ combinations per event, exclude intervals around π^0, η, η', η_c peaks



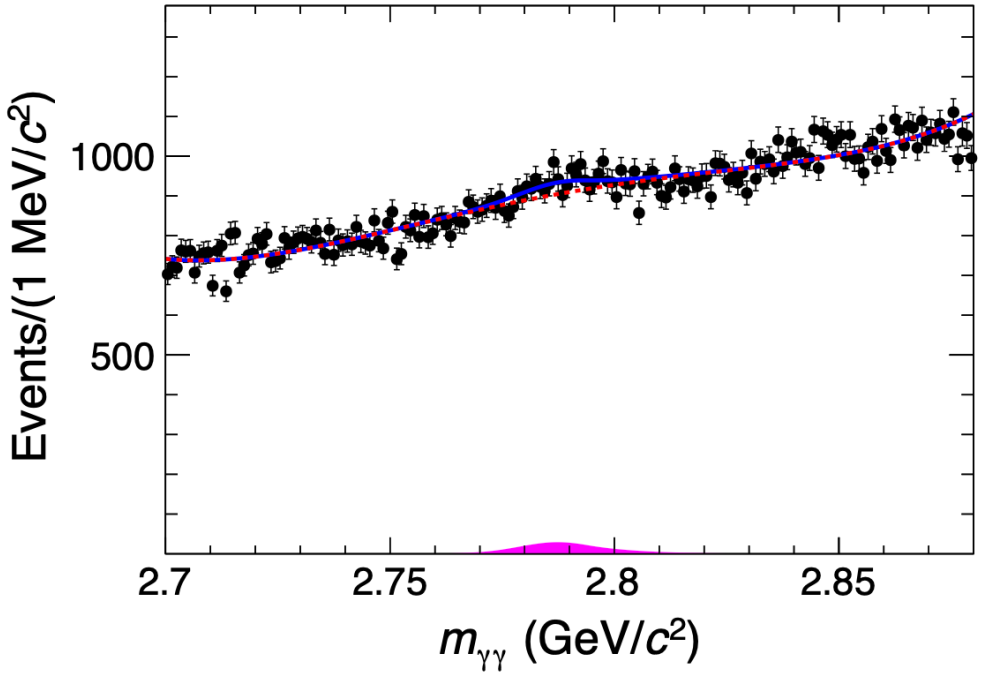
II: Search for an axion-like particle using J/ψ data

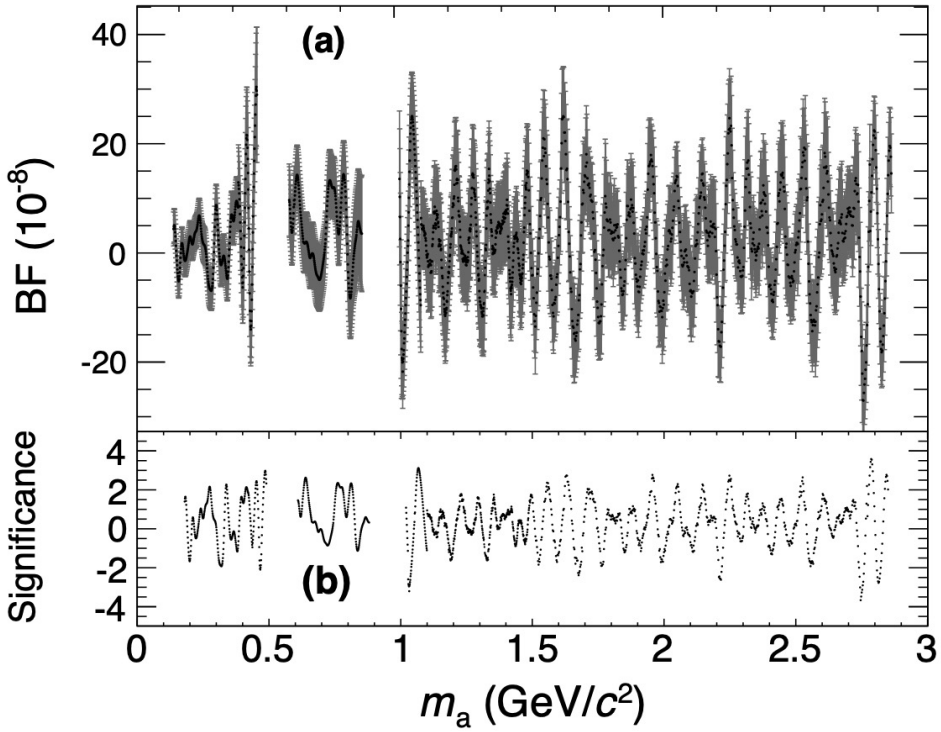
BESIII preliminary

✓ **Signal extraction:**

- The search for a narrow a resonance in the mass range of $0.18 \leq m_a \leq 2.85$ GeV/c^2
- Global significance less than 1.6σ

$$\mathcal{B}(J/\psi \to \gamma a) \times \mathcal{B}(a \to \gamma\gamma) = \frac{N_{\rm sig}}{\epsilon N_{J/\psi}}.$$



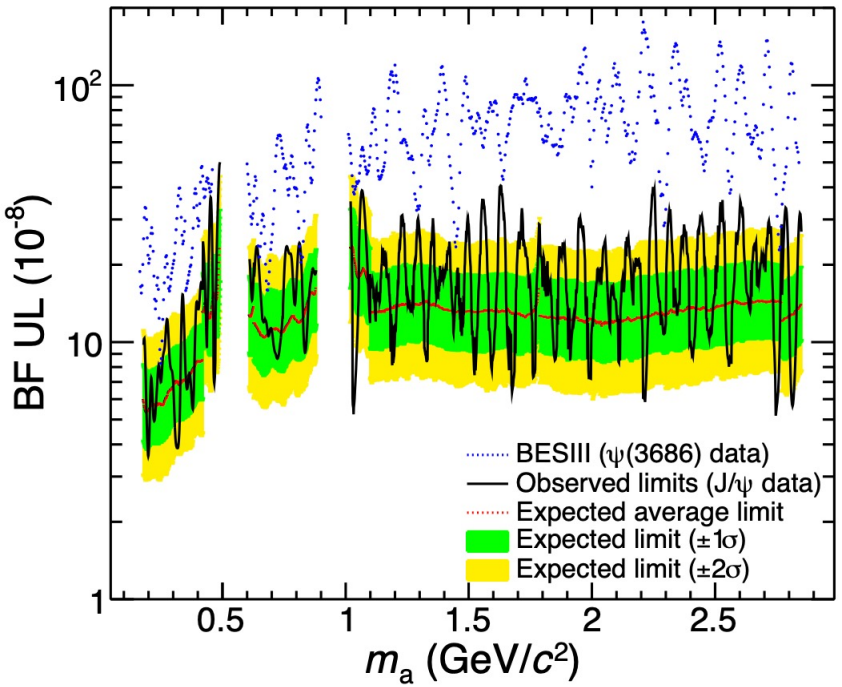


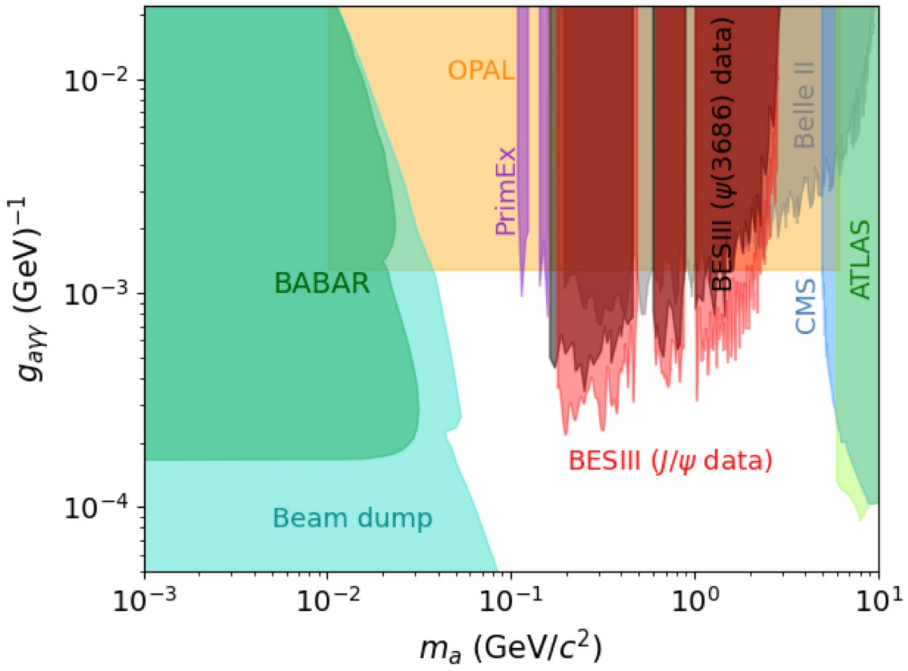
II: Search for an axion-like particle using J/ψ data

BESIII preliminary

✓ Upper limits:

- BF: UL on 95% CL (3.6 – 53.1) × 10^{-8} in 0.18 ≤ m_a ≤ 2.85 GeV/c^2
  8-9 times improvement over the $\psi(3686)$ measurement
- Most stringent limits on the ALP-photon coupling in the searched region

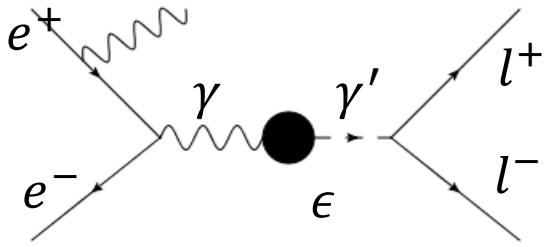




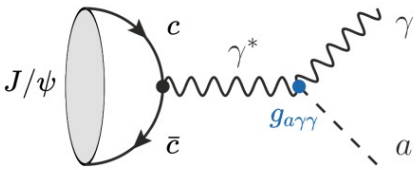
Summary

✓ BESIII plays an active role on searches for a variety of exotic particles:

- direct production or decays of hadrons
- Dark photon ($\gamma' \to l^+l^-$)
- Light higgs ($A^0 \to \mu^+\mu^-$)
- ALPs ($a \to \gamma\gamma$)



direct production



decays of hadrons

✓ Contribute to constraining the parameter space of new physics models within the MeV-GeV scale

✓ More is coming:

- muon philic $X_{0,1}$, Z', massless dark photon, X(17), fractionally charged particles …

✓ Looking forward to anomalies, enjoy the ride!

Thanks!