Search for exotic physics at BESIII

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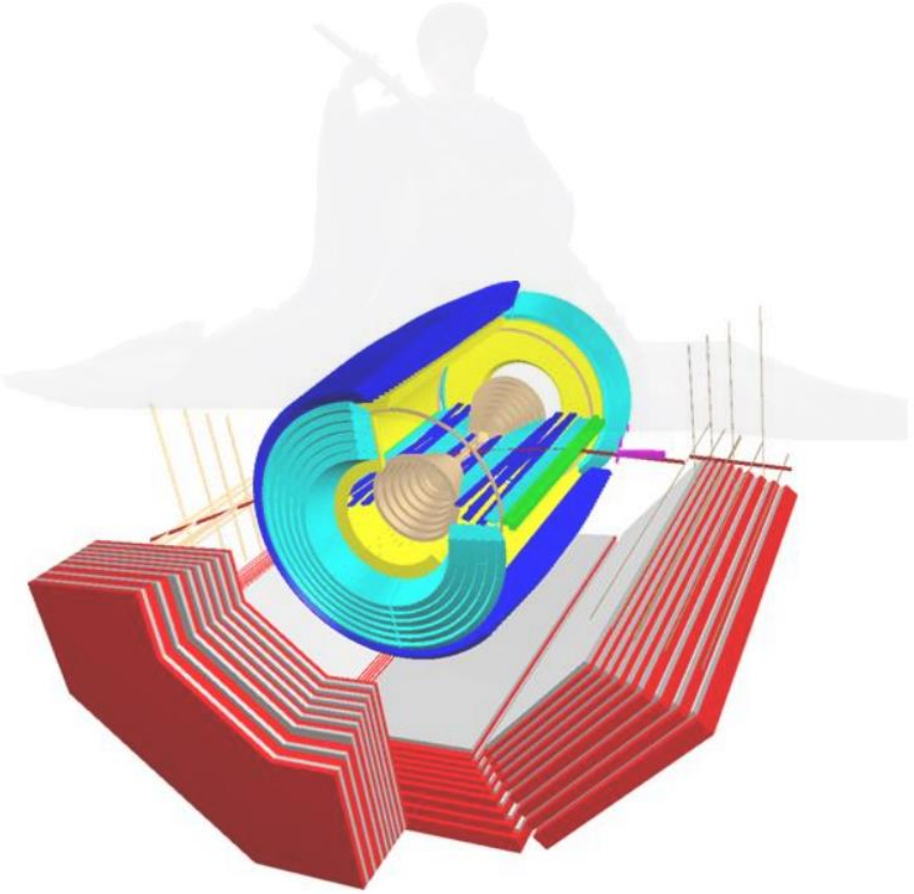
OUTLINE

- **Introduction**
- Search for the dark photon γ'
- Search for muonphilic particles $X_{0,1}$
- Search for axion particle a
- Study for glueball
- Summary



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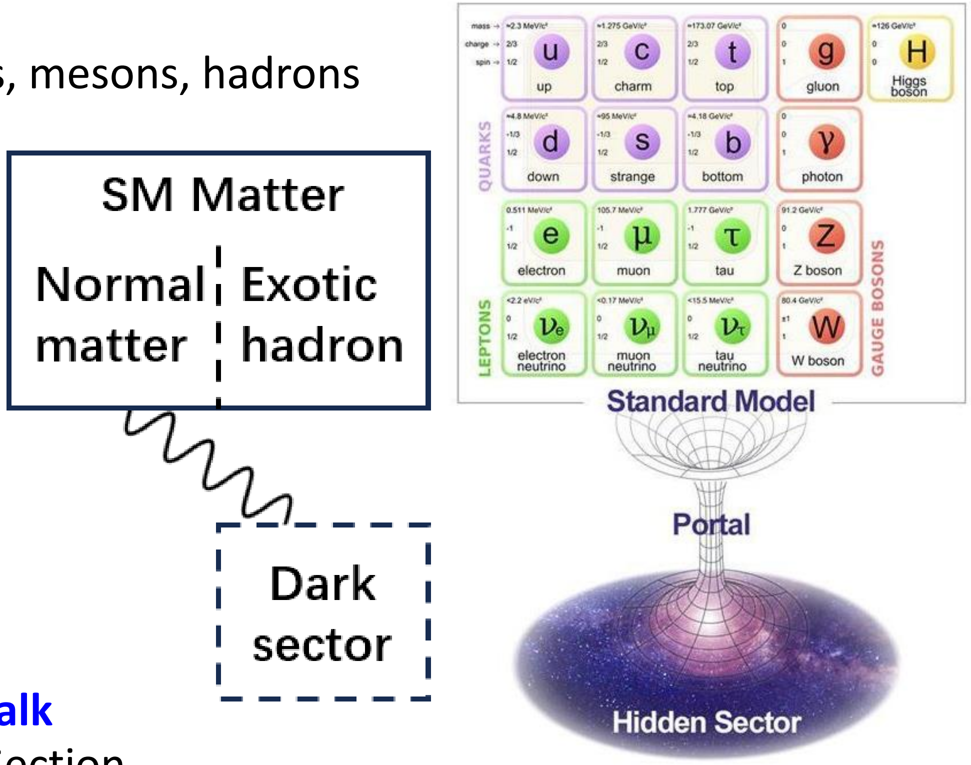
Exotic particles

- Particles in Standard model: leptons, photon, Z, $W^{\pm}$, Higgs, quarks, mesons, hadrons



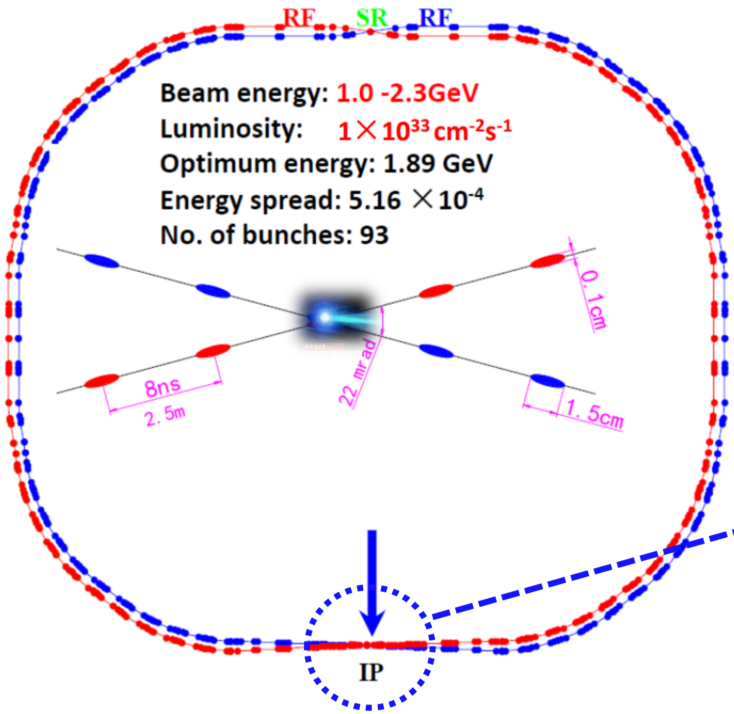
- **Exotic "dark" particles:**
  - **Dark photon**: massive or massless
  - **Muonphilic vector or scalar**
  - **Axion**: QCD axion and axion like particles
  - SUSY, dark Higgs, heavy neutrinos, dark fermion …

The main of this talk

- **Exotic hadrons:**
  - **Glueball** : composed of gluons → **Also included in this talk**
  - Multi-quark : quark number ≥ 4, eg Z_{cs}, Hang Zhou's talk at QCD Section
  - Hybrid : the mixture of quark and gluon, eg $\eta_1(1855)$, PRL 129, 192002 (2022), Moriond QCD2022
  - Other: eg. $X(2085)$, PRL 131 (2023) 15, 151901, $X(3872)$, PRL 130 (2023) 15, 151904, Moriond QCD2023

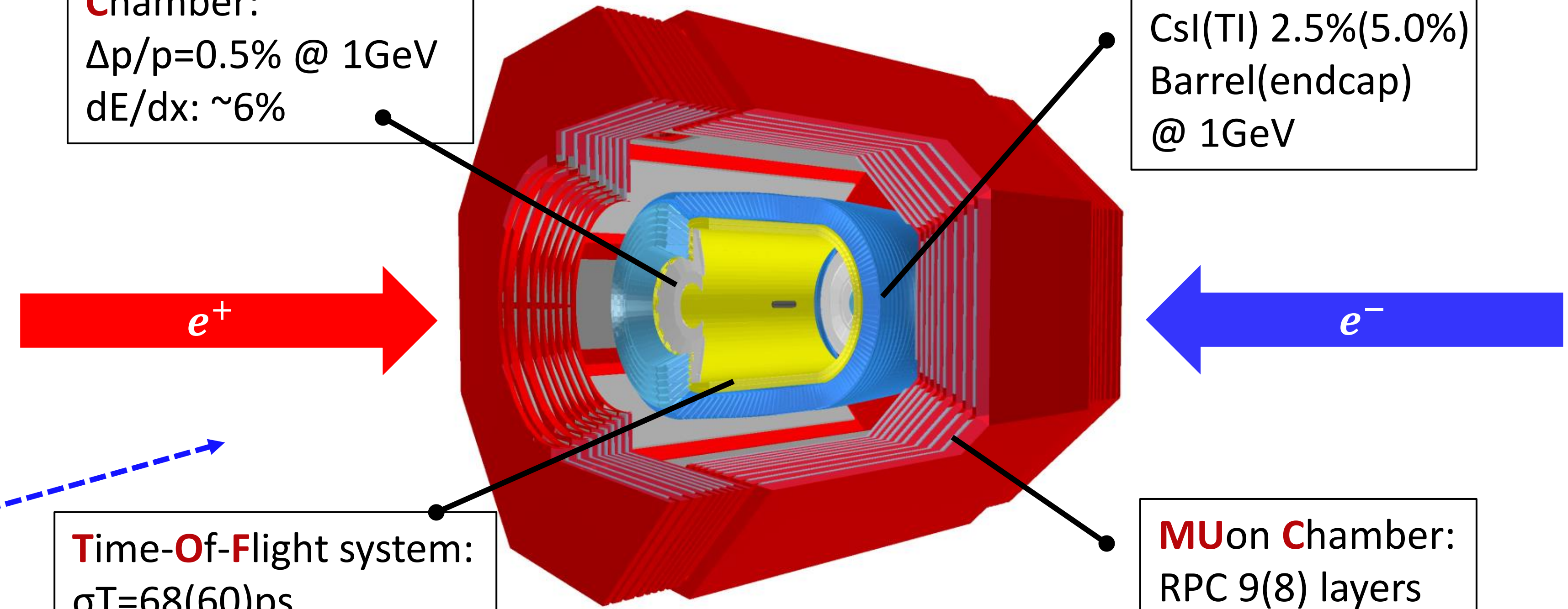
If their mass are in the **MeV-GeV range**, these exotic particles can be accessible by high intensity e^+e^- collider experiments, such as **BEPCII and BESIII** experiment.

BEPCII and BESIII



✓ **Beijing Electron Positron Collider II**

Multilayer Drift Chamber:
Δp/p=0.5% @ 1GeV
dE/dx: ~6%



ElectroMagnetic Calorimeter:
CsI(TI) 2.5%(5.0%)
Barrel(endcap)
@ 1GeV

Time-Of-Flight system:
σT=68(60)ps
barrel(endcap)

✓ **BEijing Spectrometers III**

MUon Chamber:
RPC 9(8) layers
barrel(endcap)

BESIII has collected large data samples in $\tau - c$ energy region which can benefit the search for the hidden exotic physics

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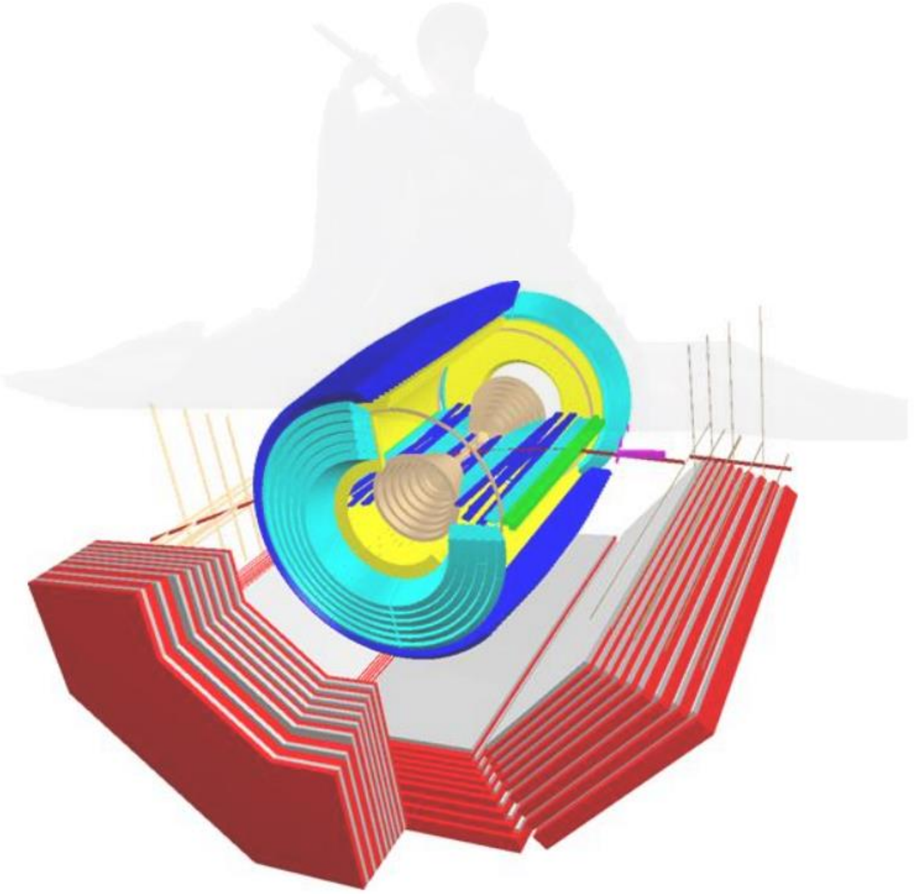
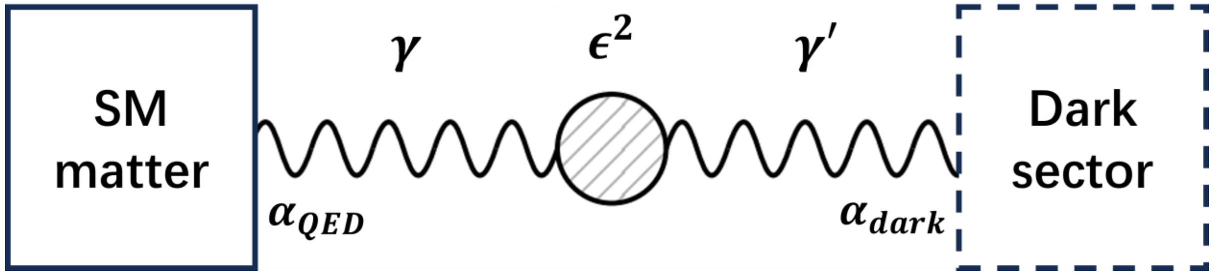


Massive dark photon

- ☐ **An extra Abelian gauge group, $U(1)_D$**
- ✓ Causing the associated gauge boson, the dark photon
- ✓ Symmetry broken spontaneously, **massive kind**



- ✓ Dark photon has a **kinetic mixing** with SM photon ($\frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu}$)
- ϵ: mixing parameter (very small!) PLB, 196 (1986)
- Effective coupling
- The interaction terms between dark photon and the SM matter

$$\mathcal{L} = \frac{e\epsilon}{\sqrt{1-\epsilon^2}} J_\mu A'^\mu$$ arXiv:2005.01515

- **Effective coupling strength with the SM matter: $e\epsilon$**

✓ **Dark photon with mass can be produced in any process by replacing SM photon**

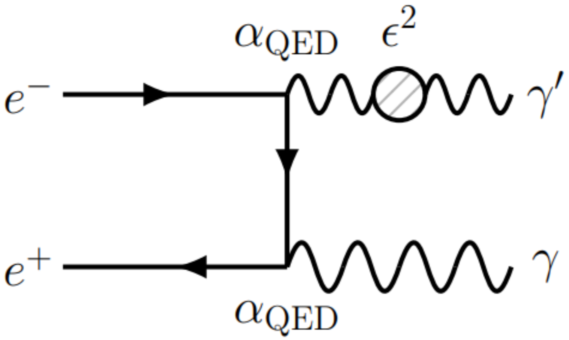
☐ Candidate channels:

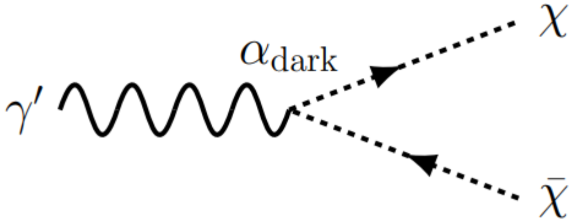
- $e^+e^- \to \gamma\gamma', \gamma' \to \text{invisible}$ **(this talk)**
  PLB 839, 137785 (2023)
- $e^+e^- \to \gamma\gamma', \gamma' \to l^+l^-$
  PLB 774, 252(2017)
- $J/\psi \to \eta\gamma', \gamma' \to e^+e^-$
  PRD 99, 012006 (2019)
- $J/\psi \to \eta'\gamma', \gamma' \to e^+e^-$
  PRD 99, 012013 (2019)

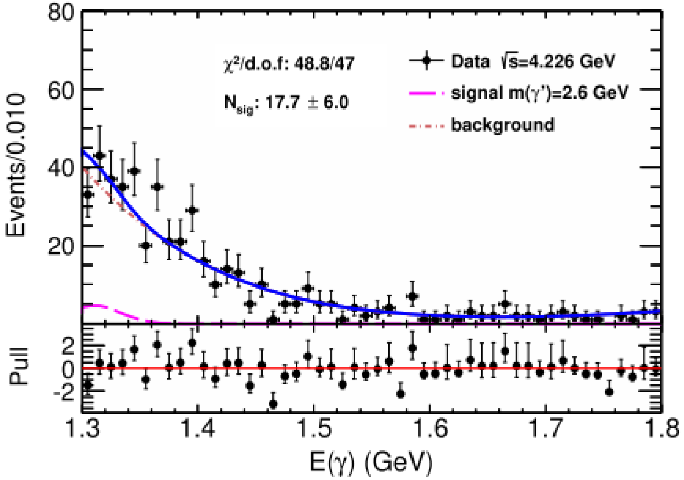
Search for Massive dark photon with $e^+e^- \to \gamma\gamma'$

- The dark photon (γ') would predominately decay into a pair of DM particles $\gamma' \to \chi\bar{\chi}$ **if $m_\chi < m_{\gamma'}/2$**
- Search for the massive dark photon with $e^+e^- \to \gamma\gamma'$, followed by an **invisible decay of the γ'**
- Data sample: $14.9\ fb^{-1}$ e^+e^- annihilation data at $\sqrt{s} = 4.13\sim4.60\ GeV$

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

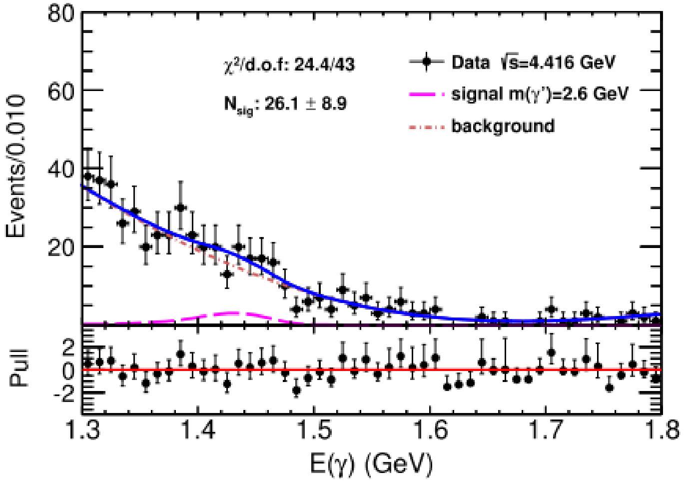






$\sqrt{s} = 4.226\ GeV$
$m_{\gamma'} = 2.6\ GeV$

SM photon energy spectrum



$\sqrt{s} = 4.416\ GeV$
$m_{\gamma'} = 2.6\ GeV$

PLB 839, 137785 (2023)

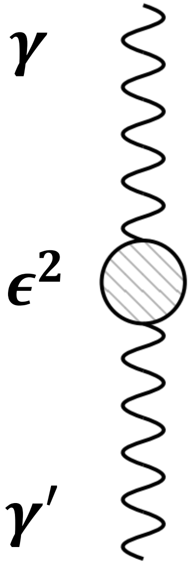
Maximum global significance: 2.2σ, no significant signals

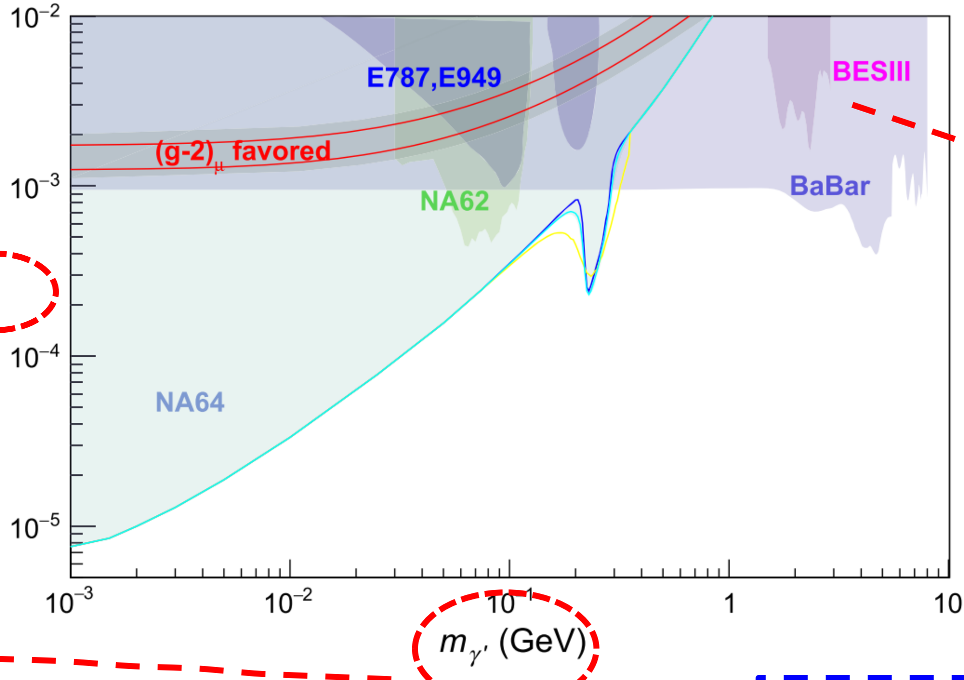
Mixing parameter constraint

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

PRD 80, 015003 (2009)

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





- The 90% CL upper limit of the mixing parameter ϵ are $(\mathbf{1.6-5.7})\times\mathbf{10^{-3}}$ **in the GeV mass region**
- The exclusion limits are consistent with what already excluded by BaBar
- BESIII will produce more competitive results with 20 fb^{-1} data taken at 3.773 GeV

Massive kind of the dark photon

PLB 839, 137785 (2023)

Search for Massless dark photon with $\Lambda_c \to p\gamma'$

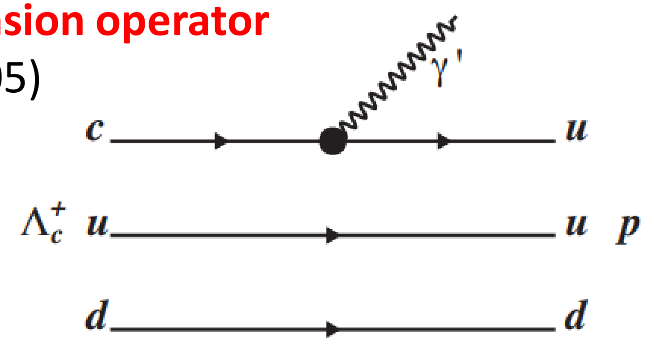
- If the symmetry of the extra Abelian gauge group is unbroken, the dark photon will be **massless**
- The massless dark photon has no direct interaction with the SM particle
- But the massless dark photon can be coupled with the SM particle in **higher dimension operator**

PRL 94, 151802 (2005)

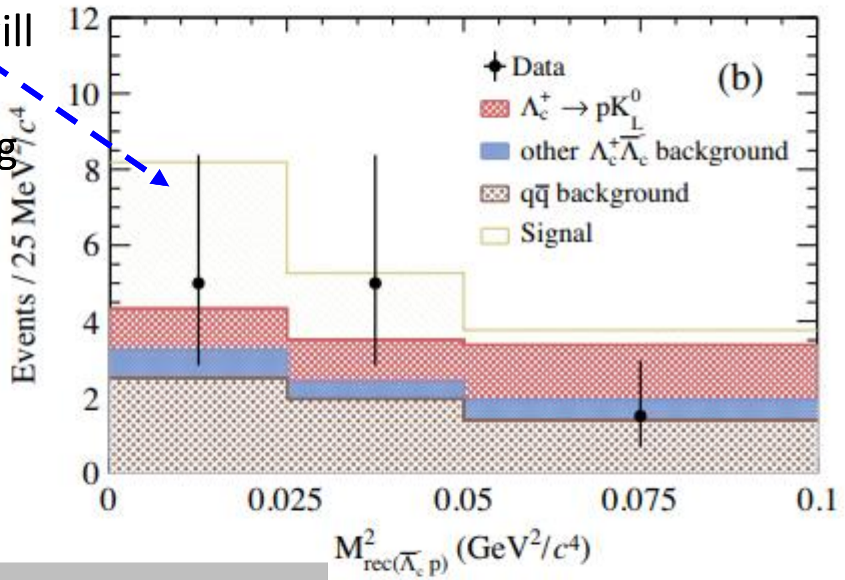
$$\mathcal{L}_{NP} = \frac{1}{\Lambda_{NP}^2}\left(C_{jk}^u \bar{q}_j \sigma^{\mu\nu} u_k \widetilde{H} + C_{jk}^d \bar{q}_j \sigma^{\mu\nu} d_k H + C_{jk}^e \bar{l}_j \sigma^{\mu\nu} e_k H + h.c.\right) \bar{F}_{\mu\nu}$$

New physics energy scale

Up type quarks coupling — Down type quarks coupling — Charged leptons coupling



Signals will have a exceeding peak around zero



PRD 106, 072008 (2022)

- Data samples: 4.5 fb^{-1} e^+e^- annihilation data at $\sqrt{s} = 4.6\sim4.7$ GeV
- No significant signal observed, $\mathcal{B}(\boldsymbol{\Lambda_c^+ \to p\gamma'}) < 8.0 \times 10^{-5}$ at 90% CL

- New physics energy scale associated with $cu\gamma'$ coupling:

$$|\mathbb{C}|^2 + |\mathbb{C}_5|^2 < \mathbf{9.6 \times 10^{-16}\ GeV^{-2}}$$

$\mathbb{C} = \Lambda_{NP}^{-2}(C_{12}^u + C_{12}^{u*})v/\sqrt{8}$, $\mathbb{C}_5 = \Lambda_{NP}^{-2}(C_{12}^u + C_{12}^{u*})v/\sqrt{8}$
related to the new physics energy scale

BESIII will produce better results with 20 fb^{-1} data taken at 3.773 GeV, such as $D \to \omega\gamma'$ and $D \to \gamma\gamma'$ with $cu\gamma'$ coupling

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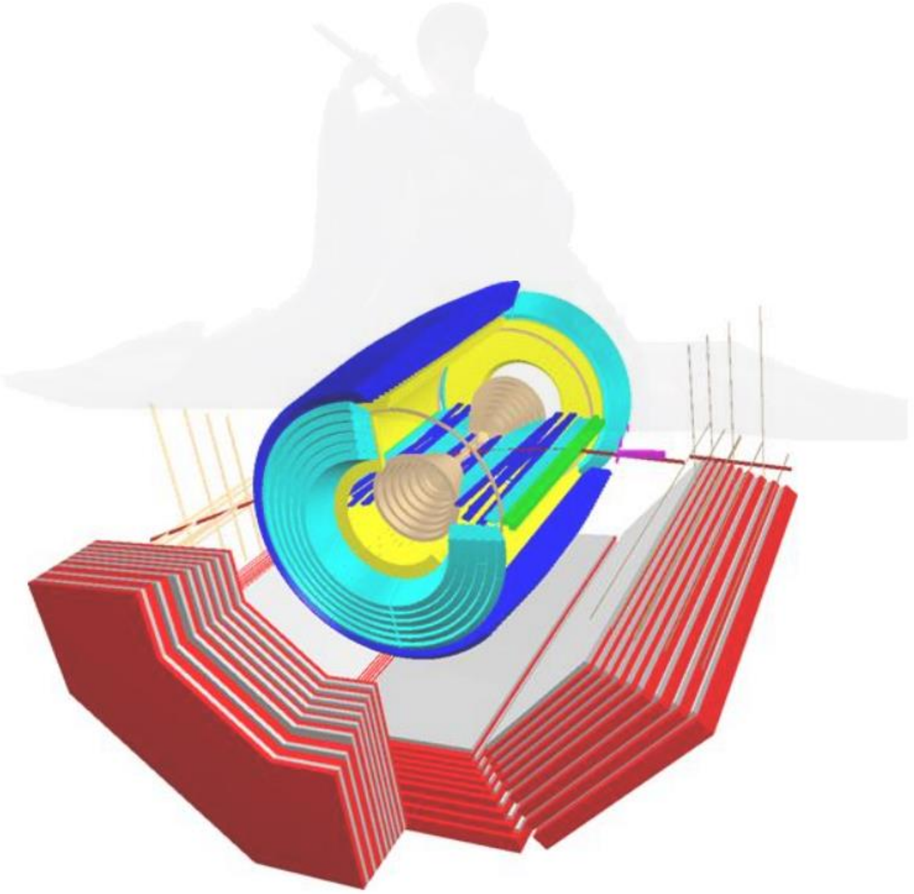


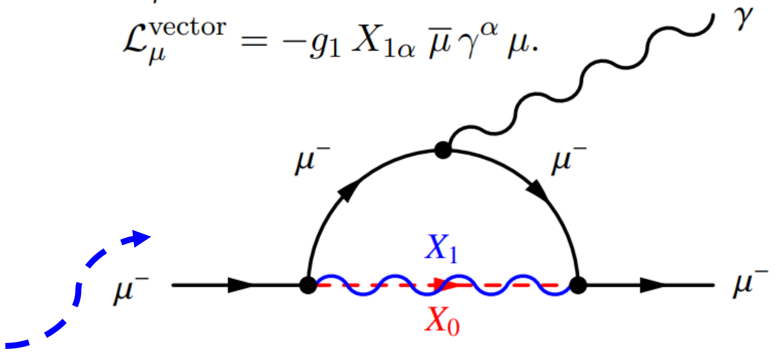
Muonphilic scalar or vector particle $X_{0,1}$

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

- $\boldsymbol{U(1)_{L\mu-L\tau}}$ **model**: A new massive scalar boson $\boldsymbol{X_0}$ or vector boson $\boldsymbol{X_1}$ **only couples to the second and third generations** of leptons $(\mu, \nu_\mu, \tau, \nu_\tau)$ with the **coupling strength** $\boldsymbol{g'_{0,1}}$

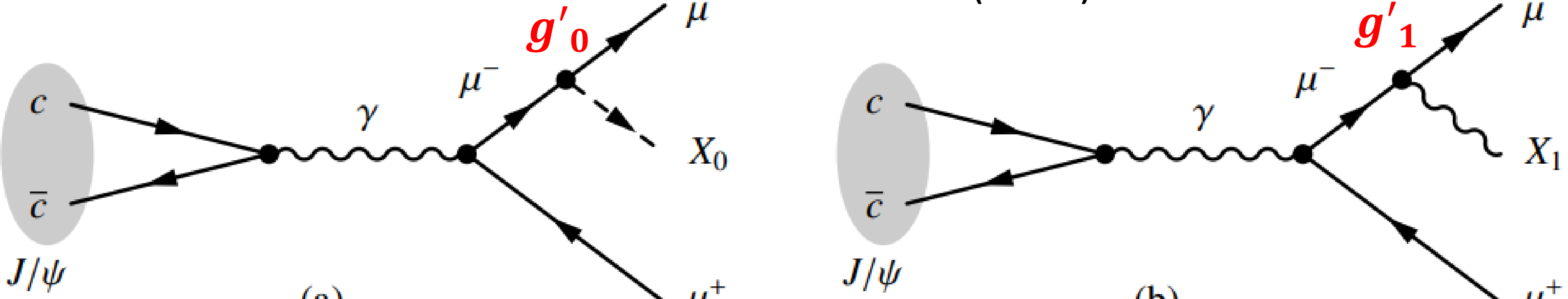
- The light muonphilic scalar or vector particles can contribute to the muon anomalous magnetic moment and **explain the** $\boldsymbol{(g-2)_\mu}$ **anomaly**

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



JHEP10(2020)207

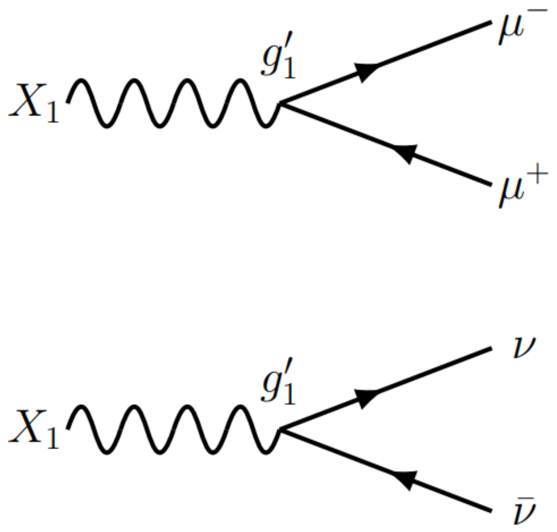
> ➢ **Can be accessible via $J/\psi \to \mu^+\mu^- X_{0,1}$ at BESIII**



(a) (b)

Three cases of muonphilic particles

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

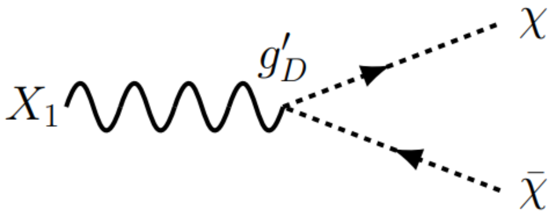


- Large mass of dark matter kind:

$$m_\chi > m_{X_1}/2$$

- $\mathcal{B}(X_1 \to \upsilon\bar{\upsilon}) = 33\% - 100\%$ with different m_{X_1}

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

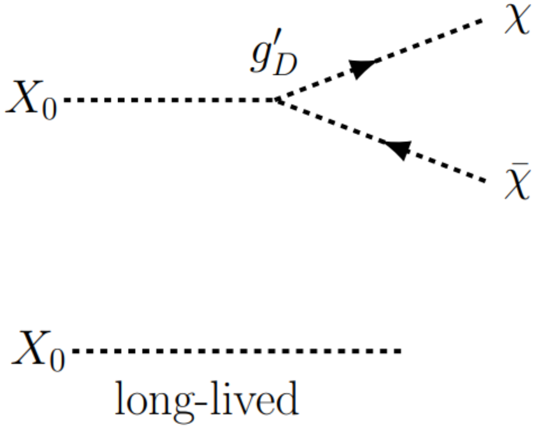


- Light dark matter kind:

$$m_\chi < m_{X_1}/2$$

- $g'_D \gg g'_1$
- $\mathcal{B}(X_1 \to \chi\bar{\chi})\sim 100\%$

"scalar" $U(1)$ model



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

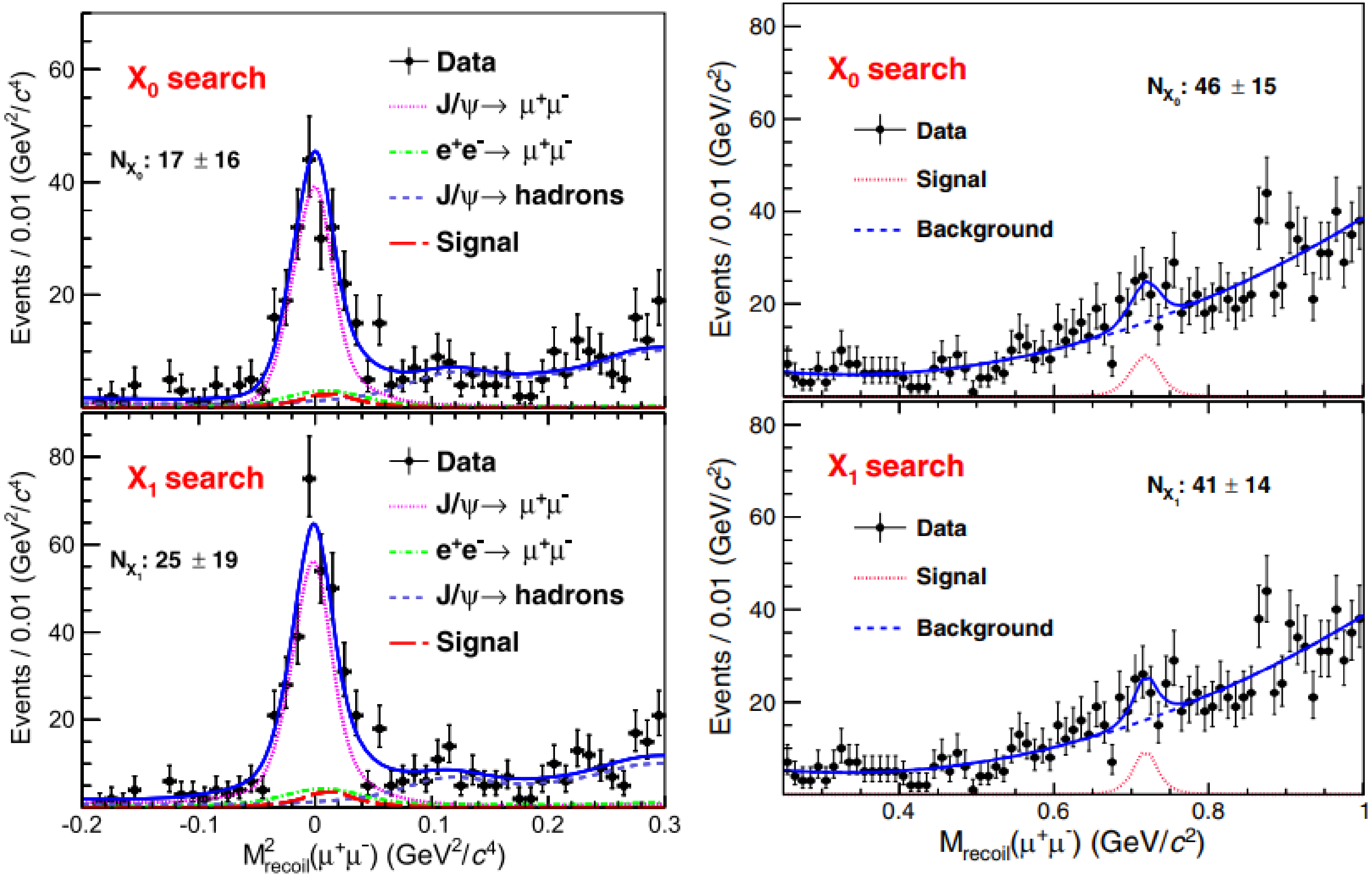
Search for muonphilic scalar X_0 or vector X_1 via $J/\psi \to \mu^+\mu^- X_{0,1}$ with $X_{0,1}$ invisible

Search for muonphilic scalar or vector with $J/\psi \to \mu^+\mu^- X$

- Data samples: $(8.998 \pm 0.039) \times 10^9$ J/ψ events
- $M^2_{recoil}(\mu^+\mu^-) = (p_J - p_{\mu^+} - p_{\mu^-})^2$
- The maximum local significance is 2.5σ at $\mathrm{M}(X_{0,1}) = 720\ MeV/c^2$
- **No evidence** for signals from $X_{0,1}$ invisible decays

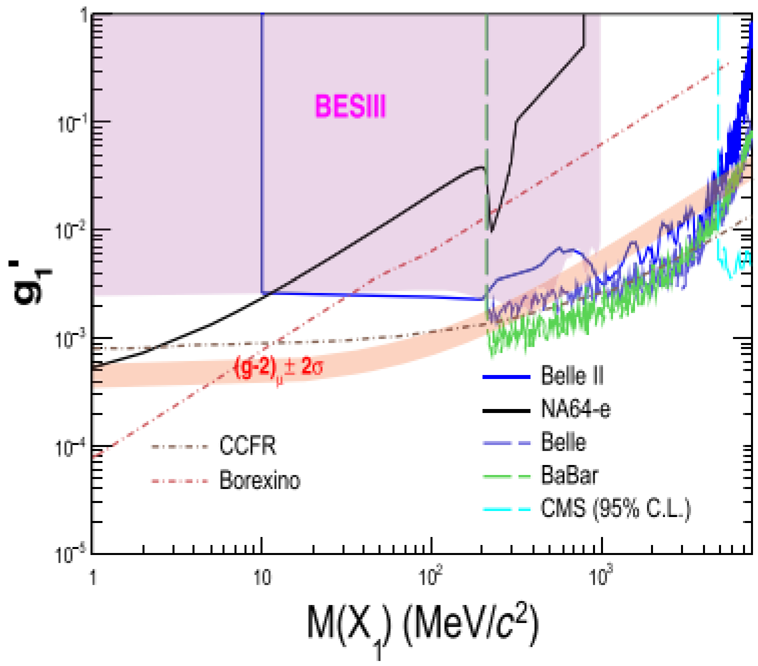
PHYS. REV. D 109, L031102 (2024)

Low mass region | High mass region



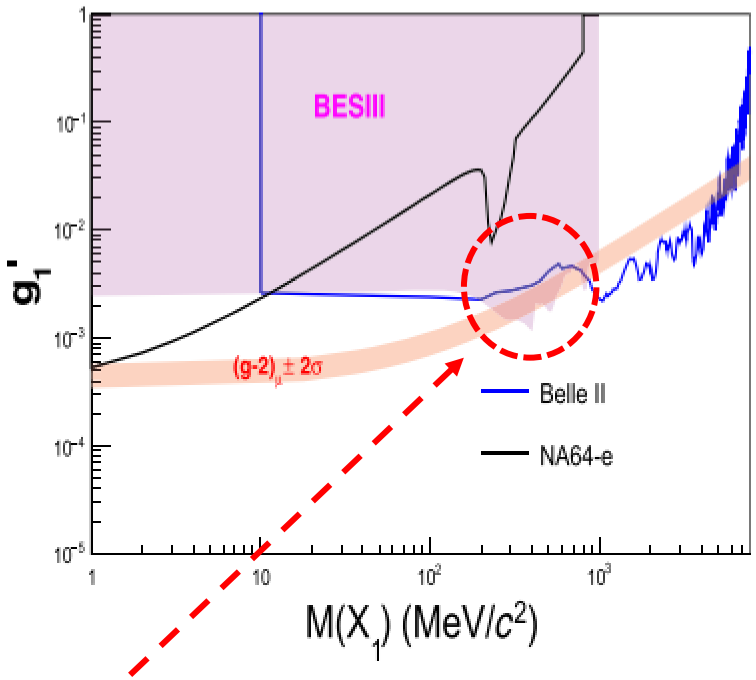
Coupling constraint with $J/\psi \to \mu^+\mu^- X$

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



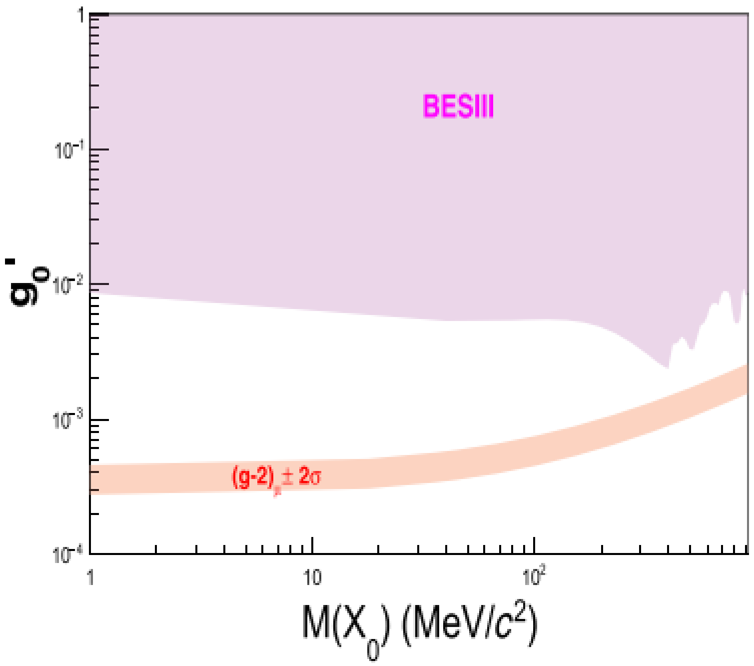
BarBar, CMS, Belle: $X_1 \to \mu^+\mu^-$
Belle II, BESIII: $X_1 \to \upsilon\bar{\upsilon}$
(Taking $\mathcal{B}(X_1 \to \upsilon\bar{\upsilon})$ into account)

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



Better sensitivity in the range 200-860 MeV/c^2

"scalar" $U(1)$ model



First constraint for the "scalar" invisible X_0 case
Belle II can also give the constraint

PHYS. REV. D 109, L031102 (2024)

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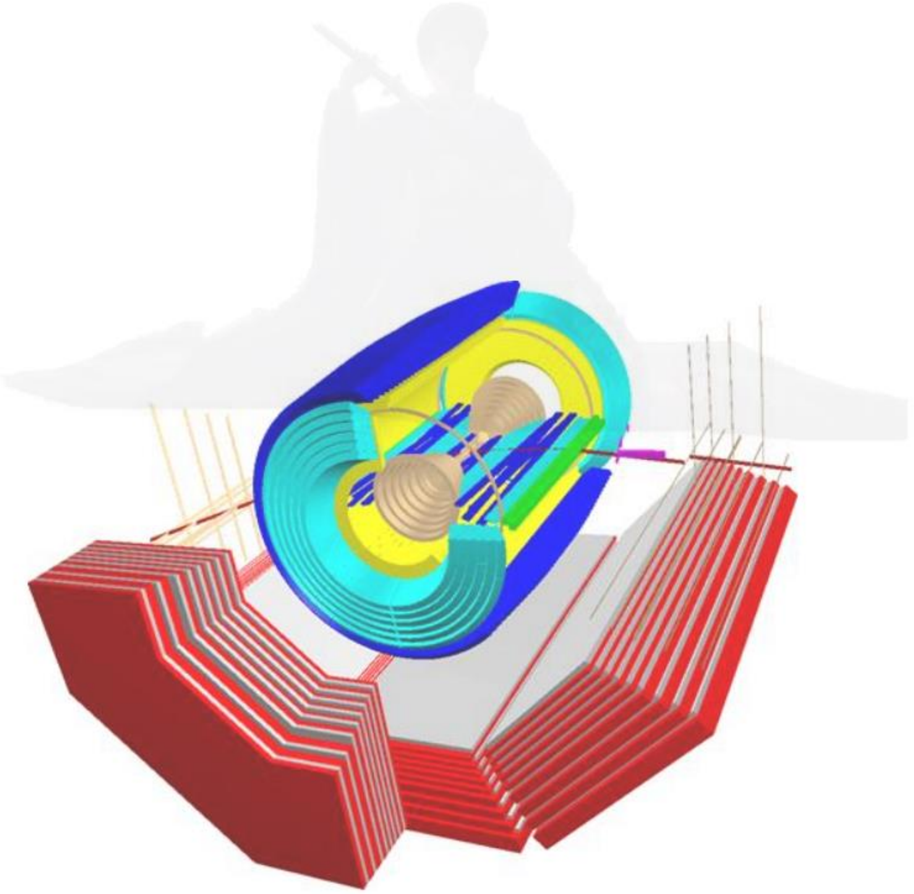


QCD axion particle

- The **QCD axion (a)** is originally predicted by the Peccei-Quinn (PQ) solution to the strong CP problem
- The QCD axion is also an excellent cold dark matter candidate

- The mass of QCD axion:

$$m_a = 5.691(51)\mu eV(\frac{10^{12}\ GeV}{f_a})$$

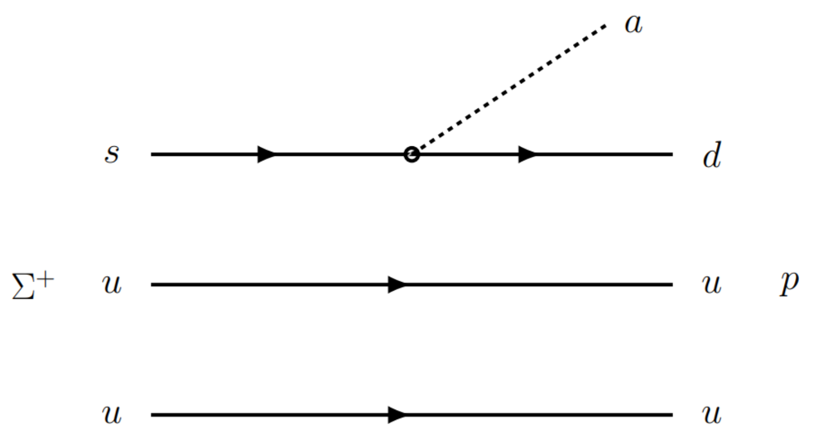
with decay constant (energy scale) $f_a \gg 10^6\ GeV$

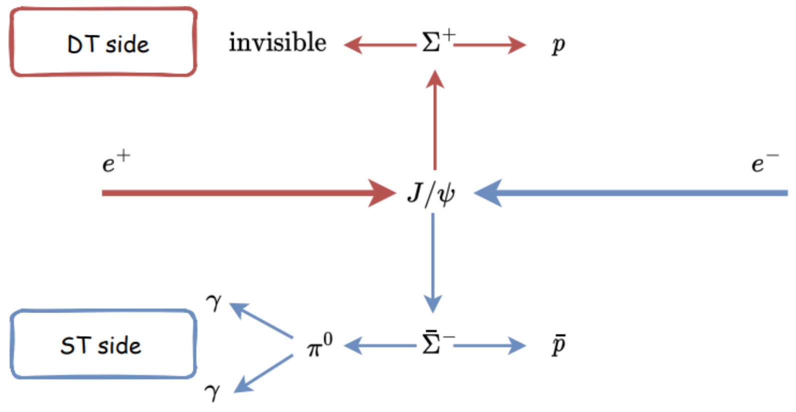
- $m_a < eV$, **"massless"** compared to the resolution of BESIII
- Long-lived (lifetime is larger than the age of the universe): **invisible**

- The interaction of the QCD axion with the SM fermions:

$\mathcal{L}_{a-f} = \partial_\mu a \bar{f}_i \gamma^\mu (\frac{1}{F_{ij}^V} + \frac{\gamma^5}{F_{ij}^A}) f_j$, F_{ij}^V and F_{ij}^A are the effective decay constants for the **vector coupling term and axial coupling term**

- **a can couples with SM fermions with different flavour**



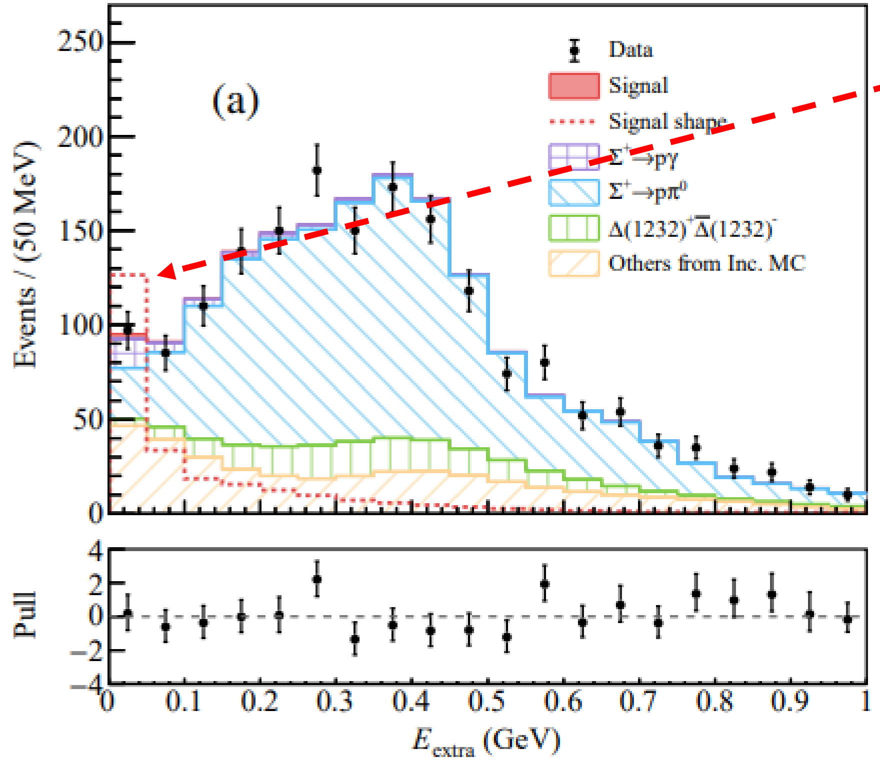


PRD 102 (2020) 1, 015023

➢ **Can be accessible at BESIII, like $\Sigma^+ \to pa$**

Search for QCD axion with $\Sigma^+ \to pa$

- Data samples: $(10087 \pm 44) \times 10^6$ J/ψ events ($\sim 10^7$ $\Sigma^+\bar{\Sigma}^-$ pairs)
- Kinematic fit to constraint the invisible axion mass to zero
- Extract signals in the energy spectrum of the extra shower in EM counter

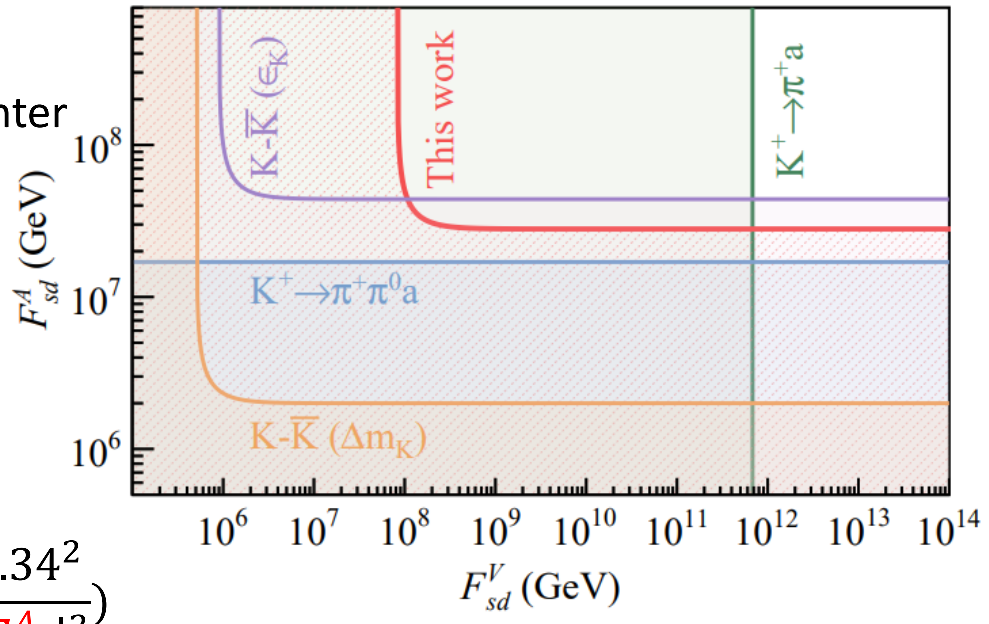


Signals will have a peak around zero

$\mathcal{B}(\Sigma^+ \to pa) < 3.2 \times 10^{-5}$

$\Gamma(\Sigma^+ \to pa) =$

$$\frac{M_{\Sigma^+}^3}{16\pi}\left(1 - \frac{M_p^2}{M_{\Sigma^+}^2}\right)^3 \left(\frac{(-1)^2}{|F_{sd}^V|^2} + \frac{0.34^2}{|F_{sd}^A|^2}\right)$$



PRD 102 (2020) 1, 015023

Competitive constraint on the axial-vectorial effective decay constant F_{sd}^A

$$F_{sd}^A > 2.8 \times 10^7 \text{ GeV}$$

- $\Sigma^+ \to p +$ invisible can also give a constraint on the massless dark photon
- $\Lambda_c^+ \to p +$ invisible (previous slide) can also give a constraint on the QCD axion: $F_{cu}^V > \sim 1.5 \times 10^7$ GeV and $F_{cu}^A > \sim 1.4 \times 10^7$ GeV

arXiv: 2312.17063

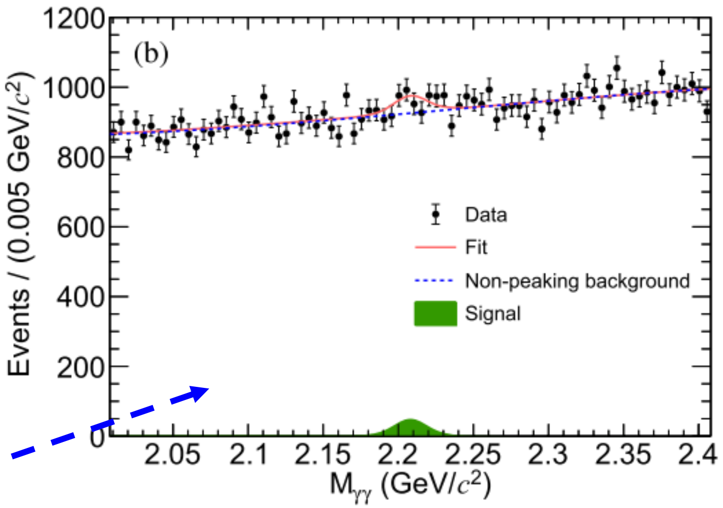
Effective PQ breaking scales: $> 10^7$ GeV

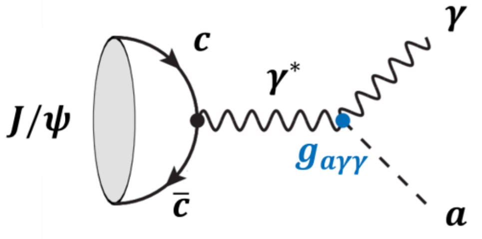
Search for axion like particle with $J/\psi \to \gamma a \to \gamma\gamma\gamma$

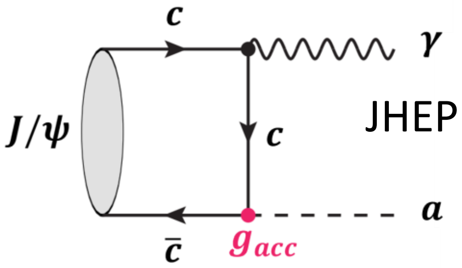
- **The axion like particles (ALPs)** have the same quantum numbers as the QCD axion, but have no strict relation between their couplings and mass, **arbitrary masses and couplings**

- ALPs can have **interaction with** fermions, gluon, **photons**: $\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$
- The decay width of $a \to \gamma\gamma$: $\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$
- Taking $g_{a\gamma\gamma} \sim 10^{-4}\ \mathrm{GeV}^{-1}$, $m_a \sim \mathrm{GeV}$, the lifetime of ALP is short in the detector **short-lived, visible via $a \to \gamma\gamma$**

> **Can be accessible at BESIII like $J/\psi \to \gamma a \to \gamma\gamma\gamma$**

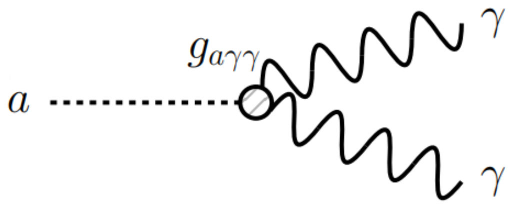






JHEP 06 (2019) 091

Assuming $g_{a\gamma\gamma} \gg g_{acc}$ later

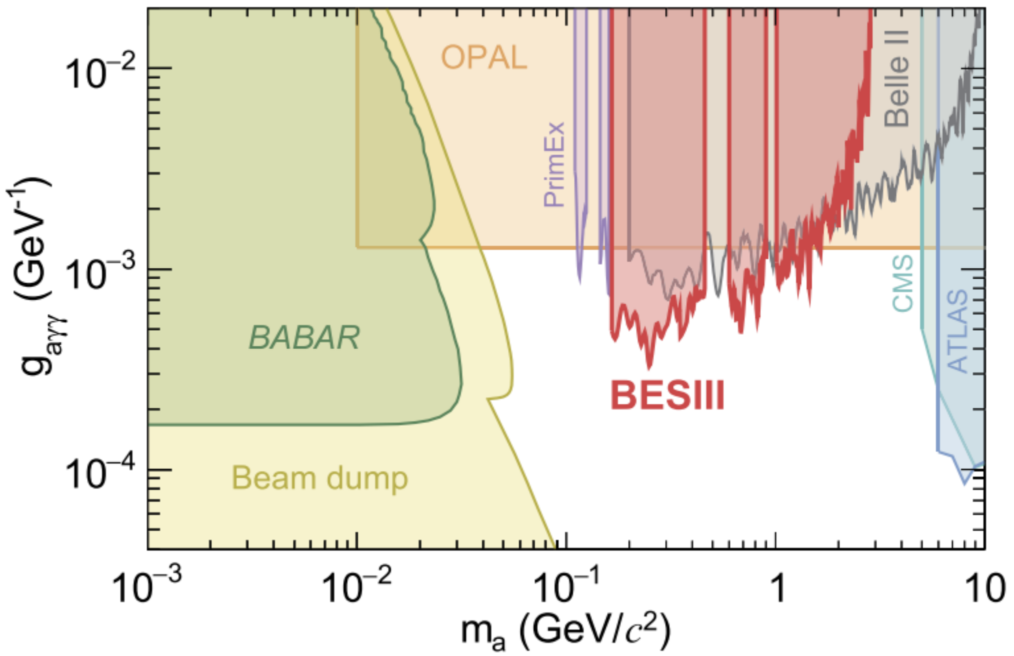


- Data samples: $(2.71 \pm 0.01) \times 10^9\ \psi(2S)$
- J/ψ obtained from $\psi(2S) \to \pi^+\pi^- J/\psi$

- **Extract signal from $M_{\gamma\gamma}$ distribution**
- The maximum local significance is 2.6σ at $M(a) = 2208\ MeV/c^2$
- **No evidence** for signals from ALPs visible decays

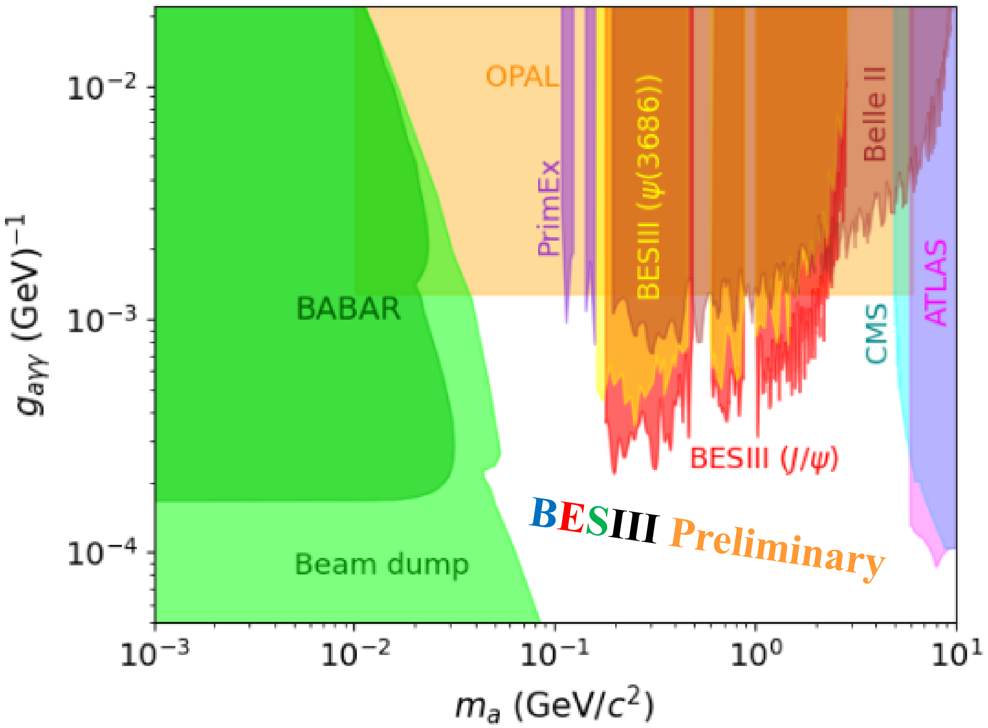
PLB 838 (2023) 137698

ALPs-photon coupling constraint



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

- **Assuming that $\mathcal{B}(a \to \gamma\gamma) \sim 100\%$**
- J/ψ samples obtained from $\psi(2S) \to \pi^+\pi^- J/\psi$ (2.7×10^9 $\psi(2S)$ events)



ALPs-photon Coupling

New preliminary result at BESIII

- J/ψ events from e^+e^- annihilation at BESIII: (10×10^9 J/ψ events)

An improvement by a factor of 5 over the previous Belle II measurement

PLB 838 (2023) 137698

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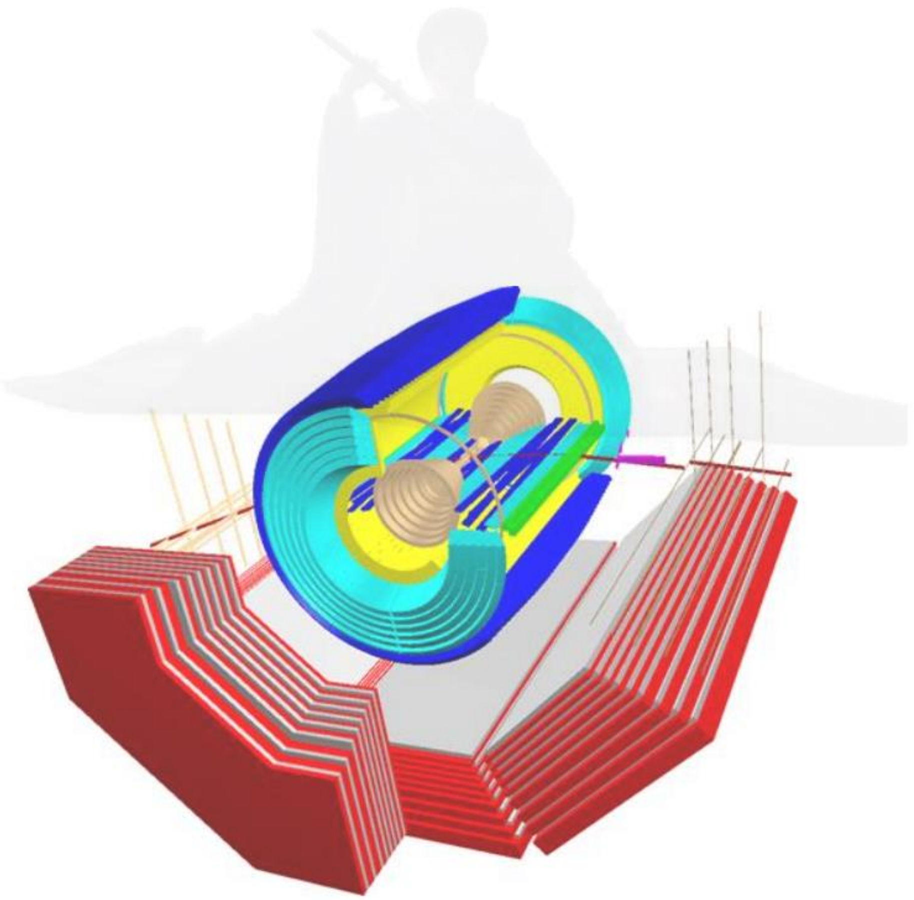
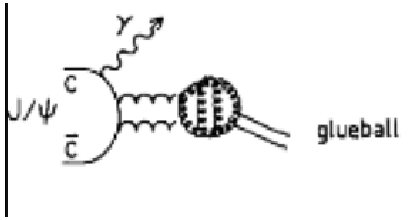
- **Study for glueball**
- Summary



Partial Wave Analysis of $J/\psi \to \gamma K_S K_S \pi^0$

- **J/ψ radiative decays provide gluon rich environment** and ideal place for glueball

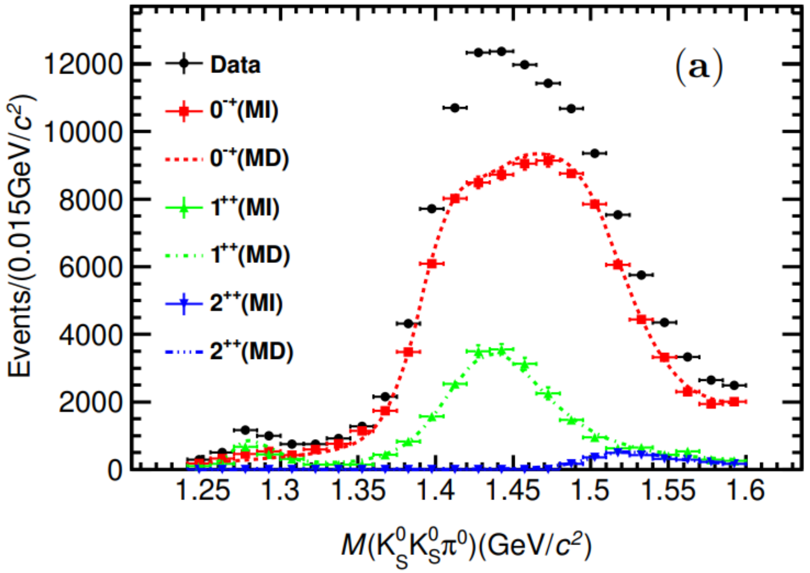


Partial Wave Analysis of $J/\psi \to \gamma \boldsymbol{K_S K_S \pi^0}$

- Mass Dependent PWA (MD): Isobar model
- Mass Independent PWA (MI): Disentangle J^{PC} in each bin
- Consistency between MI and MD results
- **Two pseudoscalar states needed: $\boldsymbol{\eta(1475)}$ and $\boldsymbol{\eta(1405)}$**

- Quark model predicts: only one pseudo-scalar meson near 1.4 GeV
- Theoretical interpretations: $\eta(1475)$ is the first radial excitation of η', **$\boldsymbol{\eta(1405)}$ is a pseudoscalar glueball candidate**
- **An important input for $\boldsymbol{0^{-+}}$ glueball**

Theorists attempt to explain $\boldsymbol{\eta(1405)/\eta(1475)}$ using one pole
- **Further study is needed** PRD 107 (2023) 9, L091505



- $M_{\eta(1405)} = 1391.7 \pm 0.7^{+11.3}_{-0.3}$ MeV$/c^2$
- $\Gamma_{\eta(1405)} = 60.8 \pm 1.2^{+5.5}_{-12.0}$ MeV$/c^2$
- $M_{\eta(1475)} = 1507.6 \pm 1.6^{+15.5}_{-32.2}$ MeV$/c^2$
- $\Gamma_{\eta(1475)} = 115.8 \pm 2.4^{+14.8}_{-11.0}$ MeV$/c^2$

JHEP 03(2023)121

- LQCD predicts: 0^{-+} glueball: 2.3-2.4 GeV/c^2
- **Another pseudoscalar glueball candidate: $\boldsymbol{X(2370)}$**

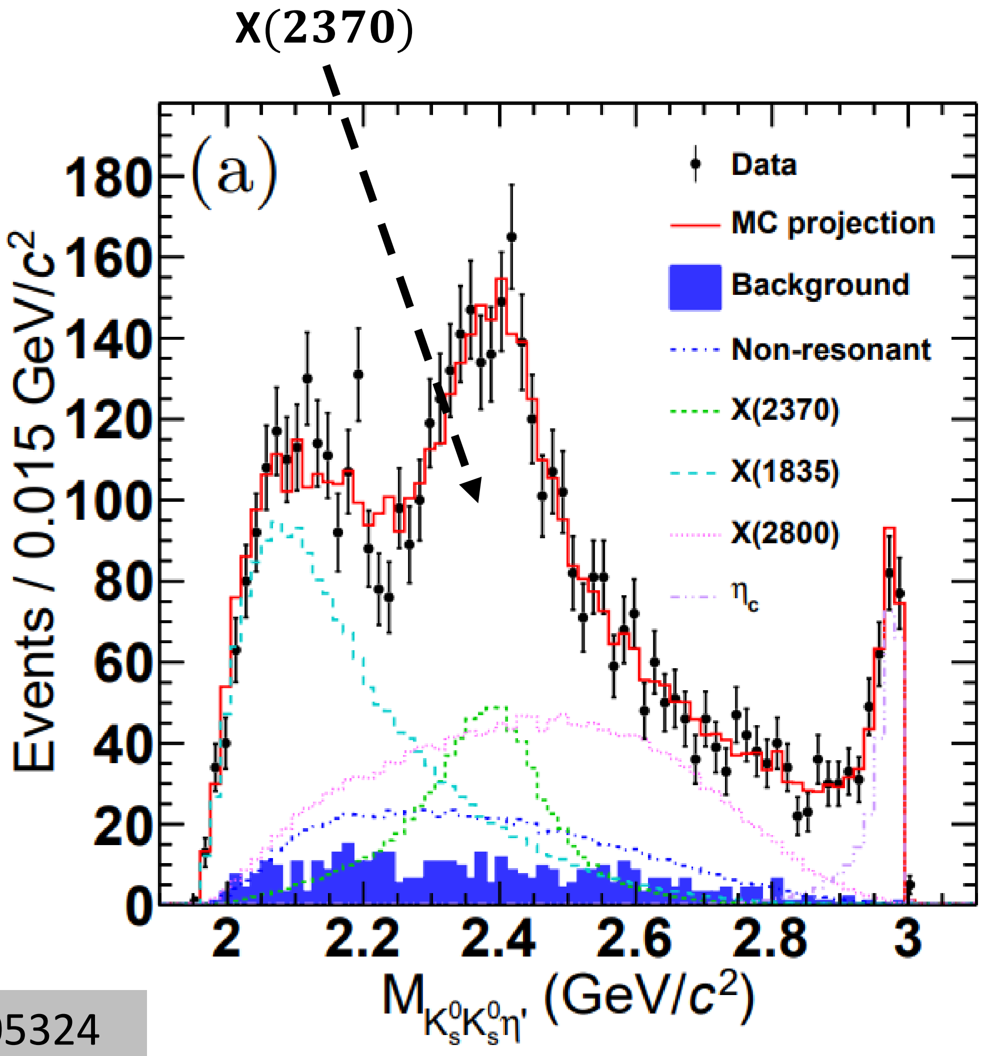
Determination of Spin-Parity of the $X(2370)$

PRL 106, 072002 (2011)

- $X(2370)$ is first observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$
- Partial wave analysis of $\boldsymbol{J/\psi \to \gamma K_S K_S \eta'}$
- $M_{X(2370)} = 2395 \pm 11^{+26}_{-0.84}\ \mathrm{MeV}/c^2$
- $\Gamma_{X(2370)} = 188\ ^{+18}_{-17}\ ^{+124}_{-33}\ \mathrm{MeV}/c^2$
- $\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma f_0(980)\eta' \to \gamma K_S K_S \eta') = (1.31 \pm 0.22^{+2.85}_{-0.84}) \times 10^{-5}$

➢ The spin-parity of **$X(2370)$** is determined to be **0^{-+} for the first time**

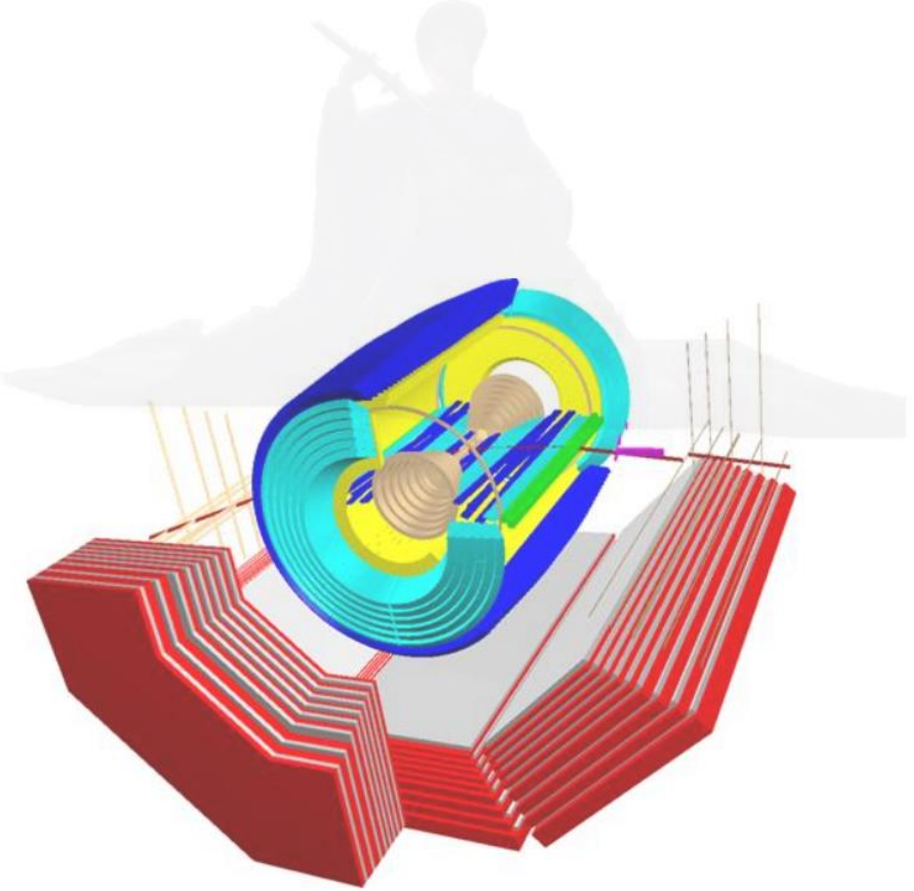
➢ The measured mass and spin-parity of the $X(2370)$ are **consistent with the predictions of a pseudoscalar glueball**



arXiv: 2312.05324

Summary

- New results of dark photon, muonphilic particle, axion and glueball at BESIII
- Unfortunately, no evidence for light exotic physics
- BESIII has collected $10^{10}\ J/\psi$, $2.7\times10^{9}\ \psi'$, $20\ \mathrm{fb}^{-1}$ @ 3.77 GeV data ($D\bar{D}$) and more…
- More & better results are coming soon

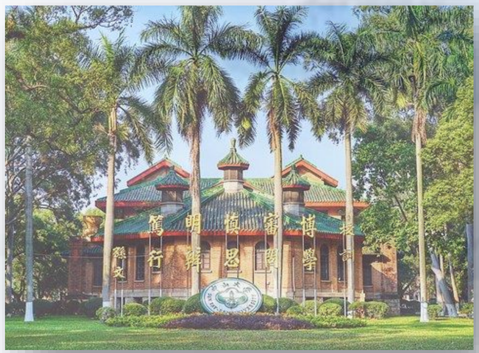


The future of Dark Sector is Bright !

BESIII

since 1966 Rencontres de Moriond

thank you



58th Rencontres de Moriond EW 2024, 24 - 31 March 2024, La Thuile, Italy

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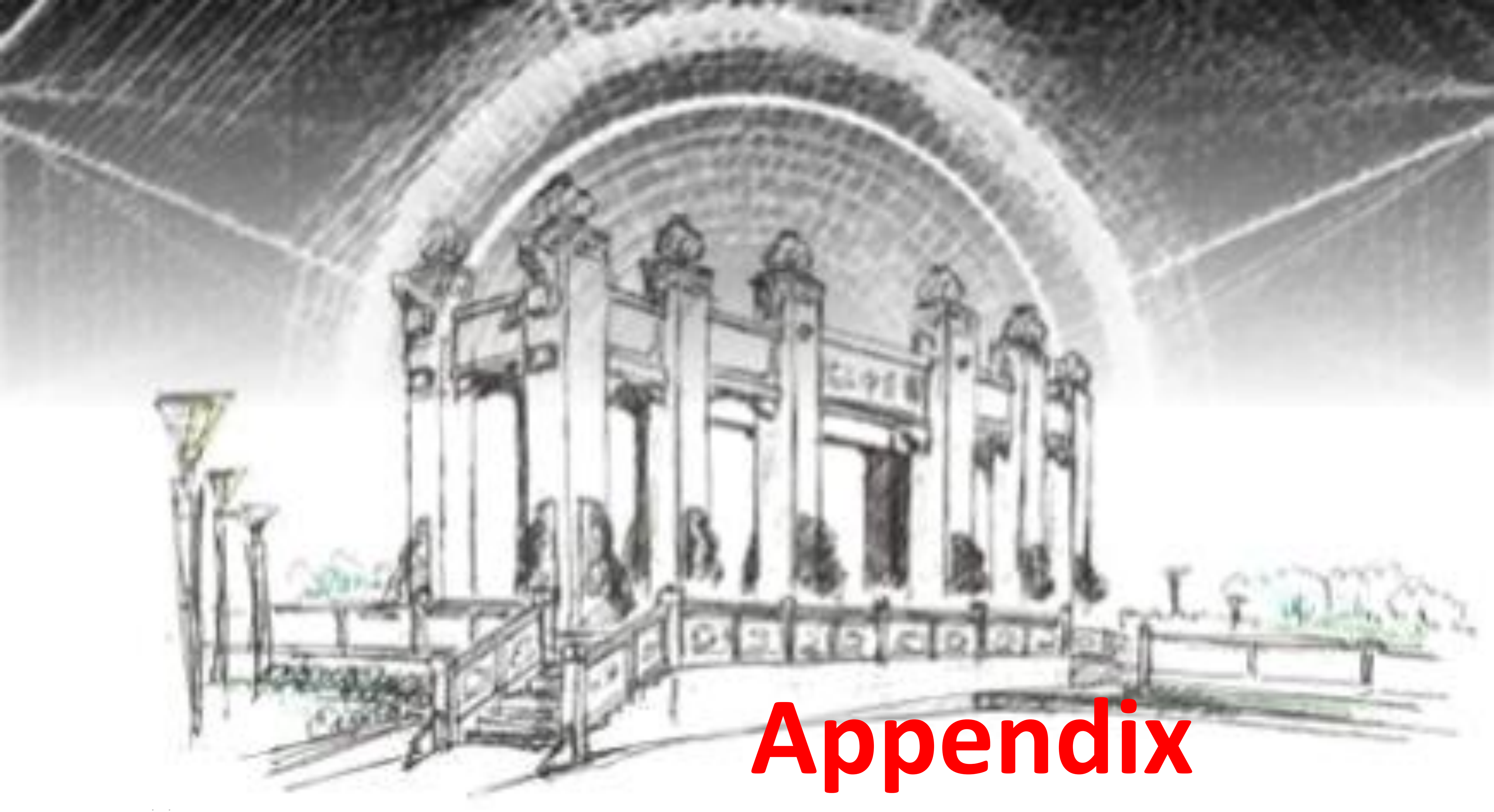


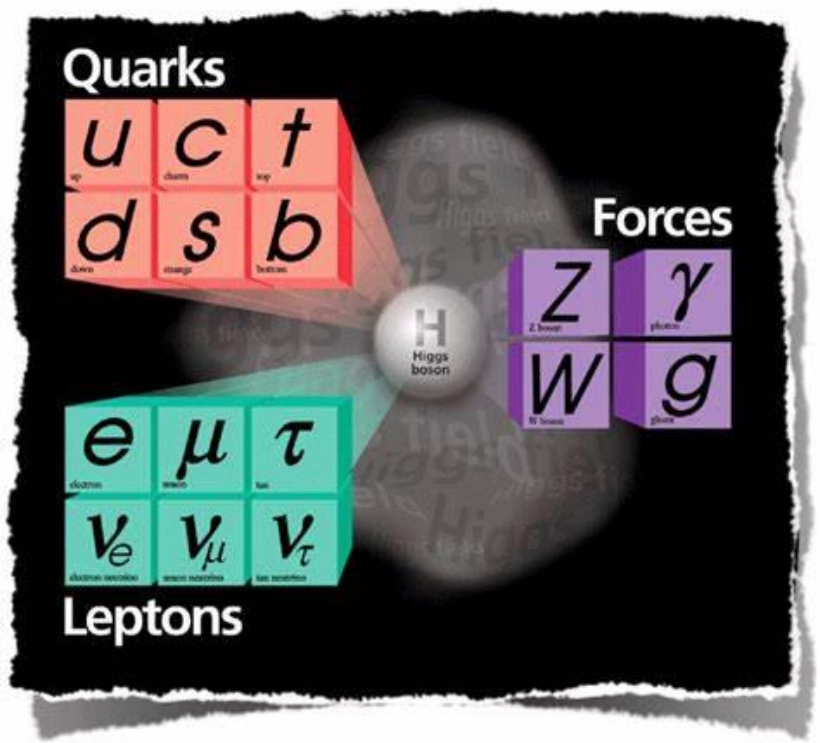
Appendix

SM and puzzles

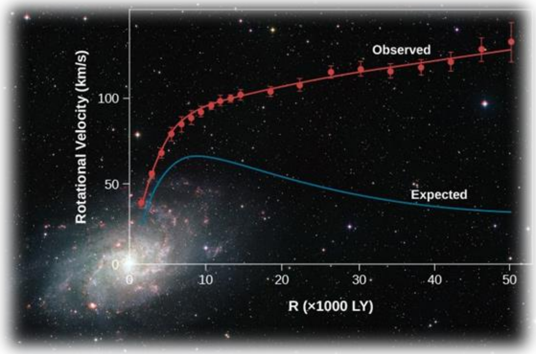
Standard model (SM):

$\boldsymbol{SU(3)_C \times SU(2)_L \times U(1)_Y}$

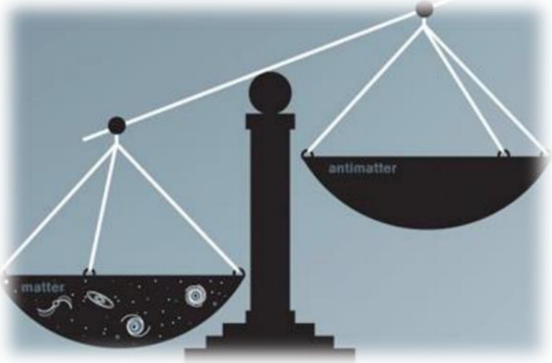
- Successful!
- But also some **puzzles**



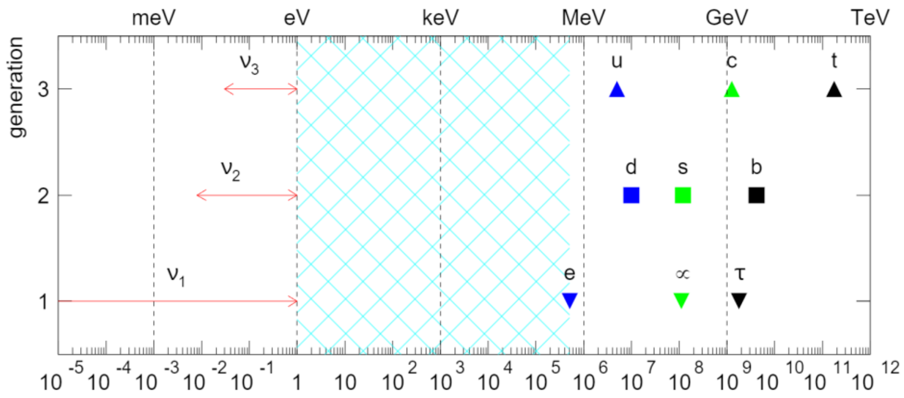
- Dark matter



- Matter and anti-matter asymmetry

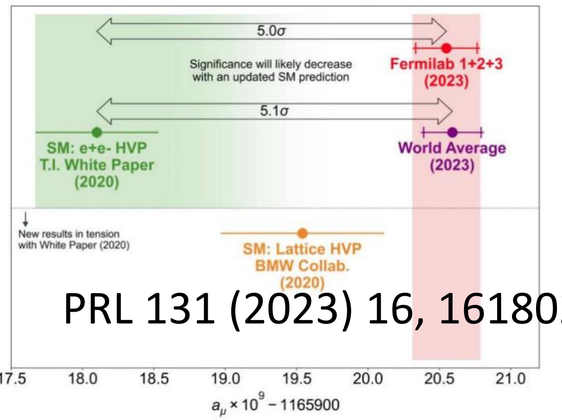


- Fermion mass hierarchy



Mod.Phys.Lett.A 19 (2004) 2799-2813

- $g_\mu - 2$ anomaly



PRL 131 (2023) 16, 161802

We believe there are something new beyond the SM: **dark sector**

- More…

Dark sector and portal

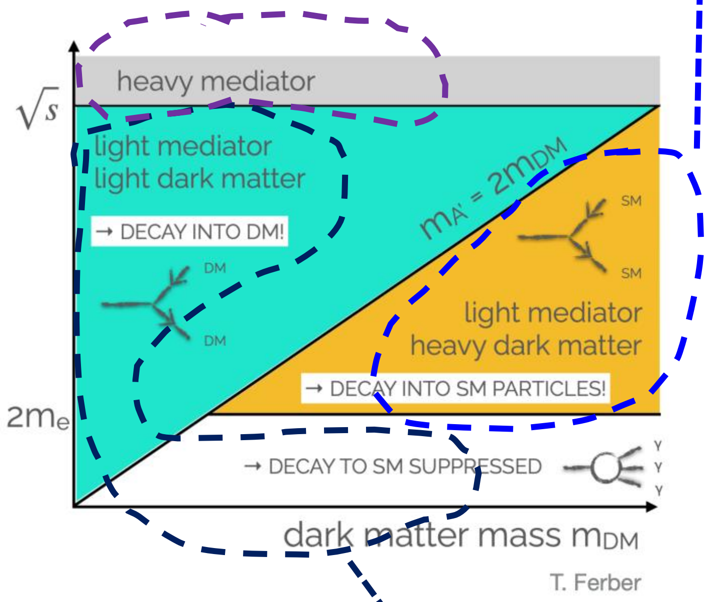
- ☐ The dark sector is hidden because of the weak interaction with the SM particle
- ☐ Some **"portal"** may connect the Standard Model matter and the Dark sector matter

- **Vector portal (dark photon)**
- **Pseudo-scalar portal (axion)**
- **Scalar portal (dark Higgs)**
- **Neutrino portal (heavy neutrinos)**

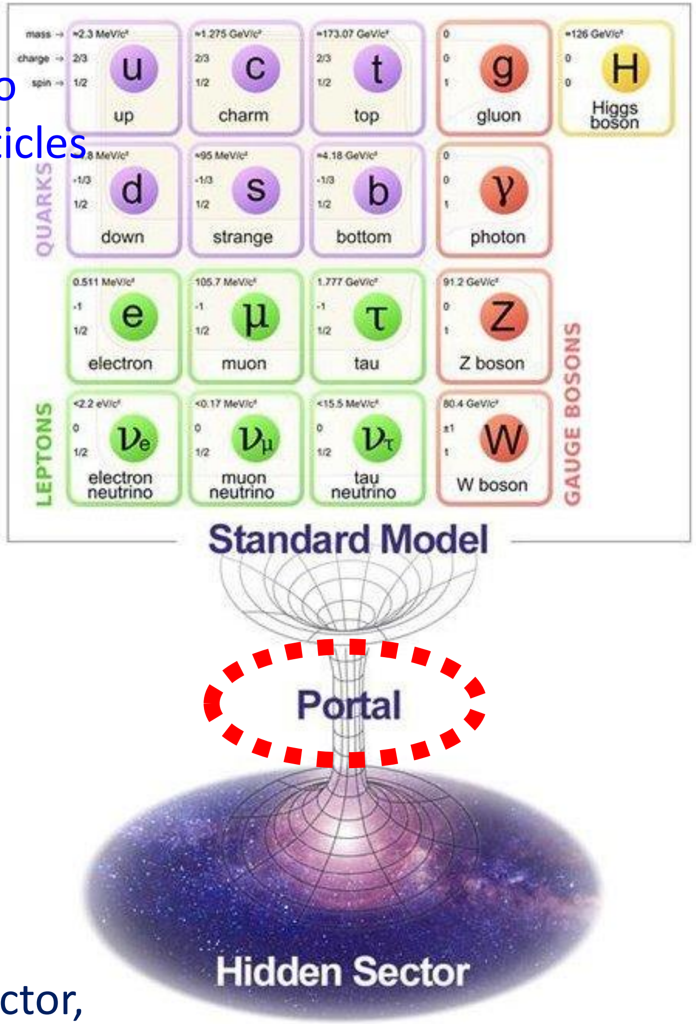
If their mass are in the **MeV-GeV range**, these exotic particles can be accessible by high intensity e^+e^- collider experiments, such as **BEPCII and BESIII** experiment.

Propagator

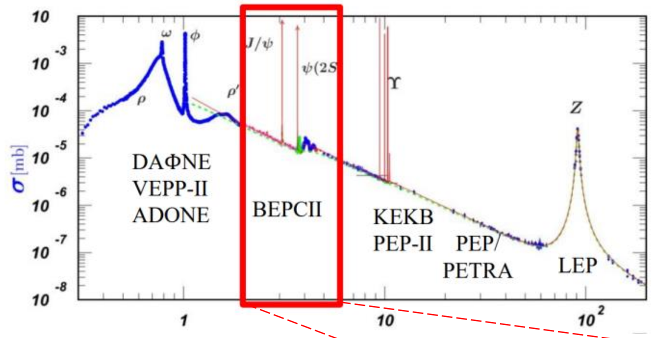
Decay to SM particles

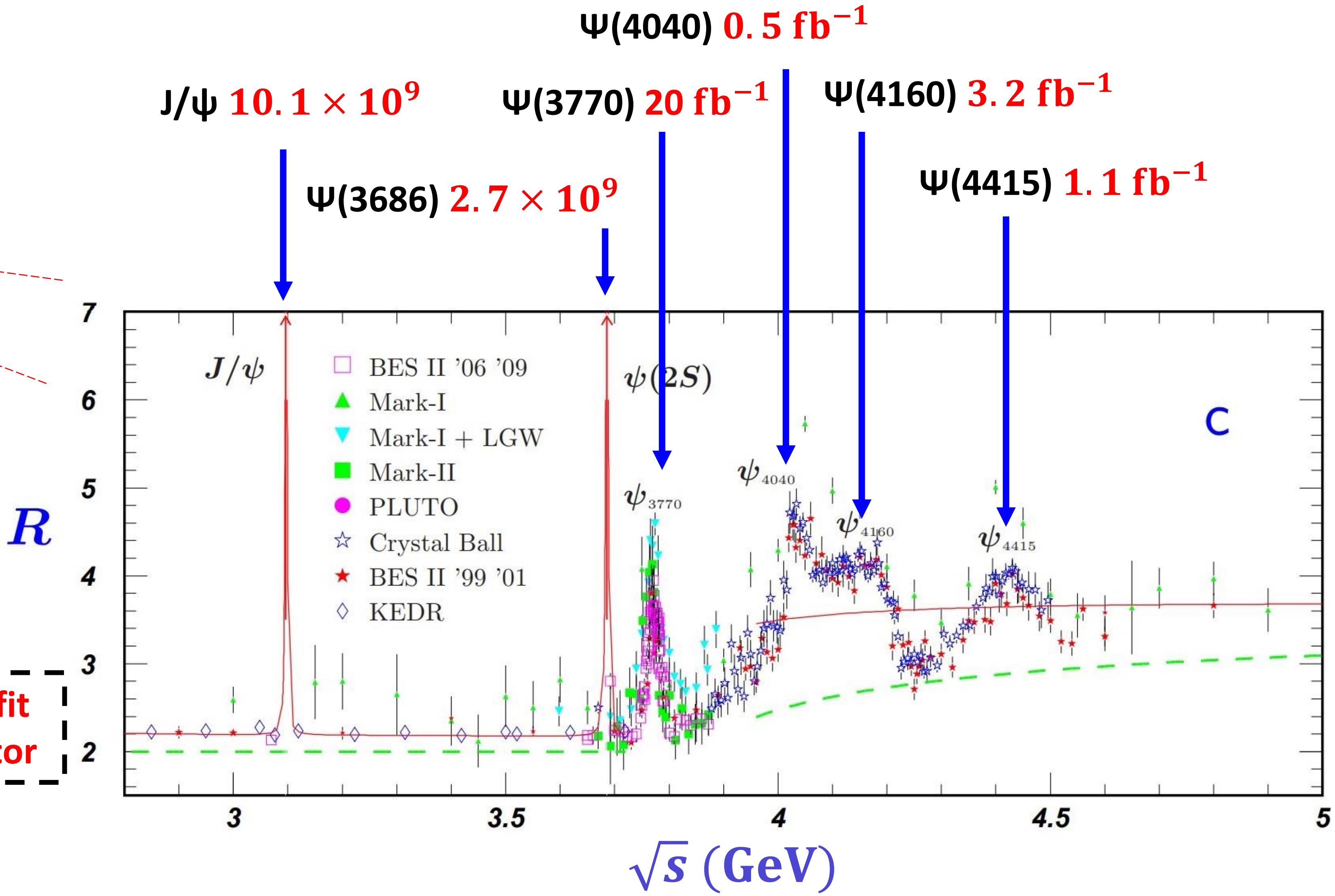


Invisible in the detector,
Something missing!



Data samples at BESIII





- ✓ BESIII has collected the largest charmonium data samples on threshold
- ✓ $> 20\ \text{fb}^{-1}$ data above 4.0 GeV in total

Such a large data sample can benefit the search for the hidden dark sector

decay width of $J/\psi \to \mu^+\mu^- X$

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

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

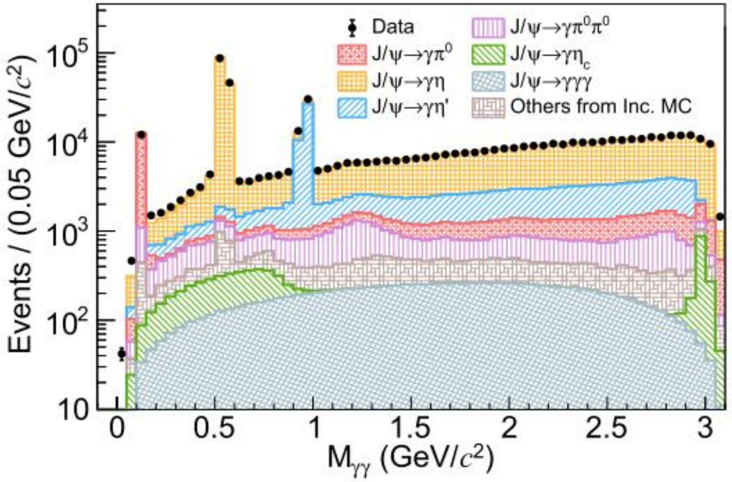
$$\Gamma_{\mu\mu X_{0,1}} = \int_{E_X^{min}}^{E_X^{max}} \int_{E_-^{min}}^{E_-^{max}} \frac{|\mathscr{M}_{\mu\mu X_{0,1}}|^2}{64\pi^3 m_J} dE_- dE_X,$$

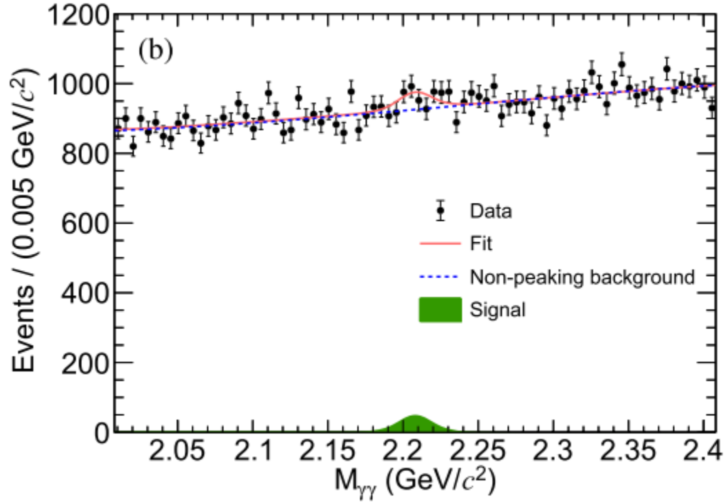
$$|\mathscr{M}_{\mu\mu X_1}|^2 = \left(\frac{2}{3}e^2\, g_1\, \frac{f_J}{m_J}\right)^2 \frac{-16}{3\, m_J^2(m_J-2\,E_-)^2(-2\,E_- - 2\,E_X + m_J)^2}\Big(16\,E_-^4\, m_J^2 + 32\,E_-^3\, m_J^2(E_X - m_J)$$
$$+2m_\mu^2\Big(4\,E_-^2\left(m_J(m_J - 2\,E_X) + m_X^2\right) - 4\,E_-\left(2\,E_X^2\, m_J - E_X\left(m_X^2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

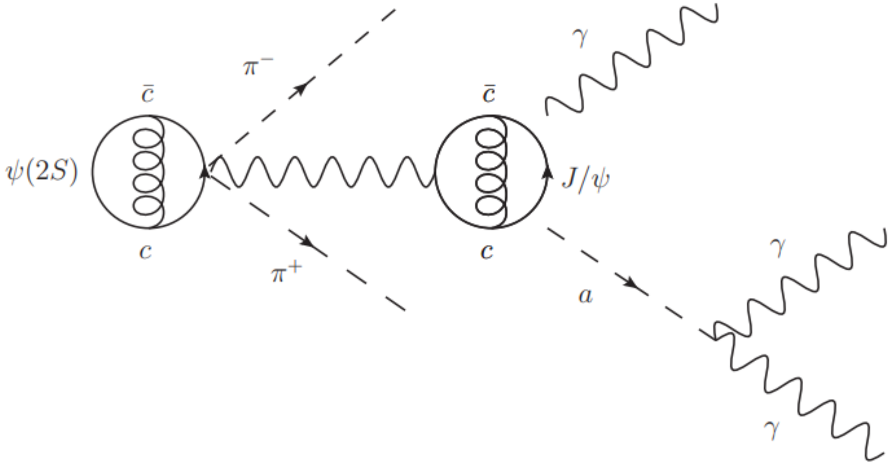
where E_-, the energy of μ^- and E_X, the energy of X_0 are measured in the rest frame of J/ψ.

Search for axion like particle with $J/\psi \to \gamma a \to \gamma\gamma\gamma$

- Data samples: $(2.71 \pm 0.01) \times 10^9\ \psi(2S)$ events
- J/ψ samples obtained from $\psi(2S) \to \pi^+\pi^- J/\psi$
  about $0.94 \times 10^9\ J/\psi$ events
- **Extract signal from $M_{\gamma\gamma}$ distribution**
- The maximum local significance is 2.6σ at $\mathrm{M}(a) = 2208\ MeV/c^2$
- **No evidence** for signals from ALPs visible decays



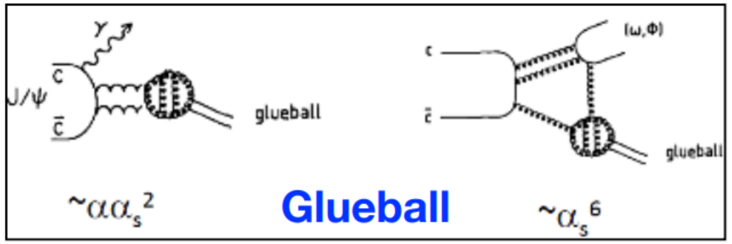


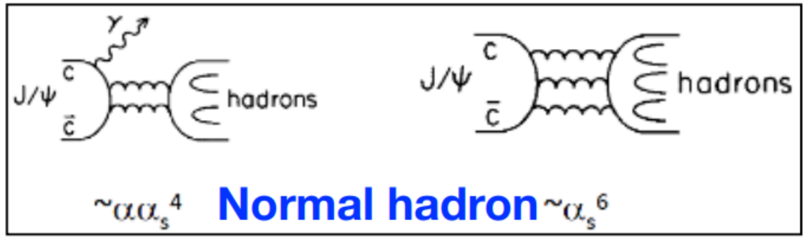


PLB 838 (2023) 137698

Glueball study at BESIII

- QCD allows the existence of **exotic hadrons, glueballs** (composed of gluons)
- **J/ψ radiative decays provide gluon rich environment** and ideal place for glueball





- No rigorous predictions on glueball decay patterns and their branching ratio

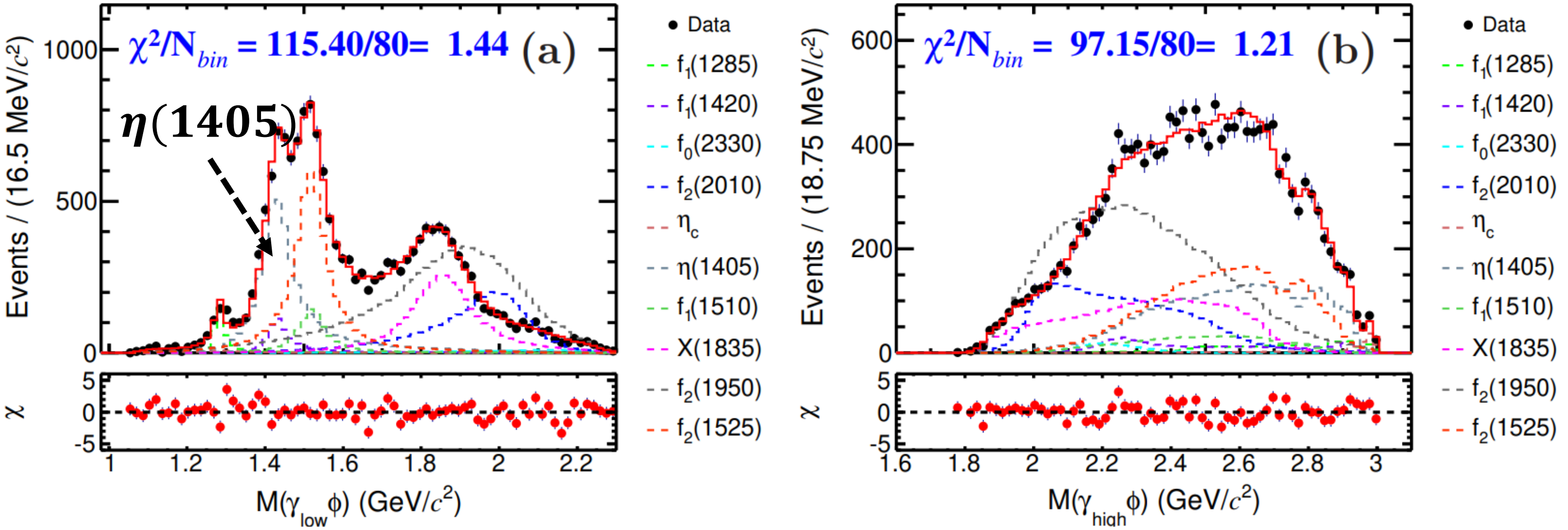
Lattice QCD predictions:
0^{++} scalar ground state: 1-2 GeV/c^2
0^{-+} pseudo-scalar ground state: 2.3-2.4 GeV/c^2
2^{++} tensor ground state: 2.3-2.4 GeV/c^2

Possible potential glueball candidates:
0^{++}: $f_0(1500), f_0(1700)$
0^{-+}: $\eta(1405), X(2370)$
2^{++}: $f_2(2340)$

This talk: some new inputs for 0^{-+} pseudo-scalar glueball

Partial Wave Analysis of $J/\psi \to \gamma\gamma\phi$

- Just **one $\eta(1405)$ state** and a $f_1(1420)$ are needed around $1.4\ \mathrm{GeV}/c^2$
- **No significant signals for $\eta(1475)$ and $X(2370)$** are observed in the $\gamma\phi$ system
- The measured upper limit of **$X(2370)$ is consistent with the prediction for a pseudoscalar** glueball



- $M_{\eta(1405)} = 1422 \pm 2.1^{+5.9}_{-7.8}\ \mathrm{MeV}/c^2,\ \Gamma_{\eta(1405)} = 86.3 \pm 2.7^{+6.6}_{-17.4}\ \mathrm{MeV}/c^2$
- $\mathcal{B}(J/\psi \to \gamma\eta(1405) \to \gamma\gamma\phi) = (3.57 \pm 0.18^{+0.59}_{-0.61}) \times 10^{-6}$
- $\mathcal{B}(J/\psi \to \gamma\eta(1475) \to \gamma\gamma\phi) < 3.80 \times 10^{-7}$ @90% CL
- $\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma\gamma\phi) < 1.08 \times 10^{-7}$ @90% CL

arXiv: 2401.00918