Axion-like particle and dark sector search at BESIII

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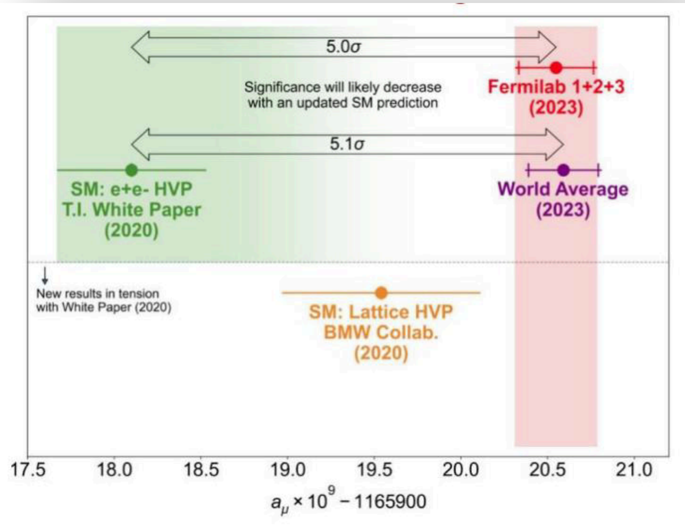
On behalf of the BESIII collaboration

July 18th, Prague

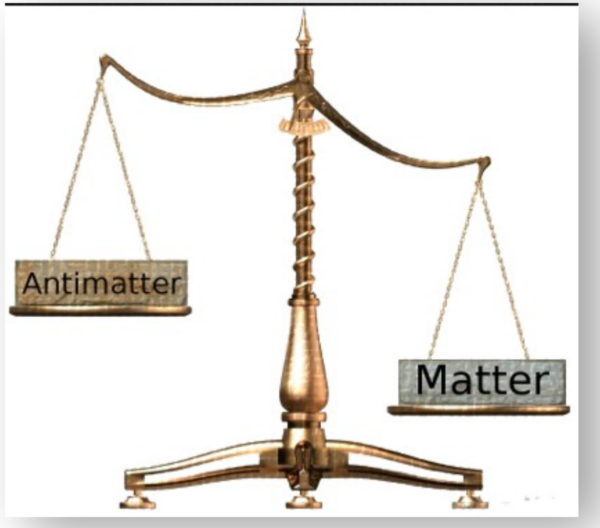
- Standard Model (SM) is incredibly successful in describing the properties of visible matter
  - ☑ *leptons, photon,* Z, $W^{\pm}$, *Higgs, quarks, mesons, hadrons*

$g_{\mu} - 2$ anomaly

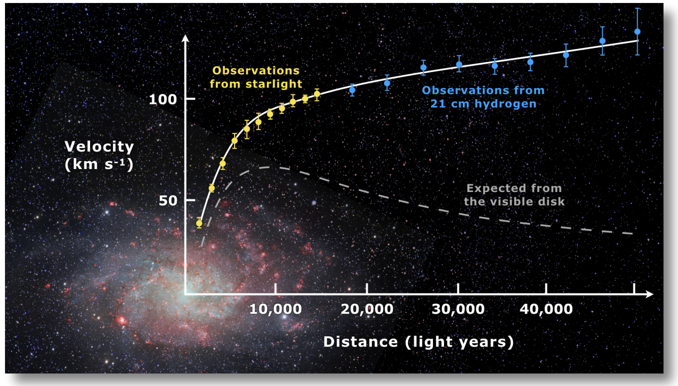


PRL 131, 161802(2023)

Matter-antimatter asymmetry

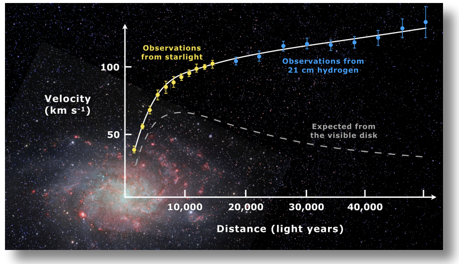


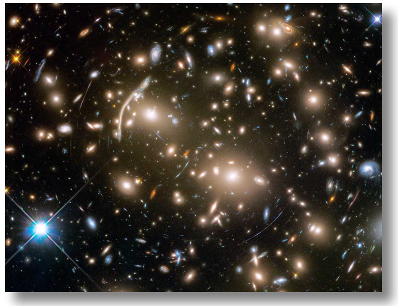
Galactic rotation curve



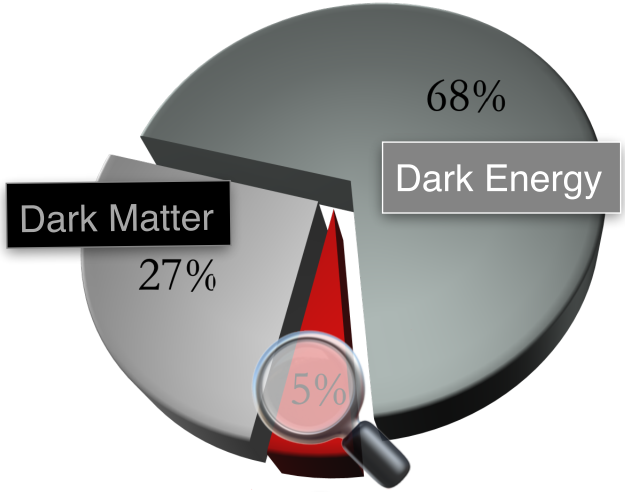
arXiv:astro-ph/0403324

There is nothing new to be discovered in physics now.

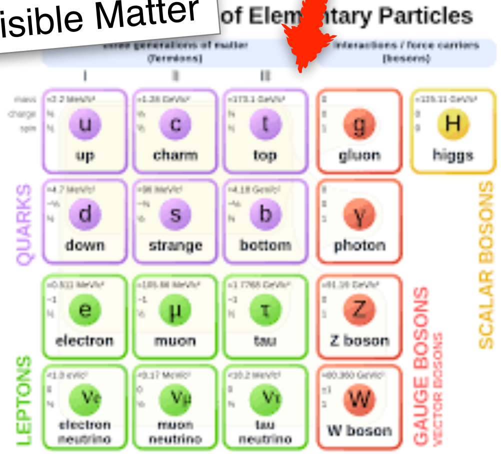




Dark Matter



Visible Matter



Physics BSM must exist!

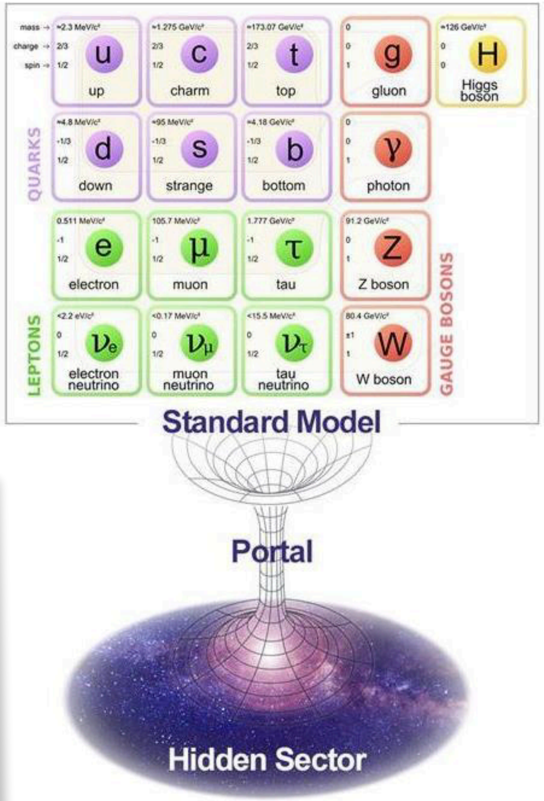
Dark sector

- A **collection of particles** that are not charged directly under the SM strong, weak, or electromagnetic forces.
  - May interact with SM particle through portal interactions, not through gravitational effect not.

➡ Dark sector particles

- **Axion:** QCD axion and axion like particles
- **Muonphilic vector or scalar**
- **Dark photon γ'** : Massive or massless
- SUSY, dark Higgs, heavy neutrinos, dark fermion

The main of this talk



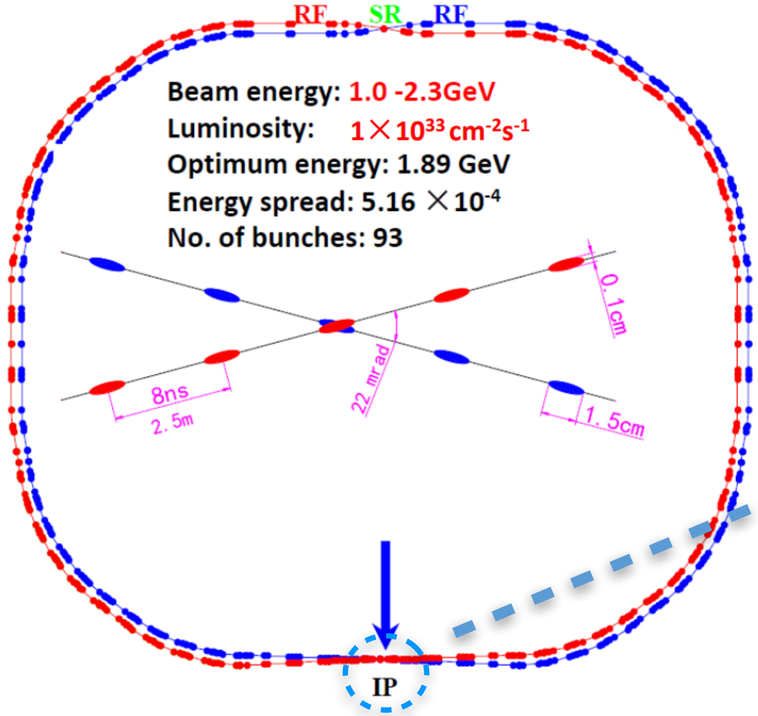
Merits of BSM search at BESIII:

- High statistic of data
- Clean background environment
- Angular coverage is almost 4π

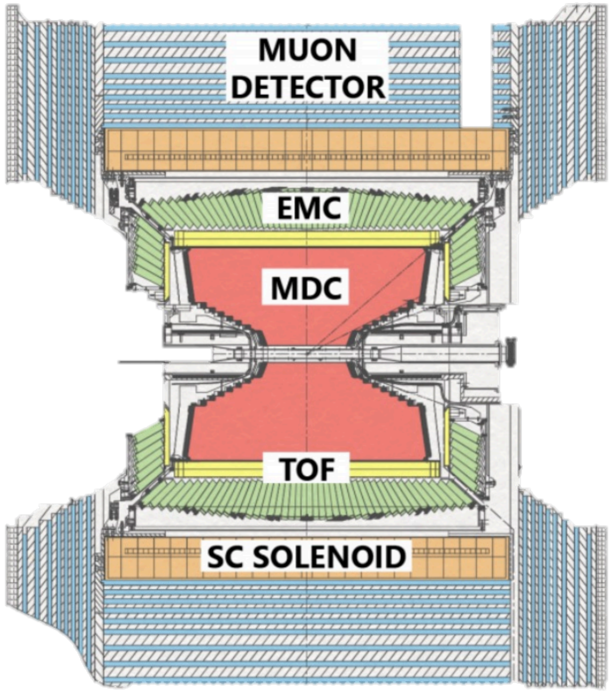
If their mass are in the **MeV-GeV** range
→ Accessible at **BEPCII and BESIII** experiment.

BESIII Experiment

Beijing Electron–Positron Collider II



Beijing Spectrometer III Detector



NIMA 614, 345 (2010)

CPC 44, 040001 (2020)

BESIII has collected the largest data samples of **10 billion J/ψ, 2.7 billion ψ(3686)** on threshold in the world

Axion-like particles (ALPs) search

- Search for an axion-like particle in $J/\psi \to \gamma a, a \to \gamma\gamma$
  - Using 2.7B $\psi(3686)$ data
  - Using 10B J/ψ data

What is ALP

QCD axion (a)

PRL. 40, 223 (1978)
PRL. 40, 279 (1978)

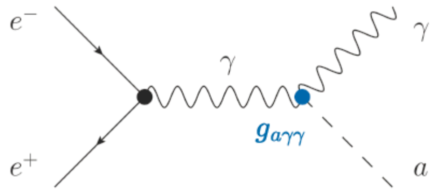
- Predicted by the Peccei-Quinn (PQ) solution to the strong CP problem, could also be a dark matter candidate

Axion-like particles (ALPs)

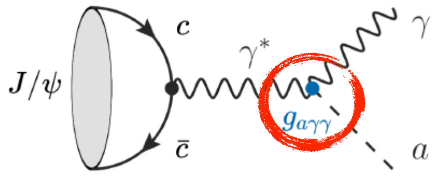
- Have the same quantum numbers as the QCD axion, but could have **arbitrary masses and couplings.**
- The ALP-photon coupling $g_{a\gamma\gamma}$ is mostly discussed → ALP decays to two photon
- Experimental bounds on $g_{a\gamma\gamma}$ with m_a range of MeV/c^2 – GeV/c^2 mainly from e^+e^- colliders

PLB 753,482 (2016)

■ Non-resonant ALP production



■ Resonant ALP production



JHEP. 06, 091 (2019)

This talk:
ALP is searched via
$J/\psi \to \gamma a,\ a \to \gamma\gamma$

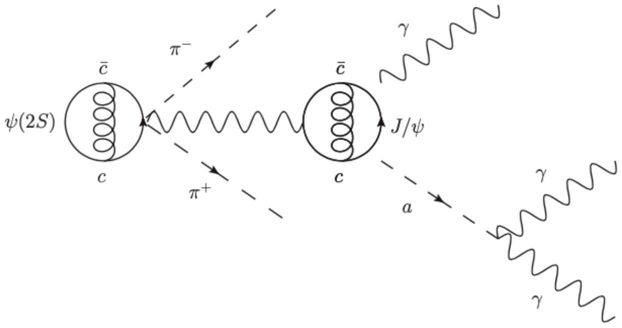
Using 2.7B $\psi(2S)$ Data, in
$0.165 < m_a < 2.84$ GeV/c^2
PLB 838(2023) 137698

Using 10B J/ψ Data, in
$0.18 < m_a < 2.85$ GeV/c^2
arXiv:2404.04640
Accepted by PRD(L)

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

PLB 838 137698 (2023)

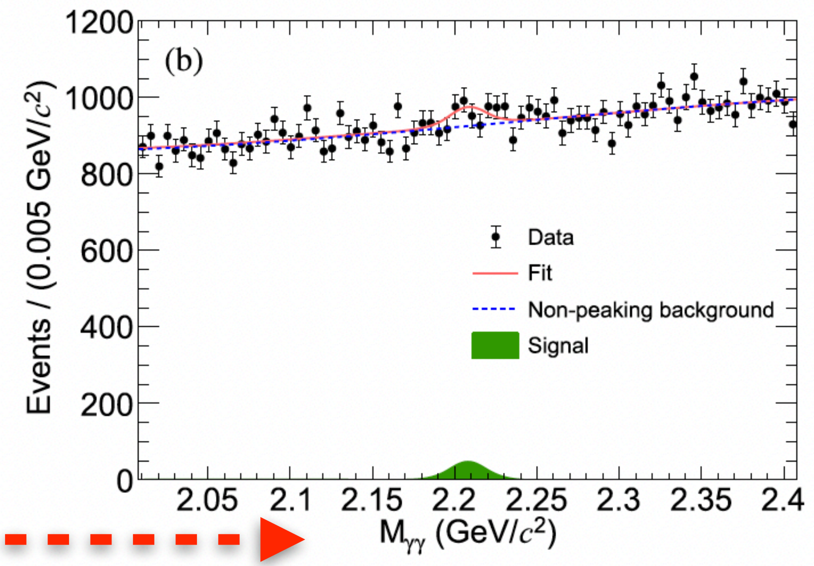
- Data samples: 2.7B $\psi(3686)$ events
- Strategy: Search for $J/\psi \to \gamma a, a \to \gamma\gamma$ with J/ψ sample obtained from $\psi(3686) \to \pi^+\pi^- J/\psi$
  - $\psi(3686)$ decay: avoid the pollution from non-resonant production $e^+e^- \to \gamma\gamma\gamma$



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

- Decay width of $a \to \gamma\gamma$: $\Gamma_a = \dfrac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$
- Taking $g_{a\gamma\gamma} \sim 10^{-4}$ GeV^{-1}, $m_a \sim$ GeV, the lifetime of ALP is short in the detector
  ➡ Assume BF($a \to \gamma\gamma$)~100%

- Three $\gamma\gamma$ combinations per event, **extract signal from $M_{\gamma\gamma}$ distribution**
  - 674 mass hypotheses



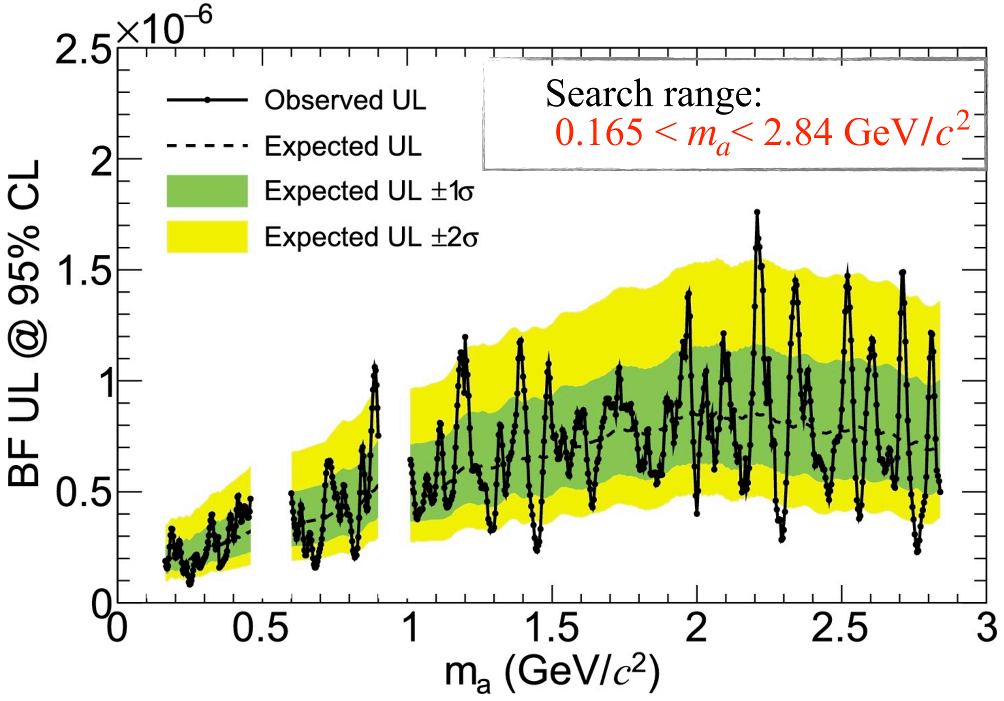
The maximum local significance is 2.6σ at $m_a = 2208$ MeV/c^2

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

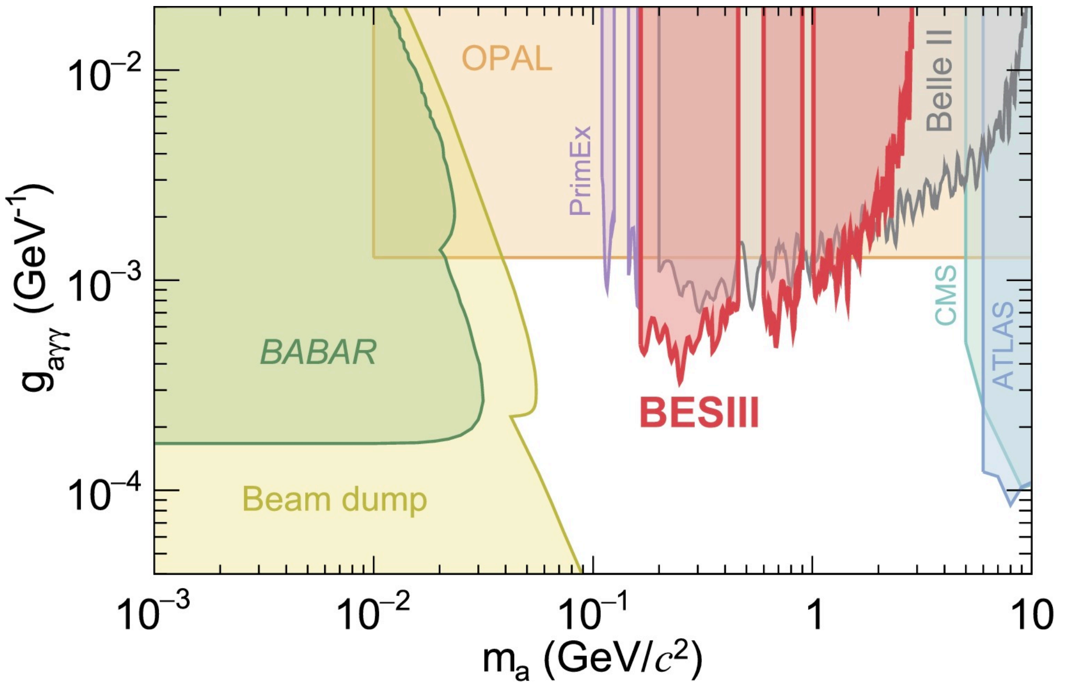
- No significant ALP signal is observed

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

BF @ 95% CL



ALPs-photon Coupling



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

arXiv:2404.04640

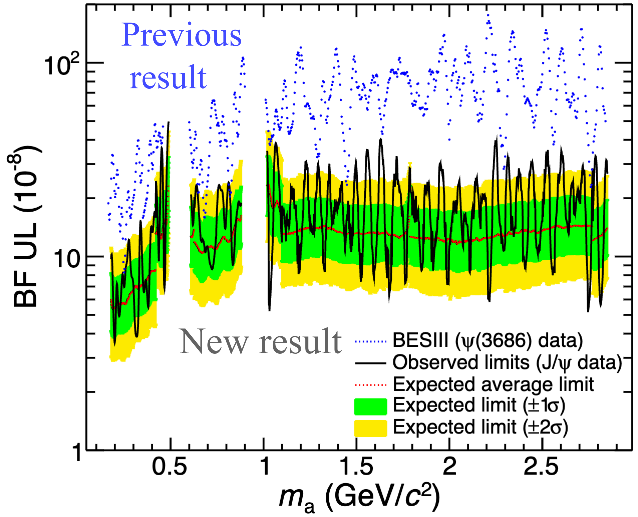
Accepted by Phys. Rev. D (Letter)

- **Data samples**: 10B J/ψ events

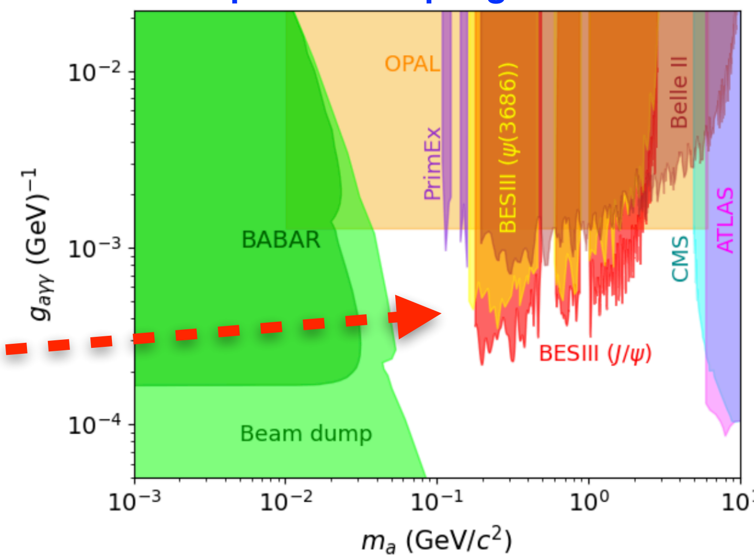
NEWEST RESULT!

- **Strategy:** Search for $J/\psi \to \gamma a, a \to \gamma\gamma$ with J/ψ data on threshold
  - Non-resonant process $e^+e^- \to \gamma a$ is indistinguishable from $J/\psi \to \gamma a$
    - The ratio, $\sigma_{non-res}/\sigma_{res}$ is calculated to be 4.4%
    - The contribution from $e^+e^- \to \gamma a$ is subtracted from the signal yields (interference between $\sigma_{non-res}$, σ_{res} is negligible).

✓ The 95% CL. upper limits of $\mathscr{B}(J/\psi \to \gamma a)$ is set based on 10B data



ALPs-photon Coupling



10B J/ψ

Most stringent constraints to date for $0.18 < m_a < 2.85$ GeV

(Other)

Dark sector search

✓Search for fully invisible decays

- Massive dark photon
- Muonphilic scalar X_0 or vector X_1

This talk

- $\Lambda, \eta, \eta', \omega, \phi$ — PRD 105, L071101 (2022); PRD 98, 032001 (2018); PRD 87, 012009 (2013)

✓Other searches with invisible signatures — PLB 852 ,138614 (2024); PRD 105, L071102 (2022); PRD 105, 106, 072008 (2022)

- FCNC process:

  $\Sigma^+ \to p+$ invisible, $\Lambda_c^+ \to p+$ invisible, $D^0 \to \pi^0 \nu\bar{\nu}$

- $J/\psi \to \gamma+$invisible — PRD 101, 112005 (2020)

✓Visible dark photon searches

- $e^+e^- \to \gamma\gamma', \gamma' \to l^+l^-$ — PLB 774, 252(2017)
- $J/\psi \to \eta\gamma', \gamma' \to e^+e^-$ — PRD 99, 012006 (2019)

What is Dark photon γ'

- An extra Abelian gauge group $U(1)_D$:
  - A minimal extension to SM, causing the associated spin-one boson the dark photon
    - **Massive γ',** if the symmetry is spontaneously **broken**
    - **Massless γ'**, if the symmetry is **unbroken**
  - The dark photon has a **kinetic mixing** with SM photon through

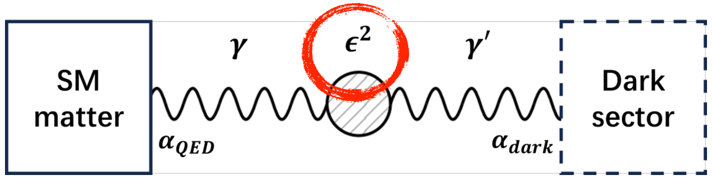
$$\rightarrow \frac{1}{2}\varepsilon F'_{\mu\nu}F^{\mu\nu}$$

PLB, 196 (1986)

with a kinetic mixing parameter $\varepsilon \sim 10^{-3}$(empirical, very small)

- ε**:** controls the coupling strength
- $F'_{\mu\nu}$: field strengths of the dark photon

- dark



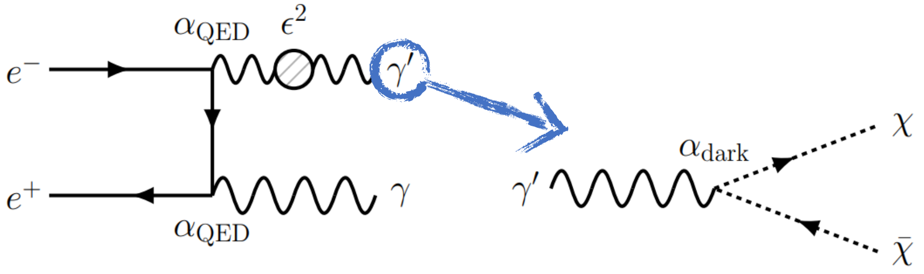
Accessible at high intensity facilities like BESIII

Phys. Rev. D 102, 015023 (2020).

Search for Massive dark photon with $e^+e^- \to \gamma\gamma'$

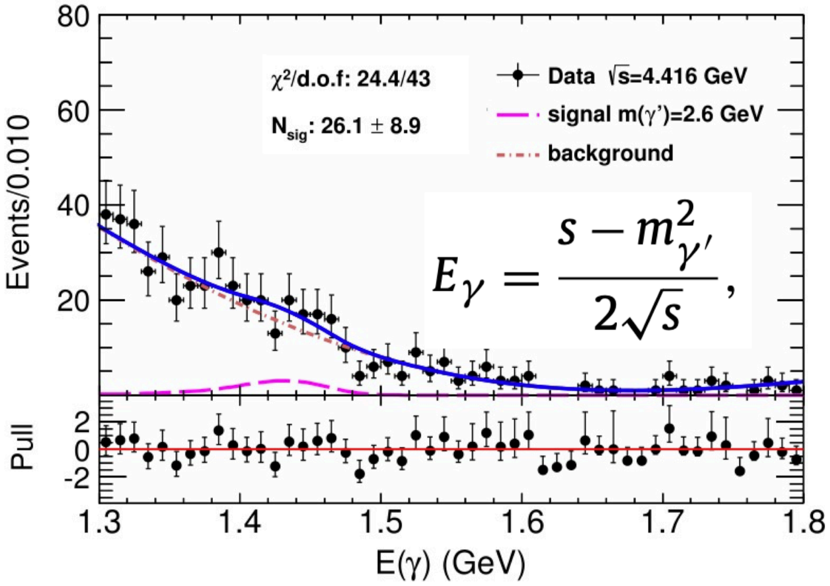
PLB 839 (2023) 137785

- Data samples: **14.9** fb^{-1} e^+e^- annihilation data at $\sqrt{s} = 4.13 \sim 4.60$ GeV
- Massive dark photon γ' is explored via $e^+e^- \to \gamma\gamma'$, $\gamma' \to$ invisible
- Search for single photon signals in $1.3 < E(\gamma) < 1.8$GeV corresponding to $1.5 < m_{\gamma'} < 2.9$GeV   29 different γ' mass hypotheses
- Extract the signal through SM photon energy spectrum

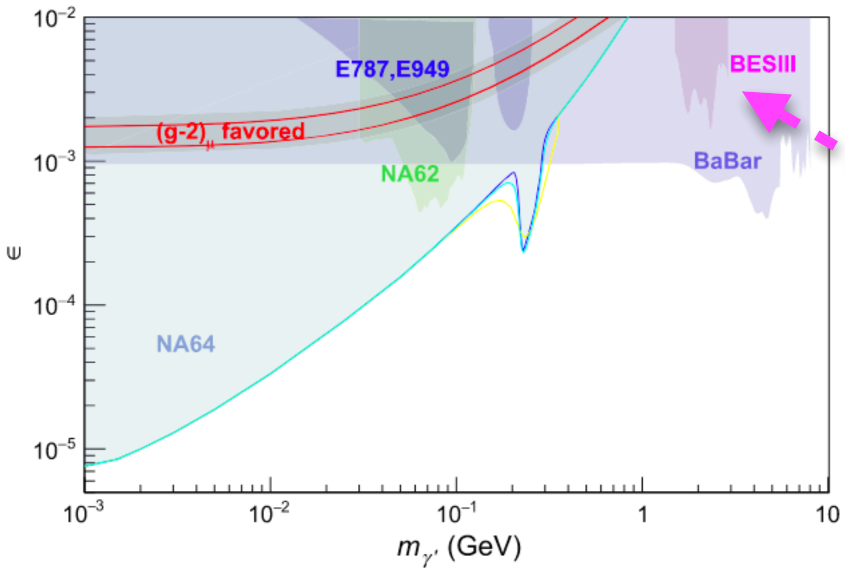


- If $m_\chi < m'_\gamma/2$, $\gamma' \to \chi\chi$
  - Invisible signature

Maximum global significance 2.2σ



Mixing parameter constraint



- ➡ 90% CL upper limits of ε are (1.6 - 5.7) $\times 10^{-3}$ in the GeV mass region,
- ➡ Consistent with what already excluded by BaBar
- ➡ More competitive results with 20 fb^{-1} data taken at 3.773 GeV can be provided in the future.

Muonphilic scalar X_0 or vector X_1

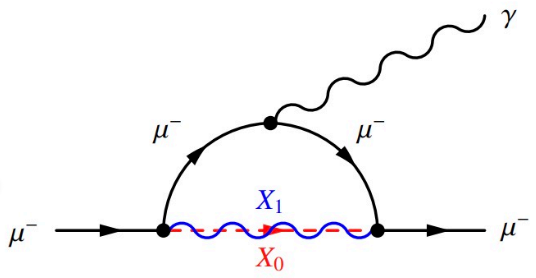
JHEP10(2020)207
Mod. Phys. Lett. A 06, 527 (1991).
PRD 43, R22 (1991)

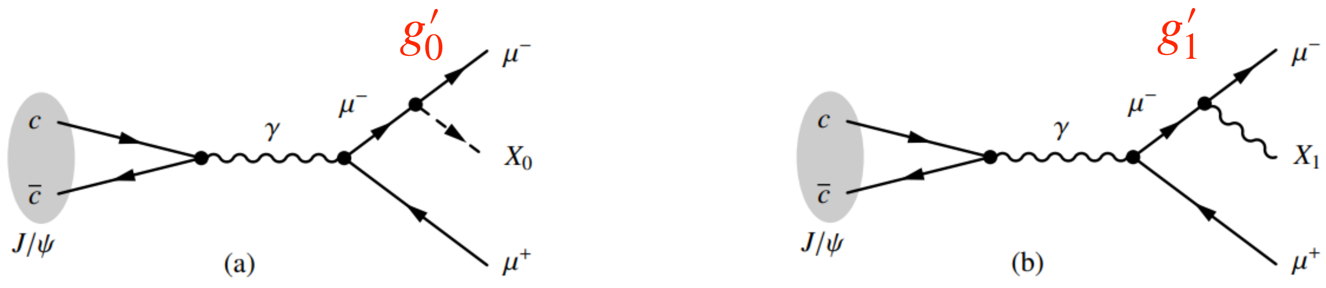
➡ Similar to the previous dark photon, an extra $U(1)$ group is added as a minimal extension to the SM

- $U(1)_{L_\mu - L_\tau}$ model : a new massive vector boson X_1 or scalar boson X_0 **only couple to the second or third generations of leptons** $(\mu, \nu_\mu, \tau, \nu_\tau)$ with the coupling strength g_1', g_0'
- The light muonphilic scalar or vector particles can contribute to the muon anomalous magnetic moment and explain the $(g-2)_\mu$ anomaly

Eur. Phys. J. C 81, 861 (2021).

$$\mathcal{L}_\mu^{\text{scalar}} = -g_0 \, X_0 \, \overline{\mu} \, \mu,$$
$$\mathcal{L}_\mu^{\text{vector}} = -g_1 \, X_{1\alpha} \, \overline{\mu} \, \gamma^\alpha \, \mu.$$

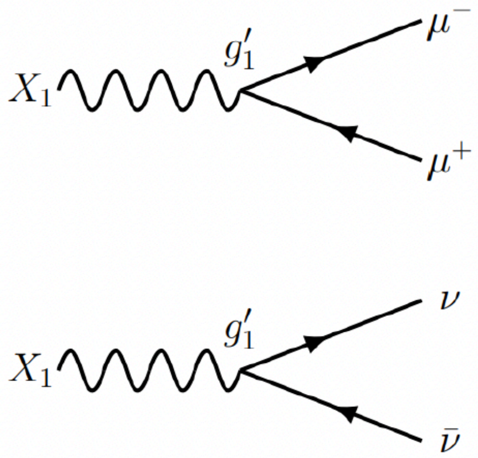




Can be accessible via $J/\psi \to \mu^+\mu^- X_{0,1}$ with $X_{0,1}$ invisible at BESIII

Three cases of muonphilic particles

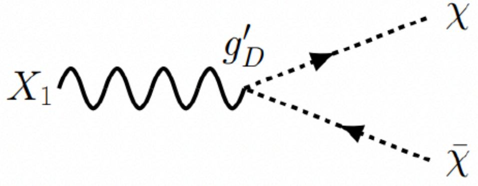
"vanilla" $L_\mu - L_\tau$ model



X_1 **only couples with SM particles**

- $\mathscr{B}(X_1 \to \nu\bar{\nu}) = 33 \sim 100\,\%$

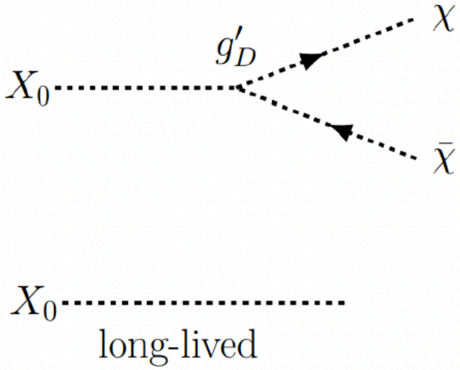
"invisible" $L_\mu - L_\tau$ model



X_1 **couples with DM particle χ with coupling $g_{D'}$**

- $m_\chi < m_{X_1}/2$
- $g_{D'} \gg g_{1'}$
- $\mathscr{B}(X_1 \to \chi\chi) \sim 100\,\%$

"scalar" $U(1)$ model



- Assume the X_0 is long lived or only decay to invisible final states

Search for X_0, X_1 via $J/\psi \to \mu^+\mu^- X_{0,1}$ with $X_{0,1}$ is invisible

Search for a muonphilic scalar X_0 or vector X_1 via $J/\psi \to \mu^+\mu^-+$ invisible decays

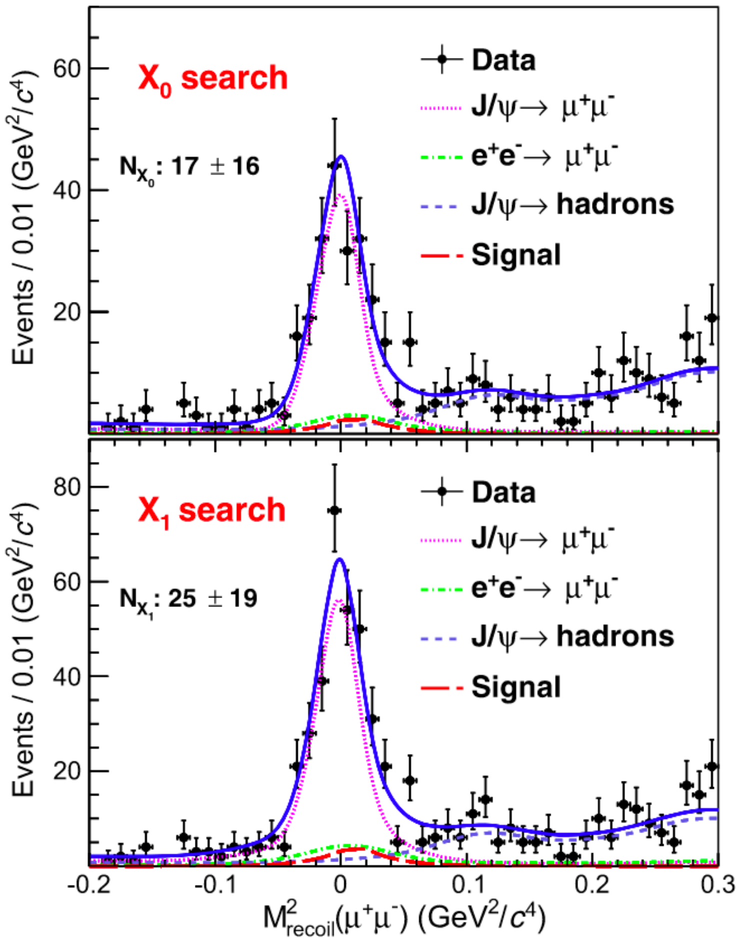
PRD 109, L031102 (2024)

- Data samples: **9B** J/ψ events
- Signal extraction**:** A series of unbinned maximum likelihood fits are performed to $M^2_{\rm recoil}(\mu^+\mu^-)$ or $M_{\rm recoil}(\mu^+\mu^-)$

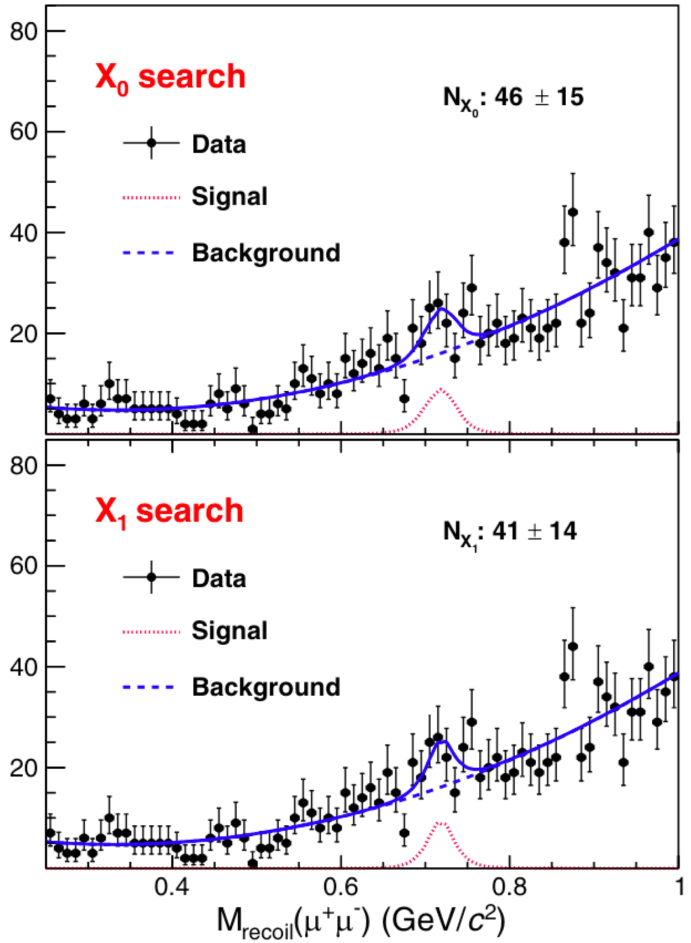
$$M^2_{recoil}(\mu^+\mu^-) = (p_J - p_{\mu^+} - p_{\mu^-})^2$$

- The maximum local significance is 2.5σ at $M(X_{0,1}) = 720$ MeV$/c^2$
- **No evidence** for $J/\psi \to \mu^+\mu^-+X_{0,1}$ signals

Low mass region, with $M(X_{0,1}) = 120\text{MeV}/c^2$



High mass region, with $M(X_{0,1}) = 720\text{MeV}/c^2$



Search for a muonphilic scalar X_0 or vector X_1 via $J/\psi \to \mu^+\mu^- +$ invisible decays

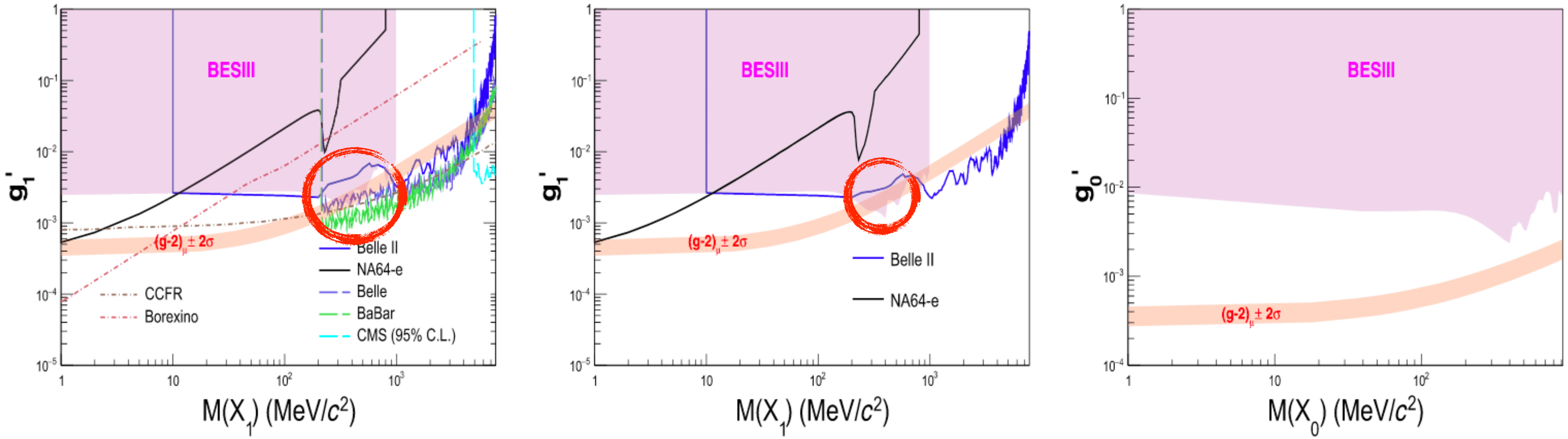
- **Constraints on the coupling $g'_{0,1}$**

BarBar, CMS, Belle : $X_1 \to \mu^+\mu^-$
Belle and BESIII: $X_1 \to \nu\bar{\nu}$

Better sensitivity in the range 200–860 MeV/c^2 is obtained

First constraint for the "scalar" invisible X_0 case

"vanilla" $L_\mu - L_\tau$ model | "invisible" $L_\mu - L_\tau$ model | "scalar" $U(1)$ model



Summary

➡BESIII plays an active role in dark sector and axion-like particle search, with many first searches or best limits

Axion-like particles (ALPs) search

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

✓ Using 2.7B $\psi(3686)$ data PLB 838 137698 (2023)

✓ Using 10B J/ψ data Accepted by PRD(L)

→ **Most stringent limits** on $g_{a\gamma\gamma}$ for $0.165 < m_a < 2.85$ GeV$/c^2$

Dark sector search

✓Search for a **muonphilic** scalar X_0 or vector X_1 via $J/\psi \to \mu^+\mu^- +$ invisible PRD 109, L031102 (2024)

→ Stringent limits on the **coupling** $g'_{0,1}$ are set

✓Search for Massive **dark photon** with $e^+e^- \to \gamma\gamma'$ PLB 839 (2023) 137785

Future

- BESIII has recently collected 20 fb^{-1} of $\psi(3770)$ data sample
  - ➡More conclusive results are ongoing!

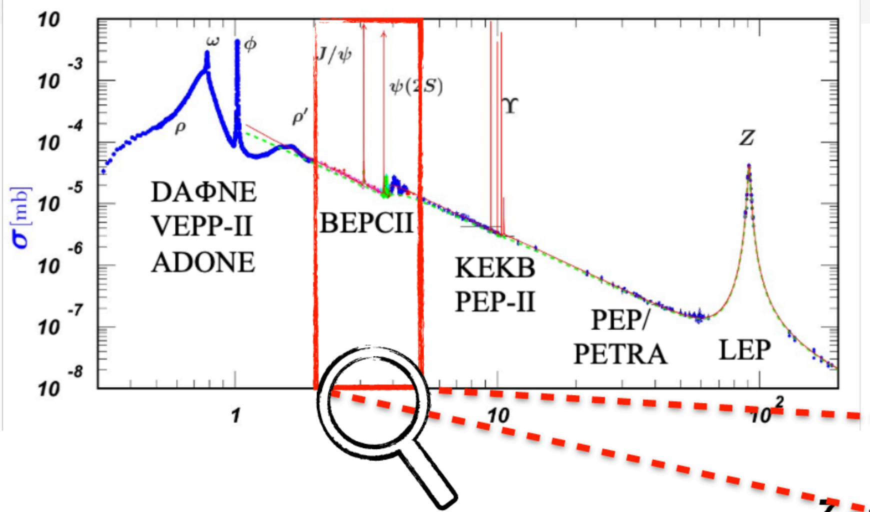
Enlightening the dark,

coming is the future!

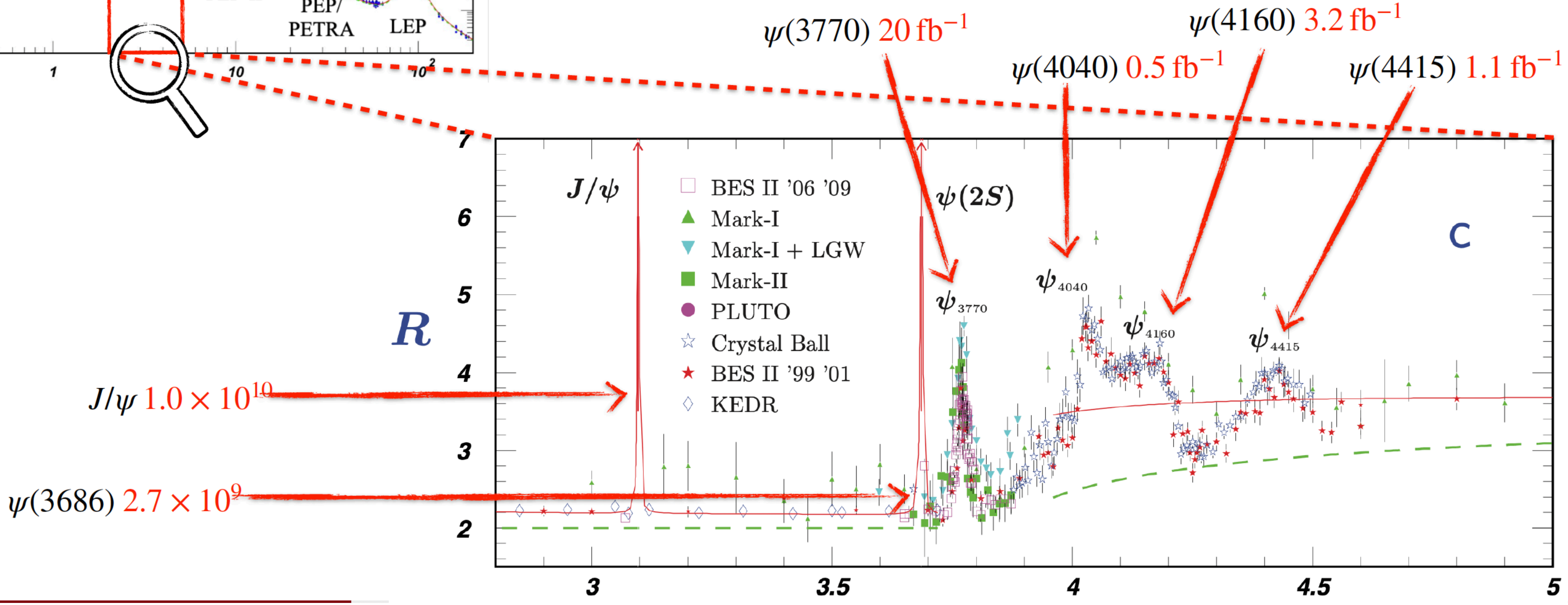
Thanks for your attention!

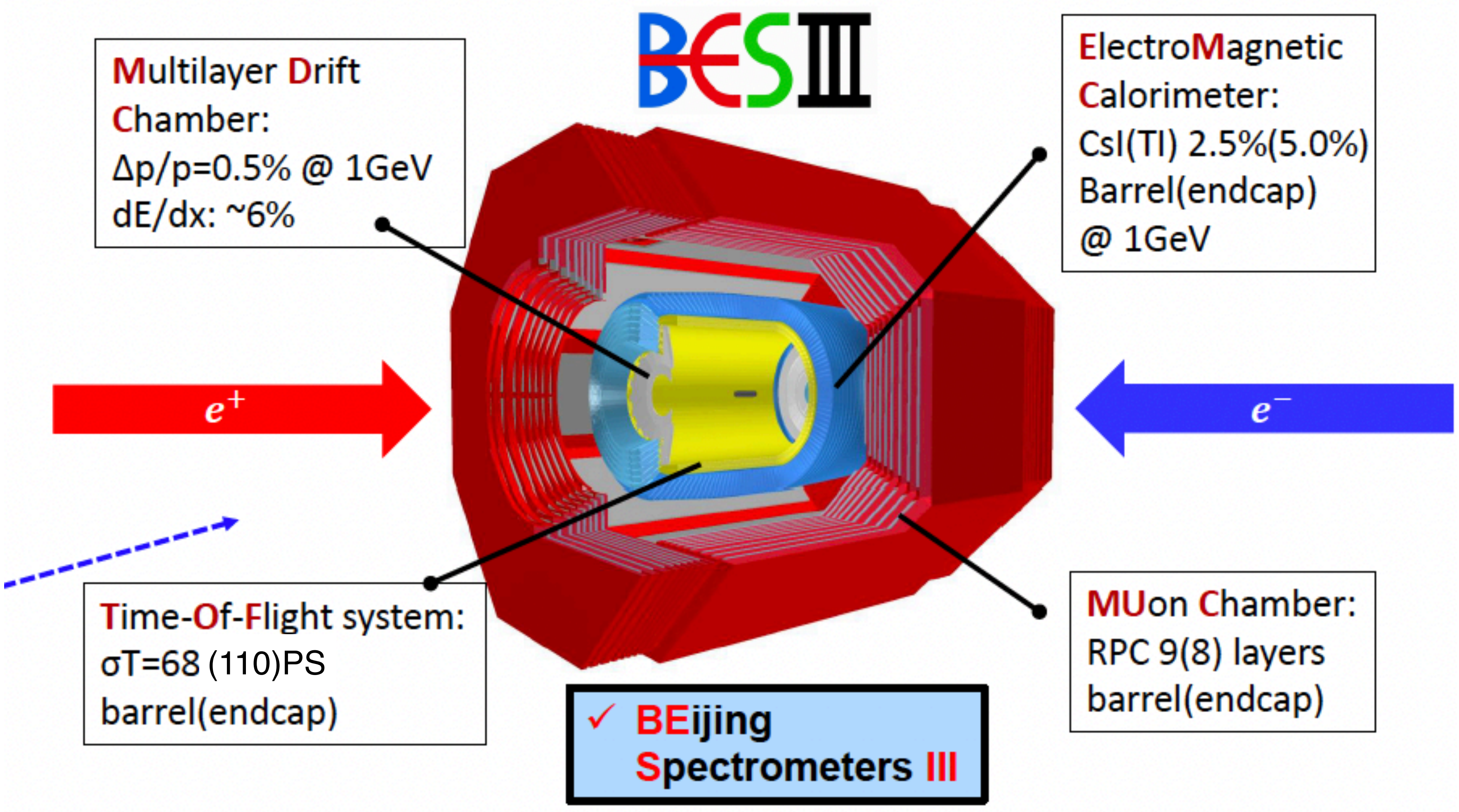
Back UP

Data samples at BESIII



- BESIII has collected the largest data samples of J/ψ and $\psi(3686)$ on the threshold in the world!
- $> 20\ \mathrm{fb}^{-1}$ data above 4.0 GeV in total

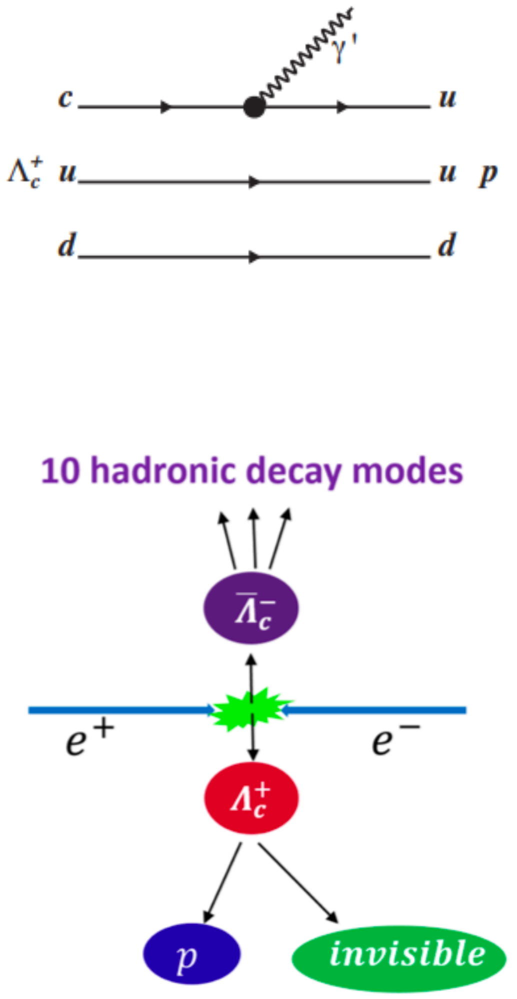


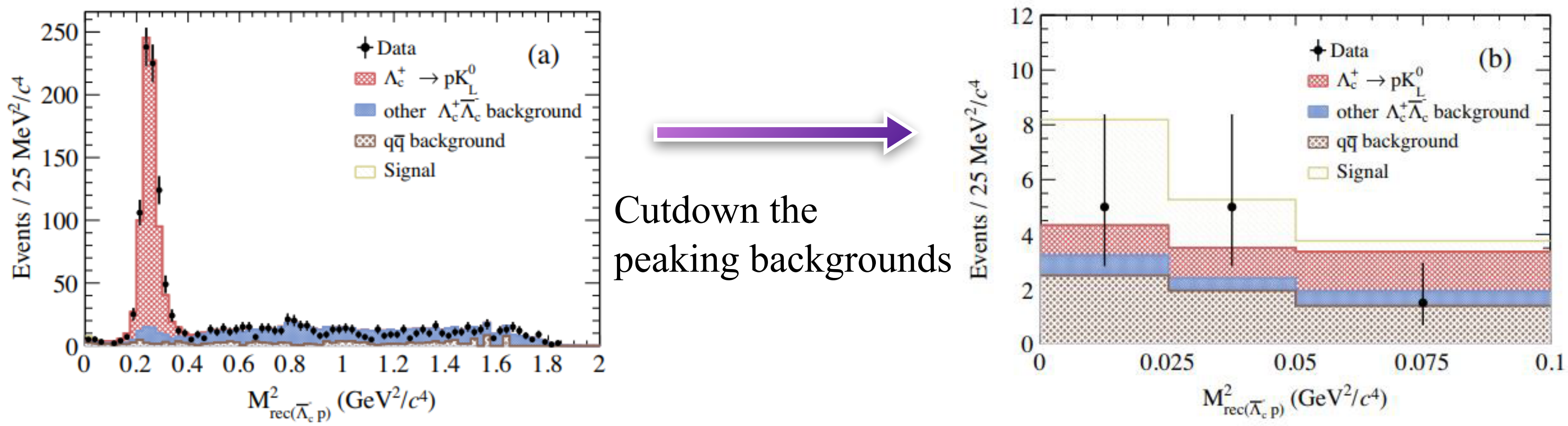

BESIII
Multilayer Drift Chamber:
Δp/p=0.5% @ 1GeV
dE/dx: ~6%
ElectroMagnetic Calorimeter:
CsI(Tl) 2.5%(5.0%) Barrel(endcap) @ 1GeV
e+
e−
Time-Of-Flight system:
σT=68 (110)PS barrel(endcap)
MUon Chamber:
RPC 9(8) layers barrel(endcap)
✓ BEijing Spectrometers III

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

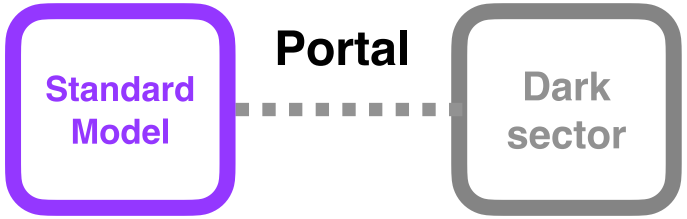
PRD 105, 106, 072008 (2022)

- The FCNC process is highly suppressed by the GIM mechanism in the charm sector
  - ➡ A massless dark photon γ' could induce FCNC process through higher dimensional operators
- **Data samples**: **4.5** fb^{-1} e^+e^- annihilation data at $\sqrt{s} = 4.6 \sim 4.7$ GeV
- **Strategy:** Double-Tag technique
- **Results:**
  - ✓ No signal is observed
  - ✓ 90% C.L. upper limit on BF is set $\mathcal{B}(\Lambda_c^+ \to p\gamma') < 8 \times 10^{-5}$





Motivation on Dark sector



- The dark sector could be light and communicate with the visible sector through a feeble portal interaction
- The dark sector models can be classified based on the mediator particle or "portal"

$$\mathscr{L} \left(\begin{array}{l} -\frac{\varepsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu} \\ (\mu\phi + \lambda\phi^2) H^\dagger H\,, \\ y_n L H N, \\ \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, \end{array} \right.$$

$-\frac{\varepsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$	Vector portal	**Dark photon γ', kinematic mixing with γ, Z**
$(\mu\phi + \lambda\phi^2) H^\dagger H$,	Higgs portal	
$y_n L H N$,	Neutrino portal	
$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$,	Axion portal	**Axion, coupling to DM**

- Beyond these, certain anomaly gauged $U(1)_{L_\mu - L_\tau}$ model

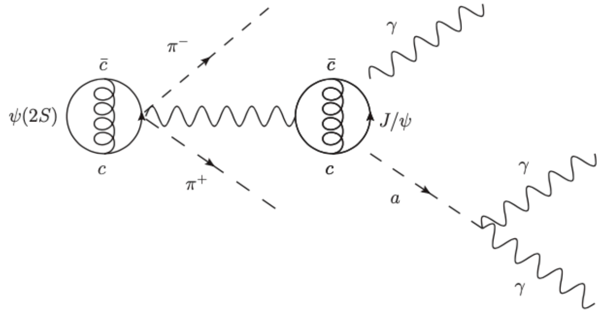
Search for an **axion-like** particle in radiative J/ψ decays

PLB 838 137698 (2023)

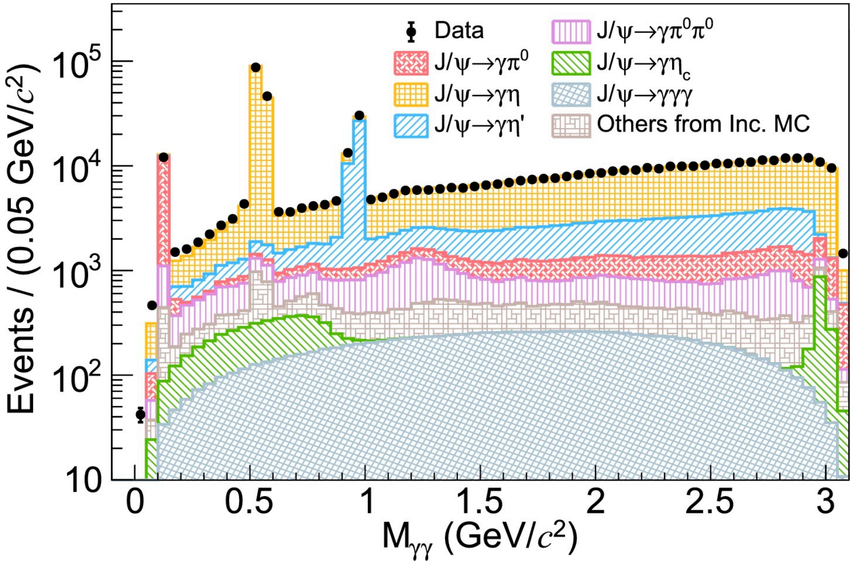
- **Data samples**: 2.7B $\psi(3686)$ events
- **Strategy:**

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 decay width and 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



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



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

PLB 838(2023) 137698

Table 1
The $M_{\gamma\gamma}$ fit intervals for various m_a points.

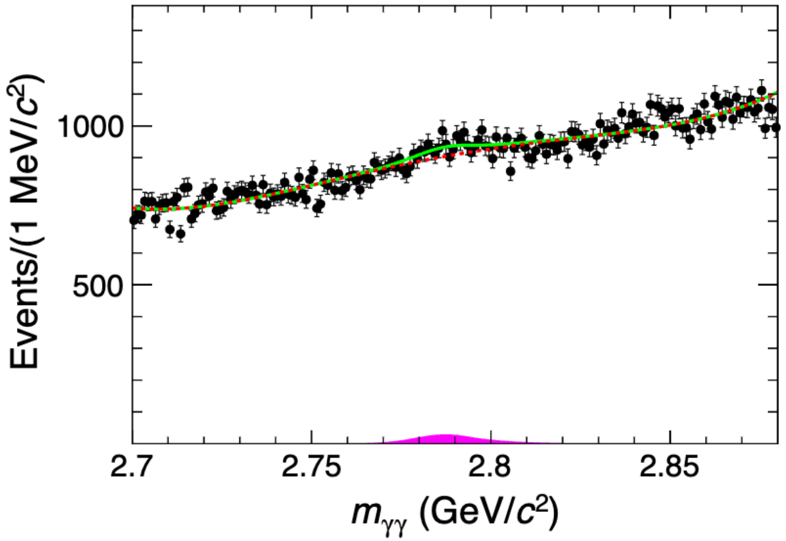
m_a points (GeV/c^2)	$M_{\gamma\gamma}$ fit intervals (GeV/c^2)
0.165 - 0.35	0.06 - 0.45
0.35 - 0.75	0.25 - 0.85
0.75 - 1.20	0.65 - 1.30
1.20 - 2.84	$(m_a - 0.2)$ - $(m_a + 0.2)$

674 hypothesis

arXiv:2404.04640

TABLE I. The fit intervals of $m_{\gamma\gamma}$ for various m_a points.

m_a range (GeV/c^2)	$m_{\gamma\gamma}$ fit interval (GeV/c^2)	Polynomial function order
$0.180 - 0.420$	$0.16, 0.46$	4^{th}
$0.421 - 0.490$	$0.39, 0.51$	5^{th}
$0.610 - 0.880$	$0.59, 0.90$	5^{th}
$1.020 - 1.099$	$1.00, 1.20$	5^{th}
$1.100 - 2.770$	$m_a - 0.10, m_a + 0.10$	3^{rd}
$2.772 - 2.850$	$2.70, 2.88$	4^{th}



The largest value of upward local significance is determined to be 3.5σ at ma = 2.786 GeV/c^2

Search for Massive dark photon with $e^+e^- \to \gamma\gamma'$

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

$\cos\theta_c = 0.6$ is the $cos\theta$ cut for the signal photon polar angle

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

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

- Low $E(\gamma)$ region $\to$ low trigger efficiency & high background level
- High $E(\gamma)$ region $\to$ saturation of the EMC electronics

Search for a muonphilic scalar X_0 or vector X_1 via $J/\psi \to \mu^+\mu^- +$ invisible decays

Decay width

$$
\begin{aligned}
|\mathcal{M}_{\mu\mu X_0}|^2 = &\left(\frac{2}{3}e^2 g_0 \frac{f_J}{m_J}\right)^2 \frac{-8}{3\, m_J^2 (m_J - 2\, E_-)^2 (-2\, E_- - 2\, E_X + m_J)^2} \Big(-4\, m_\mu^2 \Big(4\, E_-^2 \left(m_X^2 - 2\, E_X\, m_J\right) \\
&+ E_- \left(-8\, E_X^2\, m_J + 4\, E_X \left(m_X^2 + 2\, m_J^2\right) - 4\, m_X^2\, m_J\right) - E_X^2 \left(m_X^2 - 6\, m_J^2\right) - 2\, E_X\, m_J \left(m_X^2 + m_J^2\right) + m_X^2 m_J^2\Big) \\
&+ 4\, E_-^2 \Big(2\, E_X^2\, m_J^2 + m_X^2\, m_J (m_J - 2\, E_X) + m_X^4\Big) \\
&+ 4\, E_- \Big(2\, E_X^3\, m_J^2 - 2\, E_X^2\, m_J \left(m_X^2 + m_J^2\right) + E_X \left(m_X^4 + 3\, m_X^2\, m_J^2\right) - m_X^2\, m_J \left(m_X^2 + m_J^2\right)\Big) \\
&- 16\, E_X^2\, m_\mu^4 + m_J \Big(-4\, E_X^3\, m_J^2 + 2\, E_X^2 \left(3\, m_X^2\, m_J + m_J^3\right) - 2\, E_X \left(m_X^4 + 2\, m_X^2\, m_J^2\right) + m_X^2\, m_J \left(m_X^2 + m_J^2\right)\Big)\Big),
\end{aligned}
$$

where E_-, the energy of μ^- and E_X, the energy of X_0 are measured in the rest frame of J/ψ.

$$
\Gamma_{\mu\mu X_{0,1}} = \int_{E_X^{min}}^{E_X^{max}} \int_{E_-^{min}}^{E_-^{max}} \frac{|\mathcal{M}_{\mu\mu X_{0,1}}|^2}{64\pi^3 m_J} dE_- dE_X,
$$

$$
\begin{aligned}
|\mathcal{M}_{\mu\mu X_1}|^2 = &\left(\frac{2}{3}e^2 g_1 \frac{f_J}{m_J}\right)^2 \frac{-16}{3\, m_J^2 (m_J - 2\, E_-)^2 (-2\, E_- - 2\, E_X + m_J)^2} \Big(16\, E_-^4\, m_J^2 + 32\, E_-^3\, m_J^2 (E_X - m_J) \\
&+ 2 m_\mu^2 \Big(4\, E_-^2 \left(m_J (m_J - 2\, E_X) + m_X^2\right) - 4\, E_- \left(2\, E_X^2\, m_J - E_X \left(m_X^2 + 3\, m_J^2\right) + m_J \left(m_X^2 + m_J^2\right)\right) \\
&+ 2\, E_X^2 \left(m_X^2 + 3\, m_J^2\right) - 2\, E_X\, m_J \left(m_X^2 + 2\, m_J^2\right) + m_J^2 \left(m_X^2 + m_J^2\right)\Big) \\
&+ 4\, E_-^2 \left(m_J^2 \left(6\, E_X^2 - 14\, E_X\, m_J + 7\, m_J^2\right) + m_X^2\, m_J (3\, m_J - 2\, E_X) + m_X^4\right) \\
&+ 4\, E_- \left(2\, E_X^3\, m_J^2 - 2\, E_X^2\, m_J \left(m_X^2 + 4\, m_J^2\right) + E_X \left(m_X^4 + 5\, m_X^2\, m_J^2 + 9\, m_J^4\right) - m_J \left(m_X^4 + 3\, m_X^2\, m_J^2 + 3\, m_J^4\right)\right) \\
&+ 8\, E_X^2\, m_\mu^4 + m_J \left(-4\, E_X^3\, m_J^2 + 2\, E_X^2 \left(3\, m_X^2\, m_J + 5\, m_J^3\right) - 2\, E_X \left(m_X^2 + 2\, m_J^2\right)^2 + m_J \left(m_X^4 + 3\, m_X^2\, m_J^2 + 2\, m_J^4\right)\right)\Big),
\end{aligned}
$$

where E_-, the energy of μ^- and E_X, the energy of X_0 are measured in the rest frame of J/ψ.