Dark sector at BESIII

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MOSCOW STATE UNIVERSITY

Outline

- ✓ Motivation
- ✓ BESIII experiment
- ✓ Status of Dark sector searches at BESIII
    - Search for a light Higgs boson A^0 in radiative J/ψ decay
    - Search for an Axion-like particle
    - Dark photon (massive and massless)
    - Search for invisible decays of K_S^0 meson
    - Dark baryon
    - Search for invisible muon philic scalar X_0 or vector X_1 via $\boldsymbol{J/\psi \to \mu^+\mu^-}$+invisible
- ✓ Summary

Motivation

- ❖ **Standard Model (SM) is incredibly successful, it is tested by experiments**

- ❖ **However, it can’t be quantified as a theory of everything**

facing some tensions:

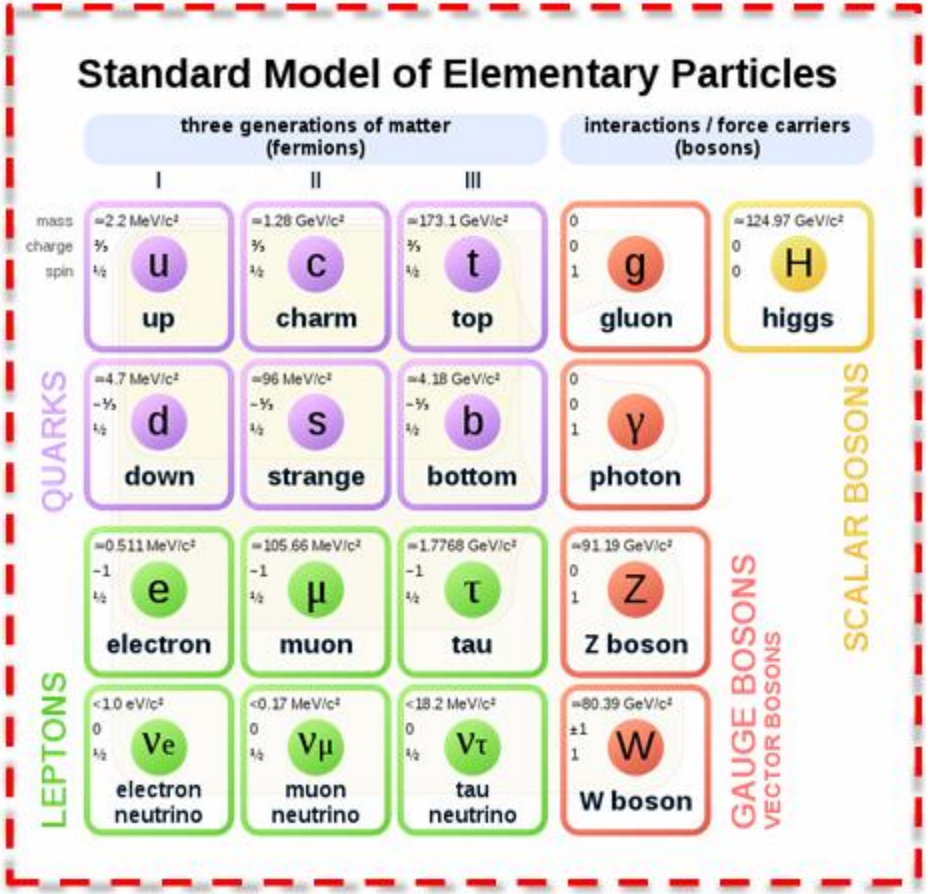
Naturalness and stability, g-2, W mass, R_K, R_D, R_{D*}, ….

Can not explain:

Existence & mechanism of dark matter and dark energy

Baryon asymmetry of the universe

Neutrino masses and oscillations, hierarchy

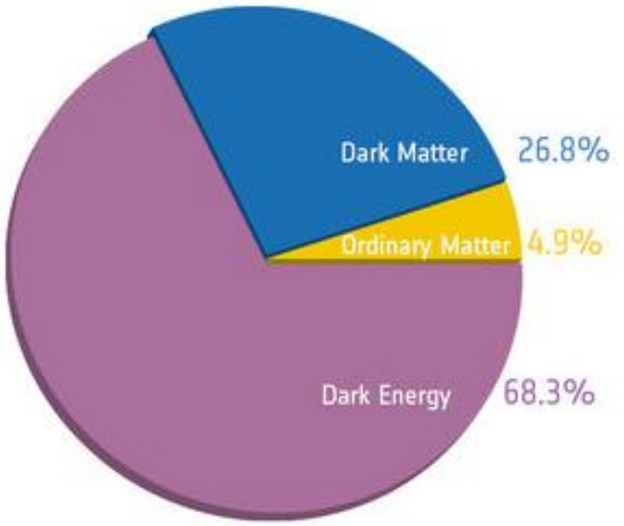


Real opportunity to search for new physics beyond the Standard Model

Motivation

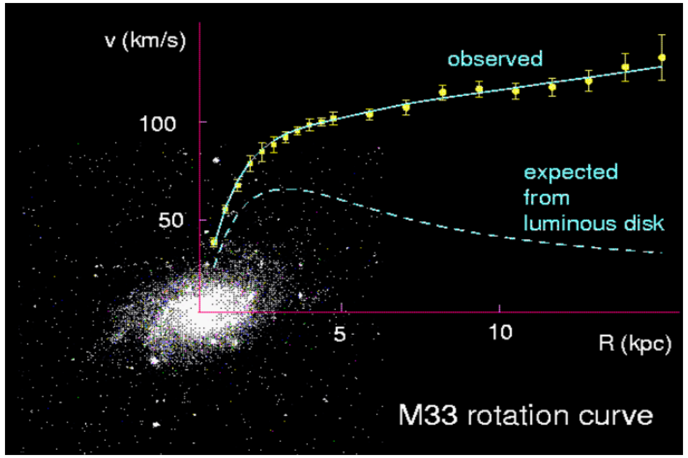
❖ **Standard Model (SM) is incredibly successful but not complete!**

❑ Extensions of the SM needed to solve several outstanding issues, including the missing description of Dark Matter (DM)

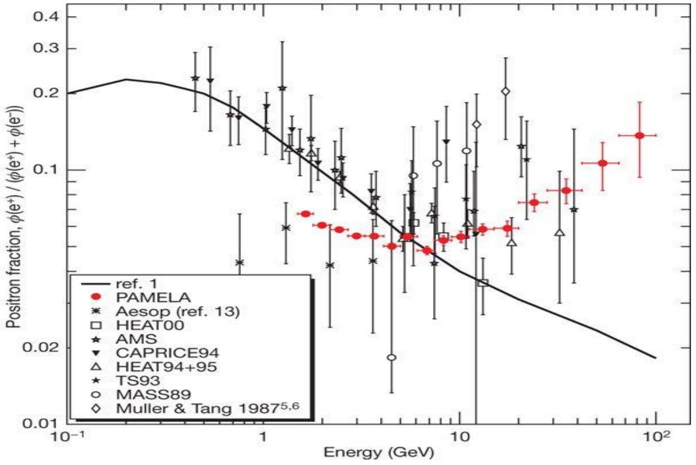


❑ Why DM?

- Amounts 27% of the total matter density of the universe
- Not interact with strong and electromagnetic interactions, it presence so far can be inferred via the gravitational effects only.
- Explain the features of recent astrophysical observations



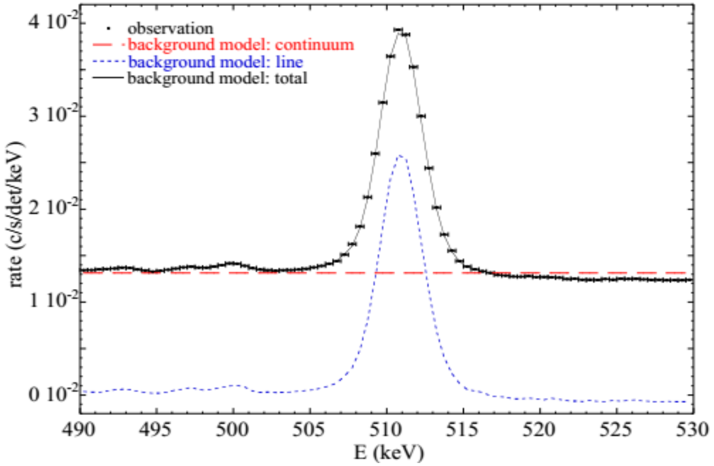
arXiv:astro-ph/0403324



PAMELA: Positron fraction

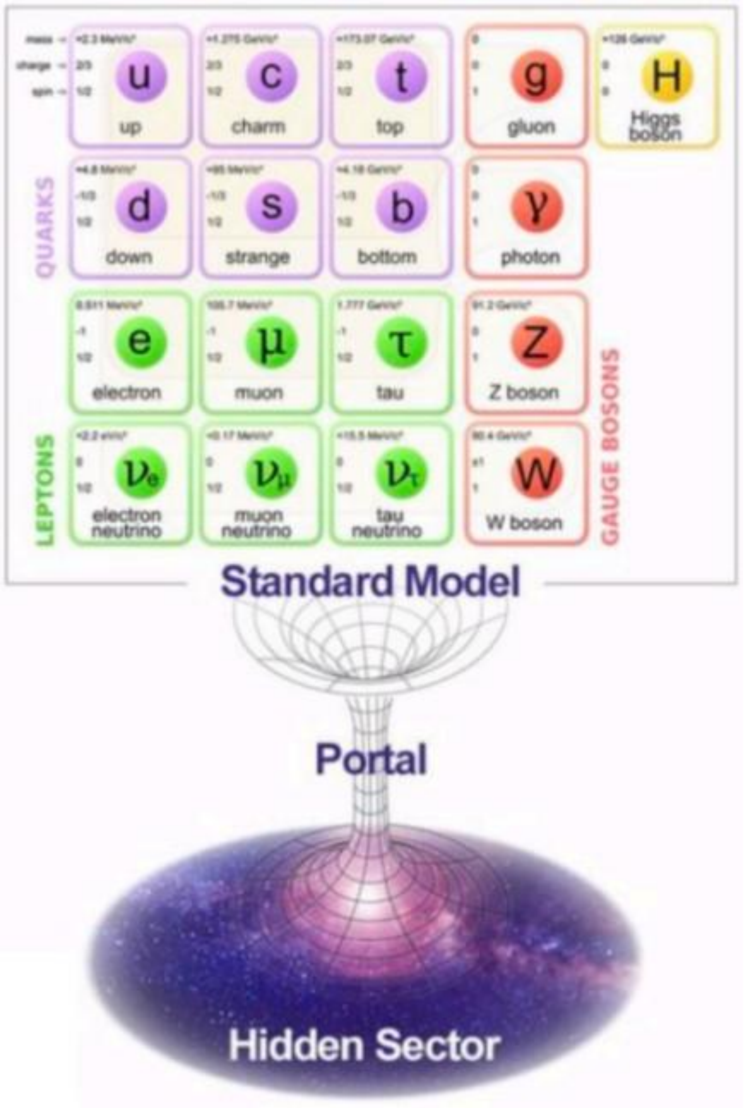
O Adriani et al., Nature **458** (2009) 607

SPI/Integral



P. Jean et al., A&A **407**, L-55-L58 (2003)

Coupling of DM with Standard Model



- Dark matter has not seen yet in particle physics experiments.
  - SM can't explain DM ⟹ Extend to the SM to include Dark matter
  - One of the simplest models is "DM hidden sector" that allows the coupling between DM and SM particles via the so called "portals"

R. Essig et al., arXiv:1311.0029 (2013)

$$\mathcal{L} \supset \begin{cases} -\dfrac{\varepsilon}{2\cos\theta_W} B_{\mu\nu}F'^{\mu\nu}\,, & \text{vector portal} \\ (\mu\phi+\lambda\phi^2)H^\dagger H\,, & \text{Higgs portal} \\ y_n LHN, & \text{neutrino portal} \\ \dfrac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}, & \text{axion portal} \end{cases}$$

A' kinetic mixing with γ, Z

Dark Higgs (mixes with SM Higgs)

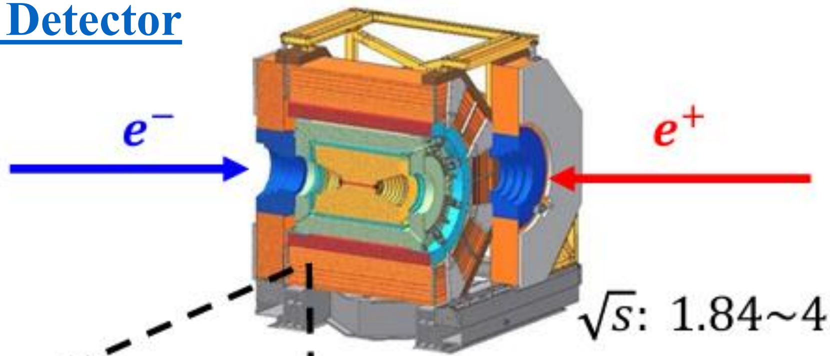
Sterile neutrino

Axion, coupling to DM

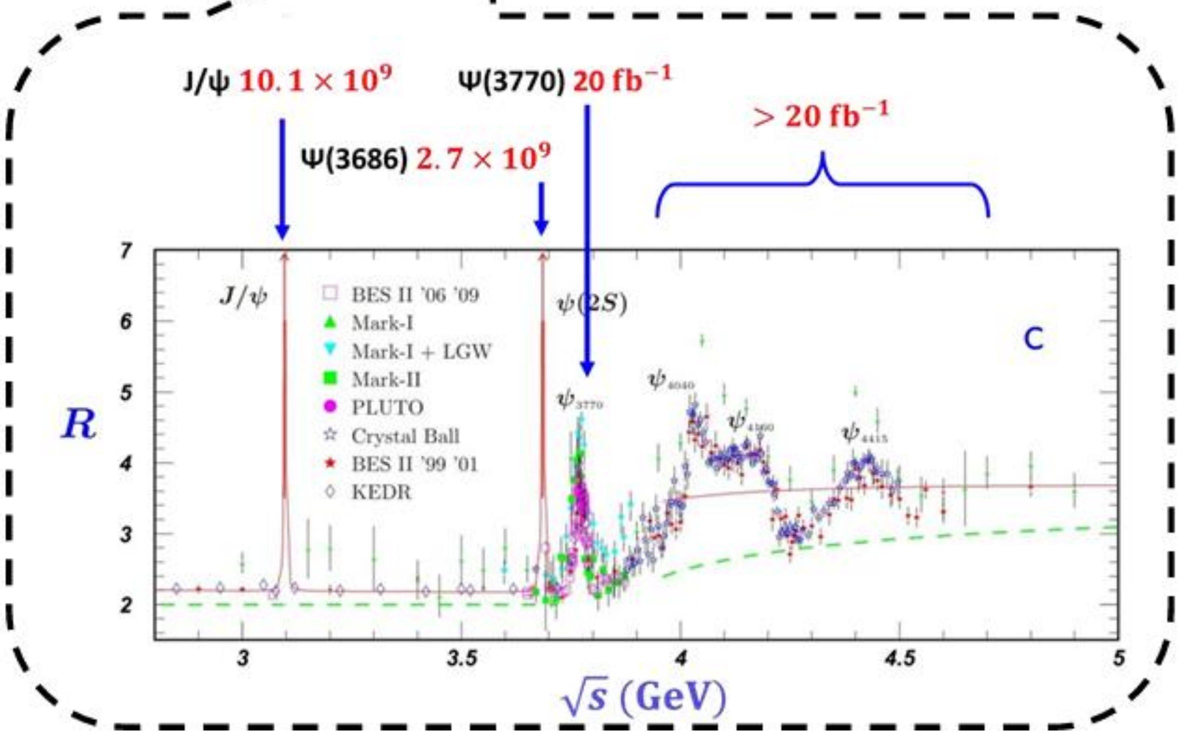
- Can be accessible by high intensity e^+e^- collider experiments, such as BESIII experiment, if their masses are a few GeV

BESIII Experiment

BESIII Detector



$\sqrt{s}$: 1.84~4.95 GeV



■ $10.1\times10^9\ J/\psi$ events

- Hyperon
- Light meson

Λ $\bar{\Lambda}$

$\Sigma^{0,+}$ $\bar{\Sigma}^{0,-}$ $\sim10^7$

$\Xi^{0,-}$ $\bar{\Xi}^{0,+}$

η η'

ϕ ω $\sim10^7$

K_S^0

■ $20\ \text{fb}^{-1}\ \psi(3770)$ ■ ……

D^0 $\bar{D}^0$ D^+ D^-

$\sim10^7$

Rich Physics with clean environment

Chin. Phys. C **44**, 040001 (2020)

Status of Dark sector searches at BESIII

Dark Matter portals

Axion-like particle (ALP) via $J/\psi \to \gamma a$

- a) With $\psi(2S)$ data
  - PLB **838**, 137698 (2023)
- b) With J/ψ data
  - PRD **110,** L031101 (2024) **(This talk)**

Light CP-odd Higgs boson via $J/\psi \to \gamma A^0$

- **Visible (di-muon) decay**
  - PRD **105**, 012008 (2022) **(This talk)**
  - PRD **93**, 052005 (2016)
  - PRD **85**, 092012 (2012)
- **invisible decay**
  - PRD **101**, 112005 (2020)

Dark photon

- **Massive**
  - a) Via $J/\psi \to U\eta(')$
    - PRD **99**, 012013 (2019)
    - PRD **99**, 012006 (2019)
    - PRD **102**, 052005 (2020)
  - b) Via ISR process
    - **(This talk)** PLB **774**, 252 (2017) (visible)
    - **(This talk)** PLB **839**, 137785 (2023) (invisible)
- **Massless**
  - a) $\Lambda_c^+ \to p\gamma'$
    - PRD **106**, 072008 (2022)
  - b) $D^0 \to \omega/\gamma\gamma'$ **(This talk)**
    - PRD **111**, L011103 (2025)
  - c) $\Sigma^+ \to p +$ invisible **(This talk)**
    - PLB **852**, 138614 (2024)

Fully invisible decays

- **Invisible decays of Λ baryon**
  - PRD **105**, L071102 (2022)
- **Invisible decays of ω/ϕ mesons**
  - PRD **98**, 032001 (2018)
- **Invisible K_S^0 decays**
  - JHEP **05**, 092 (2025) **(This talk)**
- **Invisible decays of η/η' mesons**
  - PRD **87**, 012009 (2013)
- **invisible muon philic scalar or vector meson**
  - PRD **109**, L031102 (2024) **(This talk)**

Search for dark baryon in $\Xi^- \to \pi^- \chi$

arXiv: 2505.22140 (2025)

(This talk)

Search for heavy Majorana neutrino

PRD **99**, 112002 (2019)

Light Higgs boson A^0 search

PRD 105, 012008 (2022)

- A light Higgs boson is predicted by many extensions of Standard Model, such as Next-to-Minimal Supersymmetric Standard Model (NMSSM).

➢ NMSSM contains a total of three CP-even, two CP-odd and two charged Higgs bosons.

➢ **The lighter state of the A^0 is defined as:**

$$A^0 = \underbrace{\cos\theta_A A_{MSSM}}_{\text{Non-singlet}} + \underbrace{\sin\theta_A A_s}_{\text{Singlet}}$$

[PRD 76, 051105 (2007)]

➢ Coupling of fermions and the CP-odd Higgs A^0

$$L_{\text{int}}^{f\bar{f}} = -\cos\theta_A \tan\beta \frac{m_f}{v} A^0 \bar{d}(i\gamma_5)d, \quad d = d,\ s,\ b,\ \ e,\ \mu,\ \tau$$

$$L_{\text{int}}^{f\bar{f}} = -\cos\theta_A \cot\beta \frac{m_f}{v} A^0 \bar{u}(i\gamma_5)u, \quad u = u,\ c,\ t,\ \ \nu_e,\ \nu_\mu,\ \nu_\tau$$

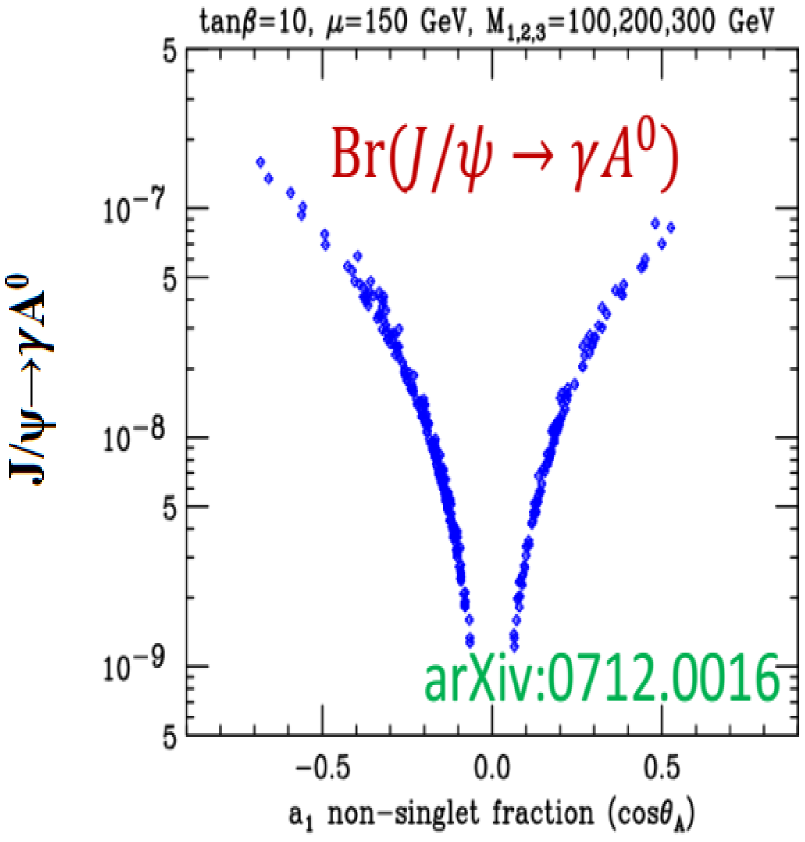
$$\tan\beta = \frac{v_u}{v_d}$$

Ratio of the VEVs of the up and down-types of Higgs doublets

E. Fullana et. al,
Phys. Lett. B 653, 67 (2007)

➢ Can be detectable via radiative decays of J/ψ and ϒ(1S)

[Phys. Rev. Lett. **39**, 1304 (1977)]

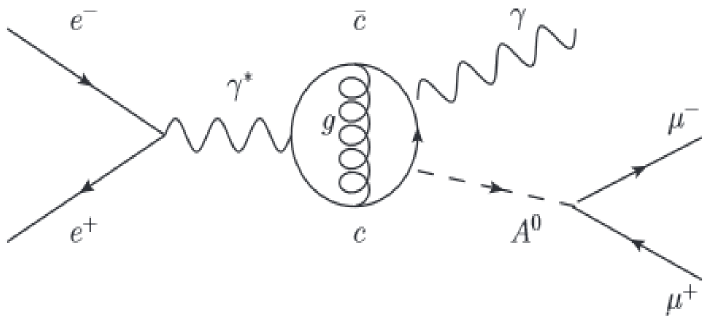


Non singlet fraction $\text{Cos}\theta_A$

Light Higgs boson A^0 search in radiative J/ψ decay

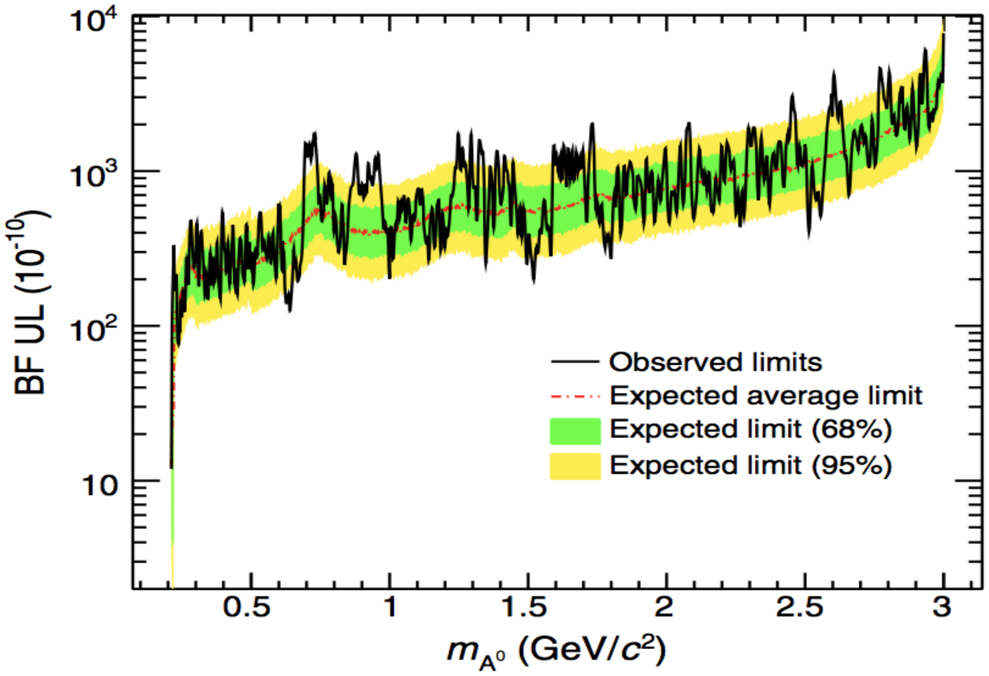
PRD 105, 012008 (2022)

Expected $B(J/\psi \to \gamma A^0) \sim 10^{-9} - 10^{-7}$ [PRD 76, 051105 (2007)]



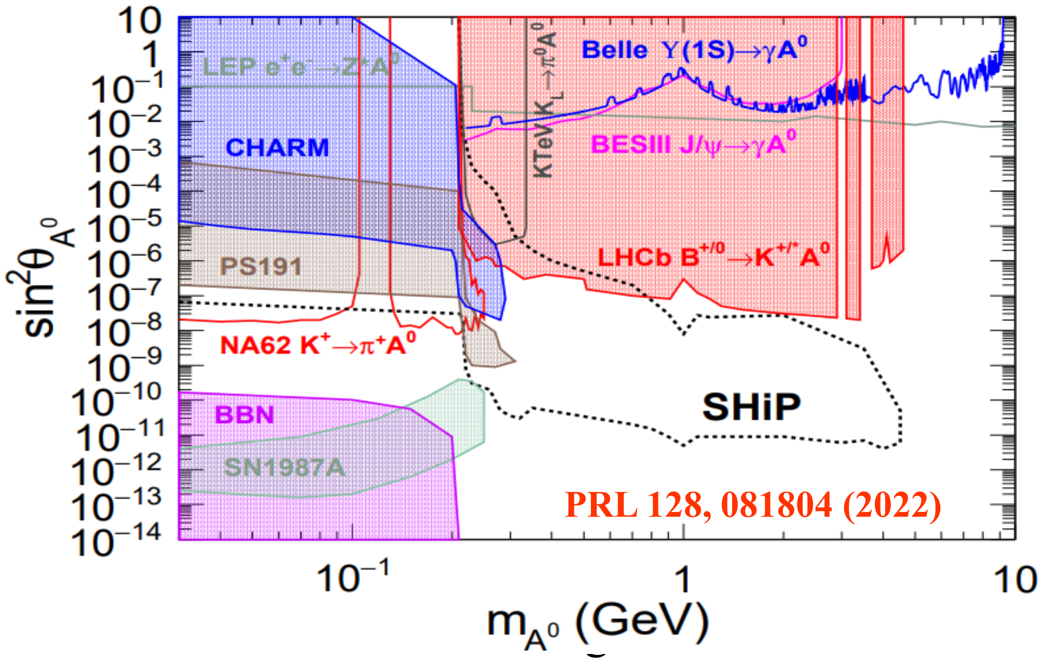
- Use 9 billion J/ψ events collected by BESIII experiment to perform this study.

- No evidence of A^0 production is found and set 90% confidence level upper limits on product BFs .



Mixing angle ($sin\theta_{A^0}$)

$$\frac{\mathcal{B}(\Upsilon(1S)\to\gamma A^0)\mathcal{B}(A^0\to\text{hadrons})}{\mathcal{B}(\Upsilon(1S)\to\ell^+\ell^-)} = \sin^2\theta_{A^0}\frac{G_F m_b^2}{\sqrt{2}\pi\alpha}\sqrt{(1-\frac{m_{A^0}^2}{m_{\Upsilon(1S)}^2})},$$



Our result in the low-mass region is better than recent BELLE measurement

Search for an Axion-like particle

An Axion-like particle (ALP), a

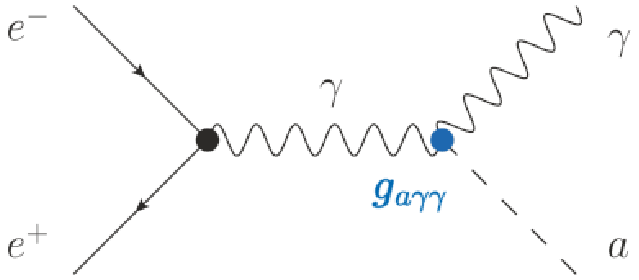
Phys. Rev. D 110, L031101 (2024)

- is a pseudo-scalar particle
- introduced by the spontaneous breaking of Peccei-Quinn symmetry to solve the strong CP problem of the QCD

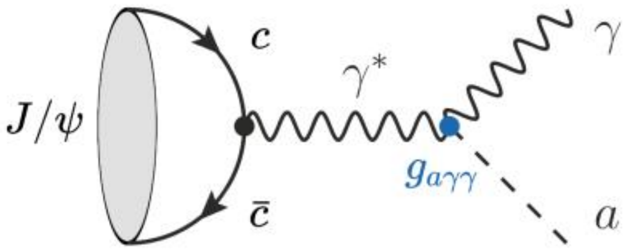
  Phys. Rev. Lett. **40**, 223 (1978); Phys. Rev. Lett. **40**, 279 (1978) Phys. Rev. Lett. **38**, 1440 (1977); Phys. Rev. D **16**, 1791 (1977)
- Predicted by many models beyond the SM and proposed to be a cold DM candidate.

  Phys. Lett. B 753, 482 (2016)
- ALP production at e^+e^- colliders
  - **ALP-Strahlung process**
  - **Radiative decay process**

Phys. Rev. D **52**, 1755 (1995)



$$\sigma_a = \frac{g^2_{a\gamma\gamma}\alpha.(\hbar.c)^2}{24}\left(1-\frac{m_a^2}{m_{J/\psi}^2}\right)^3$$

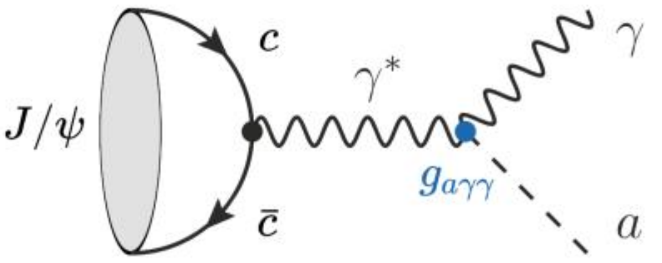


JHEP **06**, 091 385 (2019)

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

Search for ALP via radiative J/ψ decays at BESIII

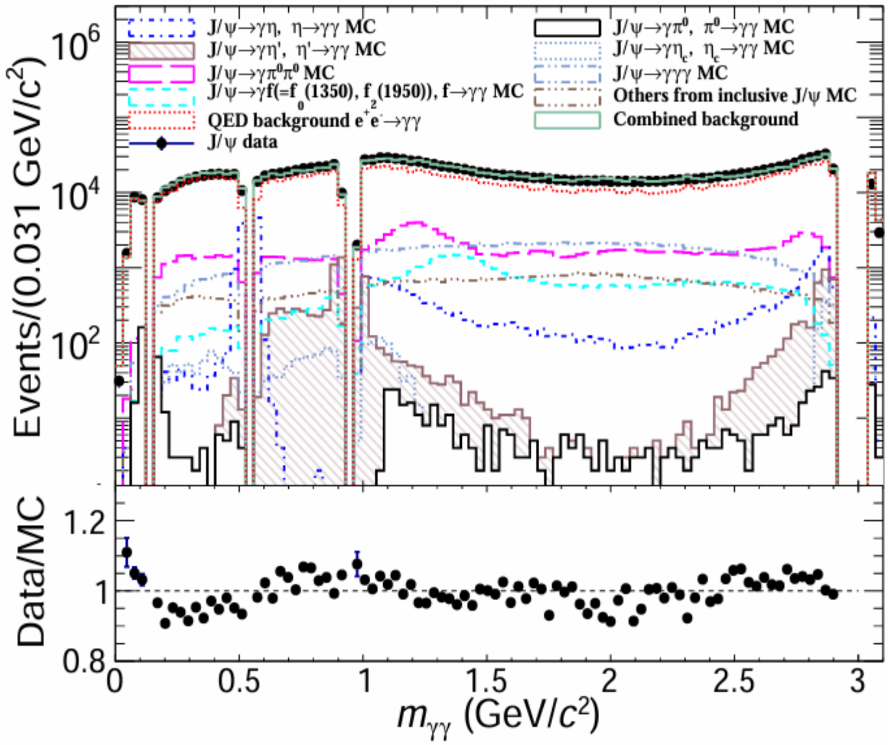
Phys. Rev. D 110, L031101 (2024)

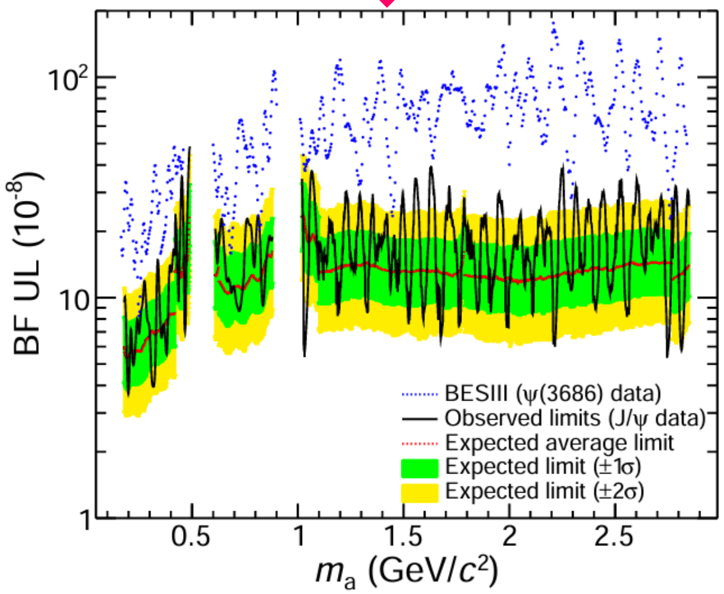


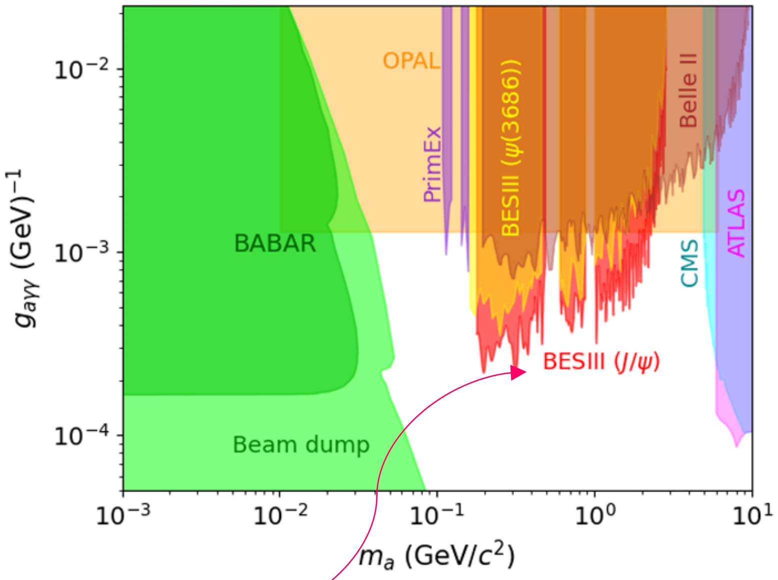
JHEP **06**, 091 385 (2019)

- 10^{10} J/ψ events
- Extract signal from $M_{\gamma\gamma}$ distribution
- Maximum signal significance: $< 3\sigma$

- UL on the BF of $\mathcal{B}(J/\psi \to \gamma a) \times \mathcal{B}(a \to \gamma\gamma)$
  $(3.6\sim53.1) \times 10^{-8}$@ 95% CL



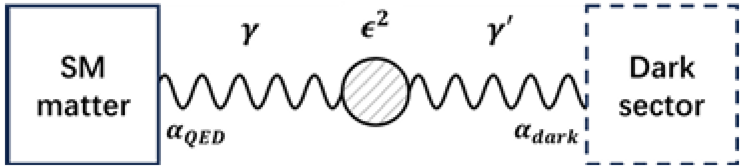




- **New stringent constraints on ALP-photon coupling for $0.18 \le m_a \le 2.85$ GeV**

Dark photon

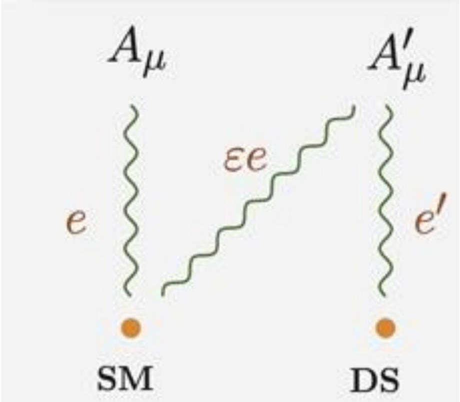
Simplest extension of the SM $\Longrightarrow$ An extra Abelian gauge group, $\boldsymbol{U(1)_D}$ $\Longrightarrow$ dark photon



B. Batell, et al, PRD **79**, 115008 (2009);
R. Essig, et al, PRD **80**, 015003 (2009)

Massive dark photon

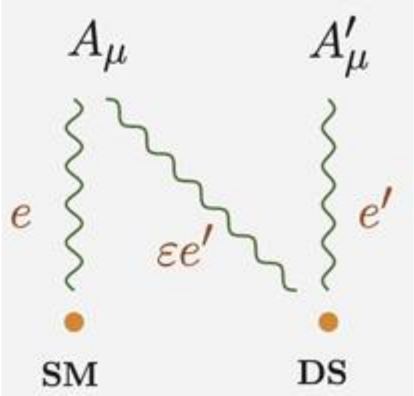
arises when the symmetry of the additional Abelian gauge group is spontaneously broken



- Massive dark photon
- Coupling with SM fermion
- Strong constraint

Massless dark photon

Symmetry remains unbroken



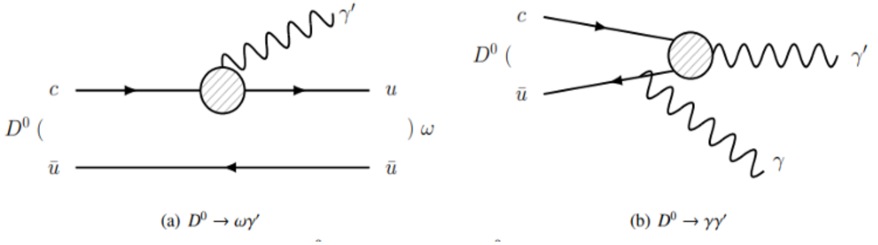
- Massless dark photon
- No direct coupling with SM fermion
- Less constraint
- Also, important role in dark sector

A dimension-six operator has been proposed to provide a connection between SM fermions and the massless dark photon

$$\mathcal{L}_{\rm NP} = \frac{1}{\Lambda_{\rm NP}^2}(C^U_{jk}\bar{q}_j\sigma^{\mu\nu}u_k\tilde{H} + C^D_{jk}\bar{q}_j\sigma^{\mu\nu}d_kH + C^L_{jk}\bar{l}_j\sigma^{\mu\nu}e_kH + \text{H.c.})F'_{\mu\nu}$$

- Naturally allow the FCNC coupling
- Less background and higher sensitivity

PRL **94**, 151802 (2005)

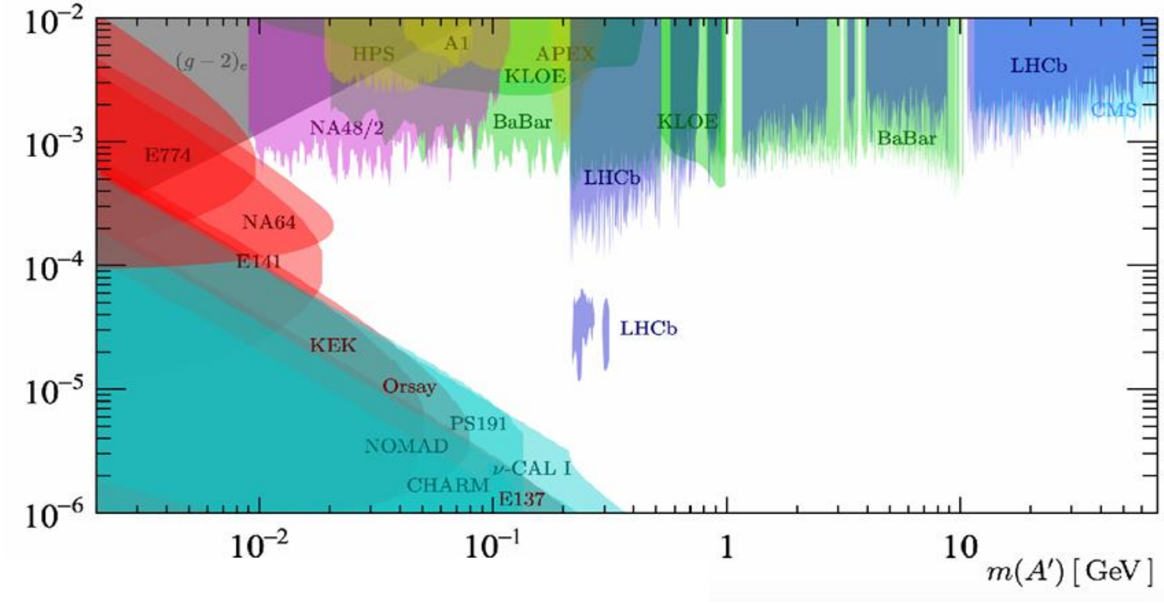


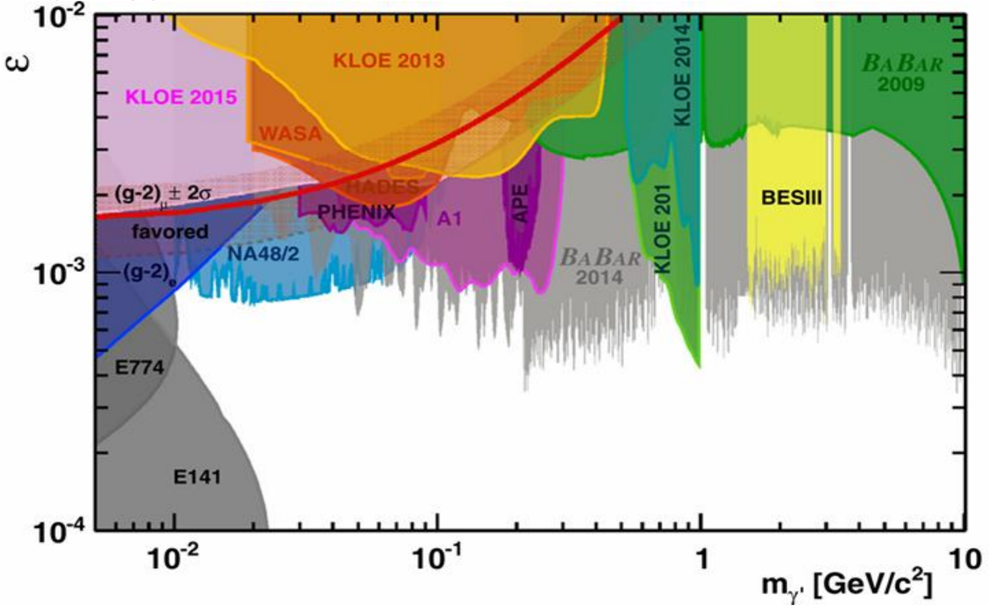
(a) $D^0 \to \omega\gamma'$

(b) $D^0 \to \gamma\gamma'$

Current status of massive dark photon searches

Visible final states



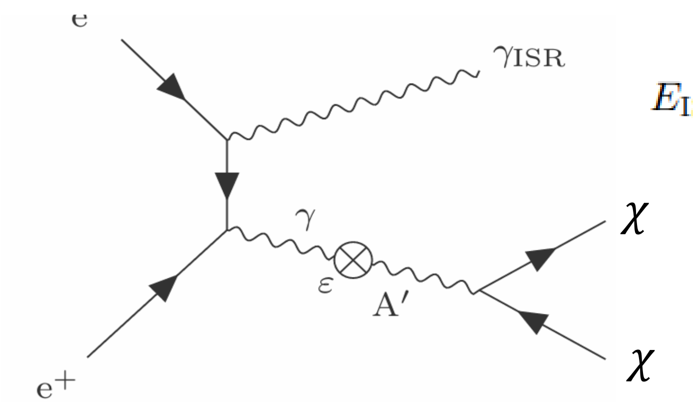


LHCb: PRL (2020) 124 041801

Babar: arXiv:1406.2980

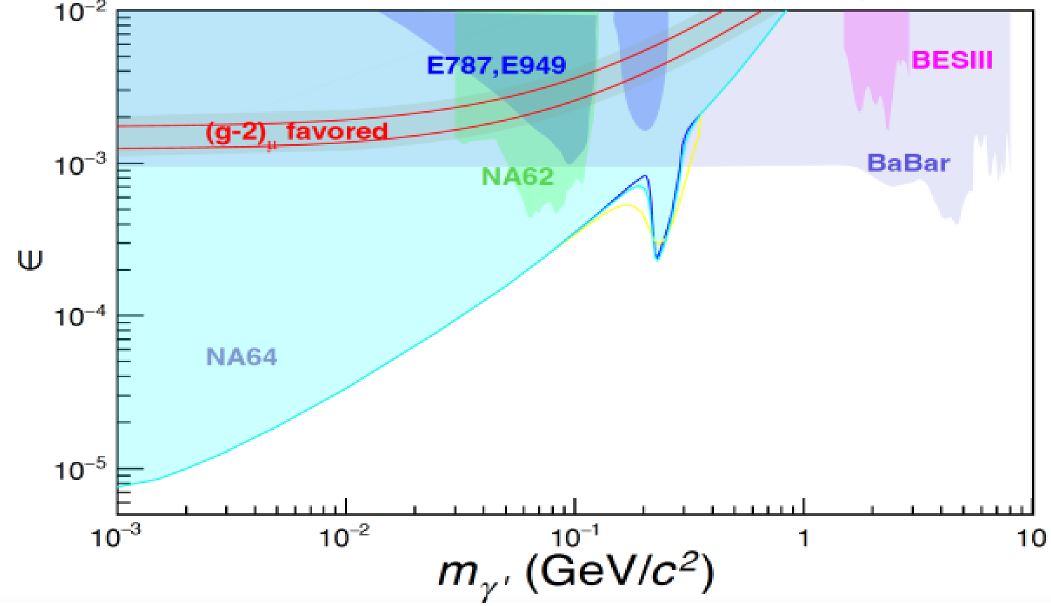
BESIII: arXiv:1705.04265

Invisible final state



$$E_{\rm ISR} = \frac{s - m_{\gamma'}^2 c^4}{2\sqrt{s}},$$

BESIII: PLB 839, 137785 (2023)



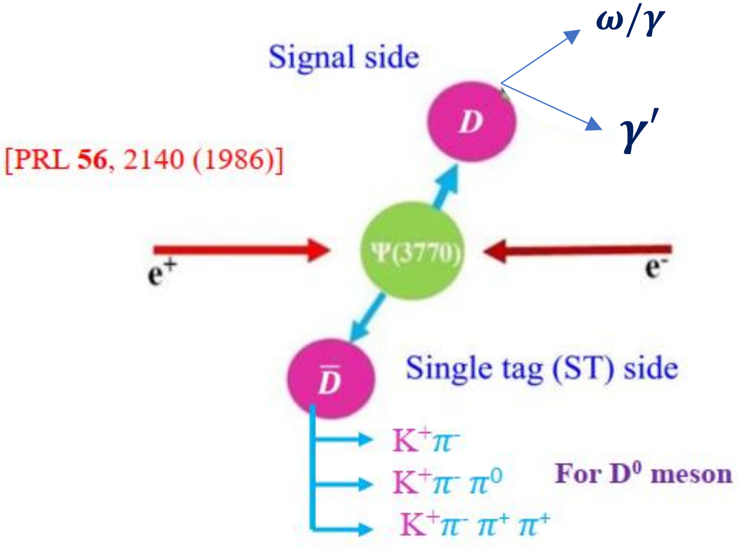
BaBar: Phys. Rev. Lett. **119**, 131804 (2017)

Search for a massless dark photon in $D^0 \to \omega/\gamma\gamma'$

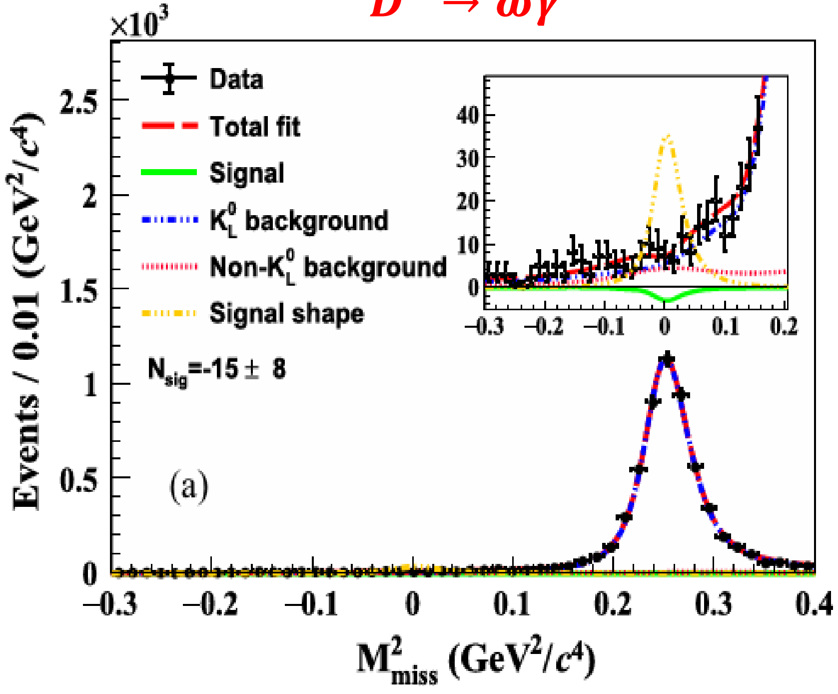
PRD 111, L011103 (2025)

- Search is based on 7.9 fb^{-1} $\psi(3770)$ data using a double tag (DT) technique
- The signals of the massless dark photon are extracted from a fit on the distribution of missing mass square

$$M^2_{\mathrm{miss}} = |p_{\mathrm{c.m.s.}} - p_{\bar{D}^0} - p_{\omega(\gamma)}|^2/c^4$$

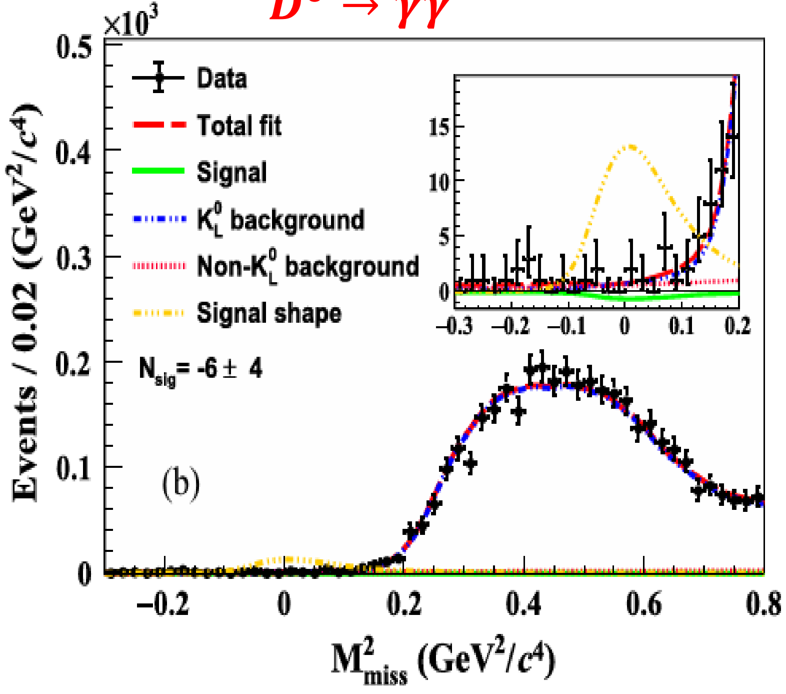


$D^0 \to \omega\gamma'$

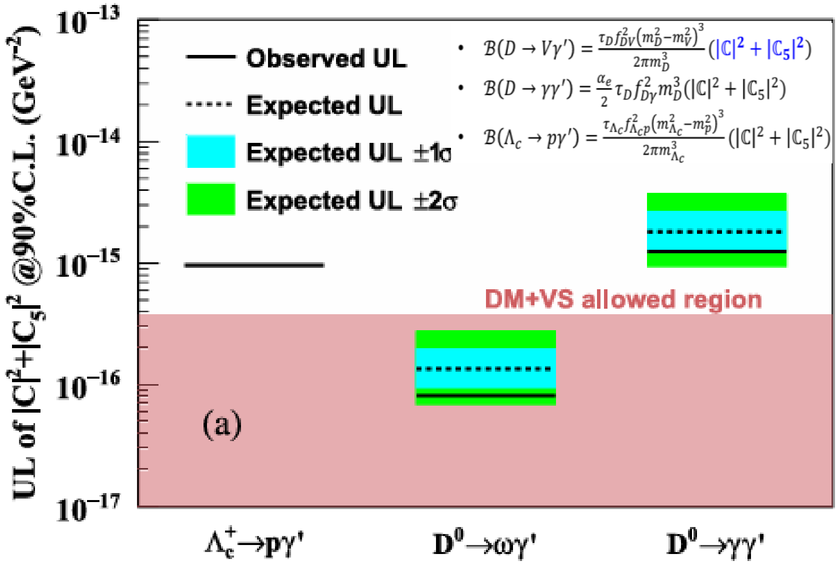


$\mathrm{B}(D^0 \to \omega\gamma') < 1.1 \times 10^{-5}$

$D^0 \to \gamma\gamma'$



$\mathrm{B}(D^0 \to \gamma\gamma') < 2.0 \times 10^{-6}$



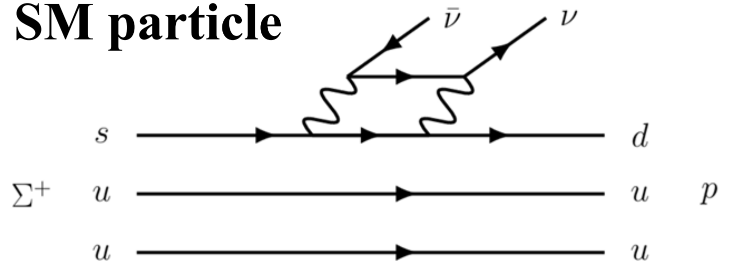
- $\mathcal{B}(D \to V\gamma') = \frac{\tau_D f_{DV}^2 (m_D^2 - m_V^2)^3}{2\pi m_D^3}(|\mathbb{C}|^2 + |\mathbb{C}_5|^2)$
- $\mathcal{B}(D \to \gamma\gamma') = \frac{\alpha_e}{2}\tau_D f_{D\gamma}^2 m_D^3(|\mathbb{C}|^2 + |\mathbb{C}_5|^2)$
- $\mathcal{B}(\Lambda_c \to p\gamma') = \frac{\tau_{\Lambda_c} f_{\Lambda_c p}^2 (m_{\Lambda_c}^2 - m_p^2)^3}{2\pi m_{\Lambda_c}^3}(|\mathbb{C}|^2 + |\mathbb{C}_5|^2)$

$\Sigma^+ \to p +$ invisible and QCD axion

PLB 852, 138614 (2024)

$\Sigma^+ \to p +$ invisible

Decay to SM particle



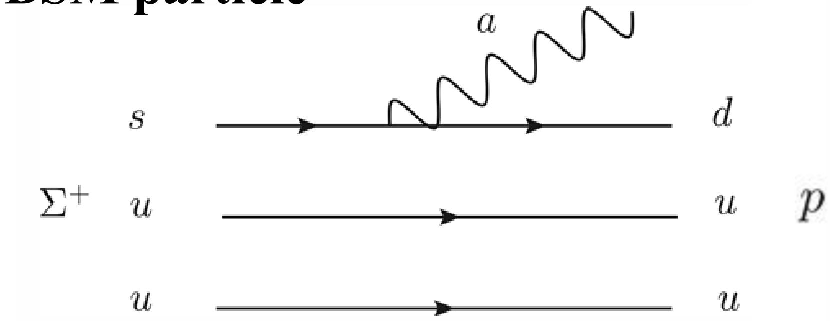
- $s \to d\nu\bar{\nu}$ is a FCNC process and highly suppressed by GIM mechanism

PRD **2**, 1285 (1970)

- BF $< 10^{-11}$

Rep. Prog. Phys. 86, 016201 (2023)

Decay to BSM particle

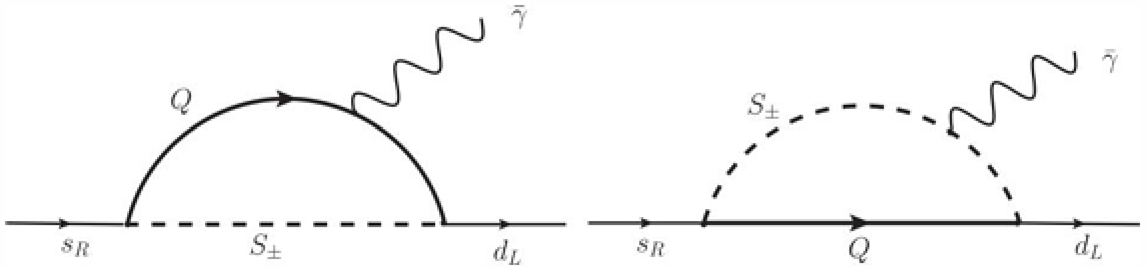


$$m_a \propto 1/f_a \Rightarrow m_a \ll 1\text{eV}$$

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

$$\frac{M^3_{\Sigma^+}}{16\pi}\left(1-\frac{M_p^2}{M^2_{\Sigma^+}}\right)^3\left(\frac{(-1)^2}{|F^V_{sd}|^2}+\frac{0.34^2}{|F^A_{sd}|^2}\right)$$

Our measurement can set limits on axion-fermion effective decay constants



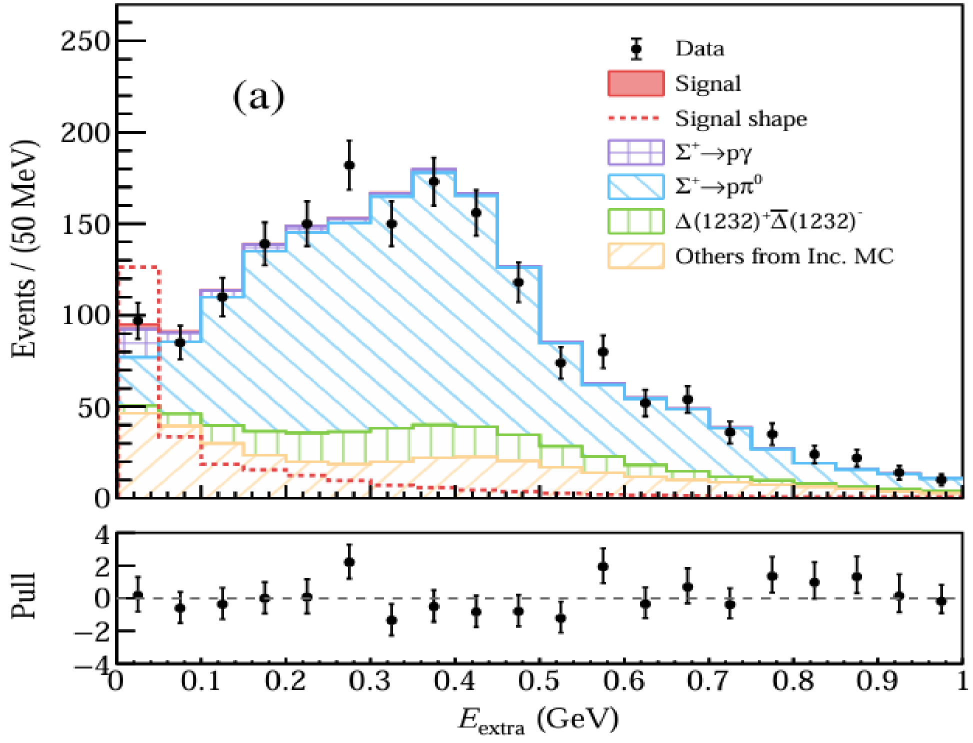
PRD 102 015023 (2020)

Massless dark photon

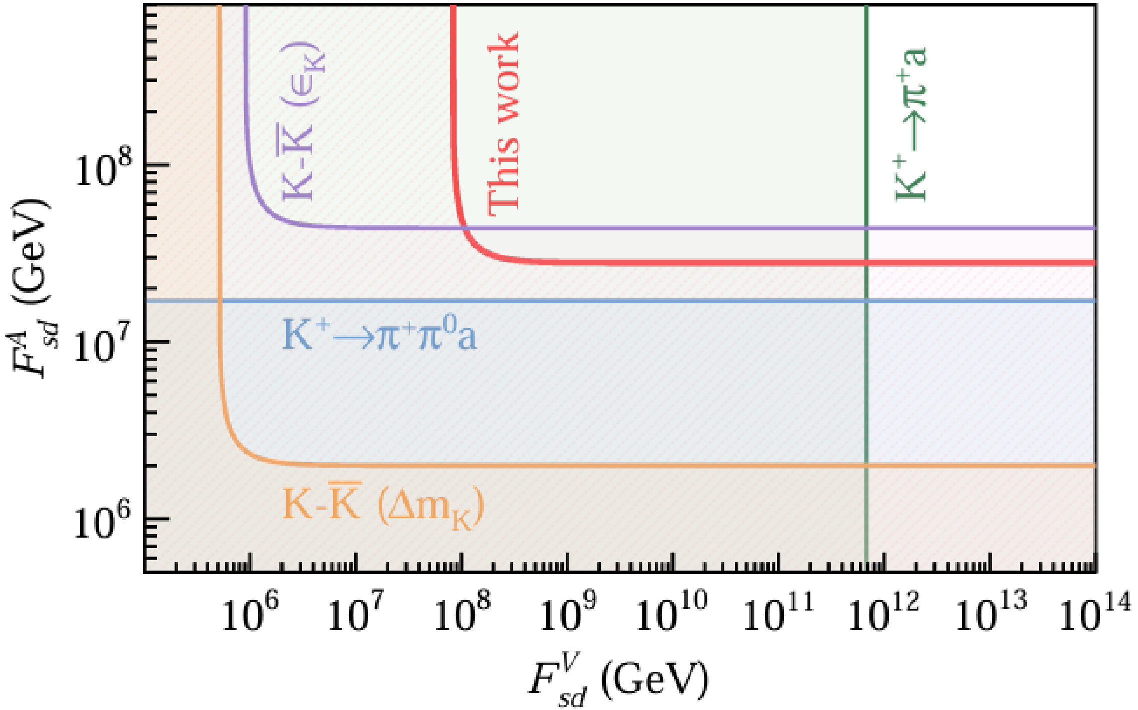
Search for $\Sigma^+ \to p + \text{invisible}$ at BESIII

PLB 852, 138614 (2024)

- Search is performed via $J/\psi \to \Sigma^+\bar{\Sigma}^-$ using 10 billion J/ψ events using double tag technique
- Invisible particle with mass hypothesis of zero
- Total energy deposited in EMC by extra photons is used to extra the signal



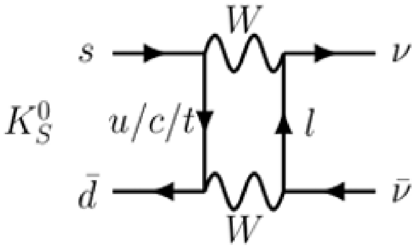
$$B(\Sigma^+ \to p + invisible) < 3.2 \times 10^{-5} \text{ @ 90\% C.L.}$$



Competitive limits on the axial-vectorial part of axion-fermion effective decay constant F_{sd}^A

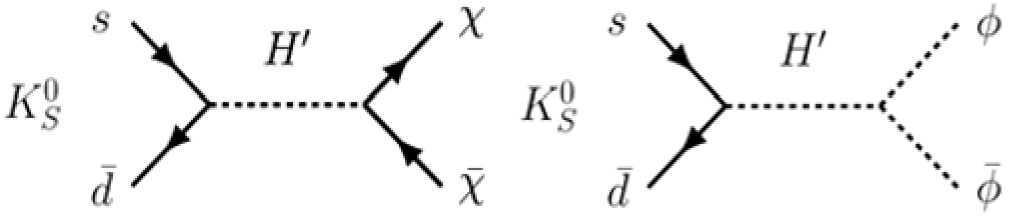
Invisible K_S^0 decays

✓ **SM decays**



Very rare (BF < 10^{-16})
FCNC and Helicity suppression
Phys. Rev. D **91**, 015004 (2015)

✓ **Decay to DM particles**



Two Higgs doublet model (2HDM)
BF~$\mathcal{O}(10^{-6})$
Natural Sci. Rev. **1**, 5 (2024)

✓ **Ordinary matter particle oscillation**

$K_S^0 \dashrightarrow K_S^{0\prime}$

Mirror matter model
BF~$\mathcal{O}(10^{-6})$

arXiv: 2006.10746

✓ **Input for CP test**

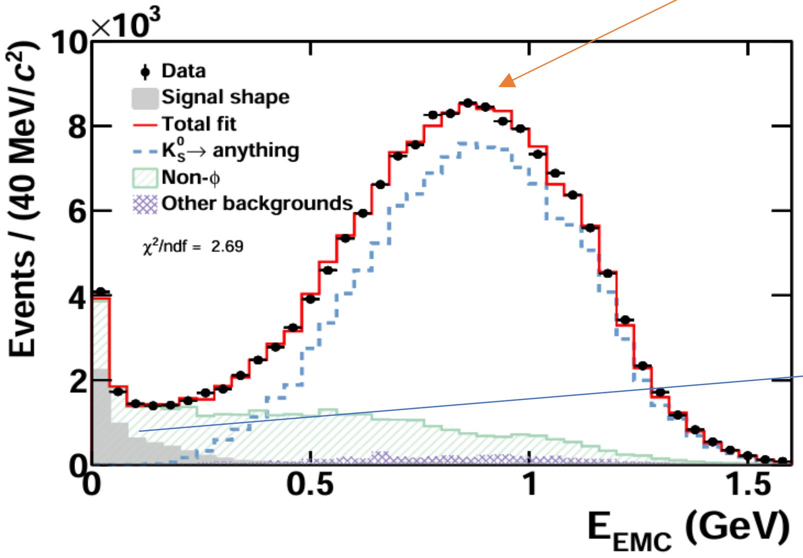
Bell-Steinberger relation **connects CPTV** to the amplitudes of all decay channels of neutral kaons.
BUT currently assumes no invisible modes

Invisible K_S^0 decays

JHEP 05, 092 (2025)

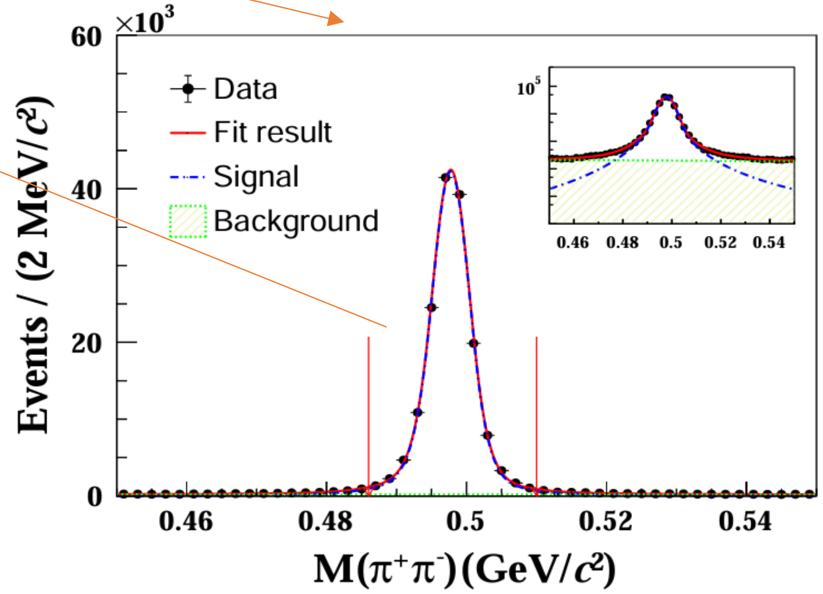
- Search is based on 10 billion J/ψ events collected by the BESIII detector via $J/\psi \to \phi K_S^0 K_S^0$ decay.
- $J/\psi \to \phi K_S^0 K_L^0$ is forbidden by C-parity conservation.
- K_S^0 →invisible decay rate can be calculated as,

$$\mathcal{B}(K_S^0 \to \text{ invisible}) = \frac{N_{\text{signal}}}{N_{\text{non}-\pi^+\pi^-}\left(\varepsilon_{\text{signal}}/\varepsilon_{\text{non}-\pi^+\pi^-}\right)}\left(1 - \mathcal{B}(K_S^0 \to \pi^+\pi^-)\right)$$



Backgrounds from four-pion and non-phi backgrounds are subtracted

No evidence of the signal production for K_S^0 →invisible is found



$B(K_S^0$ →invisible) $< 8.4 \times 10^{-4}$ at the 90% CL (First direct measurement).

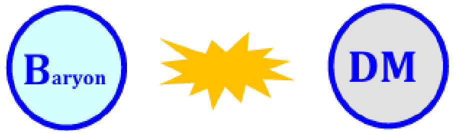
Dark baryon

arXiv: 2505.22140 (2025)

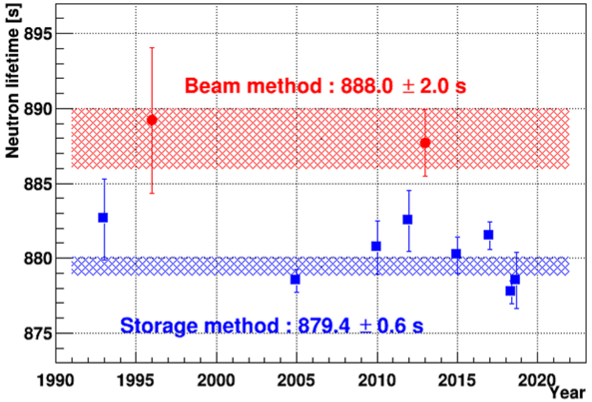
- **Coincidence issue:** Similarity between DM and baryon densities: $\rho_{DM} \approx 5.4\rho_{baryon}$

Potential connection between their origins

DM may have non-zero baryon number



- **Neutron lifetime puzzle**



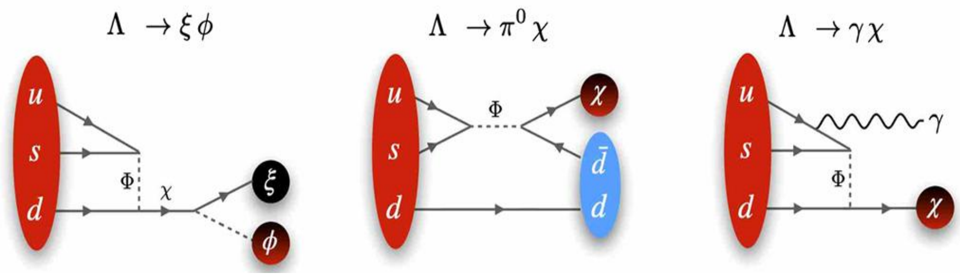
$$\tau_n^{\text{beam}} = \frac{\tau_n^{\text{bottle}}}{\text{Br}(n \to p + \text{ anything })}$$

$$\mathcal{B}(n \to \text{dark}) \sim 1\%$$

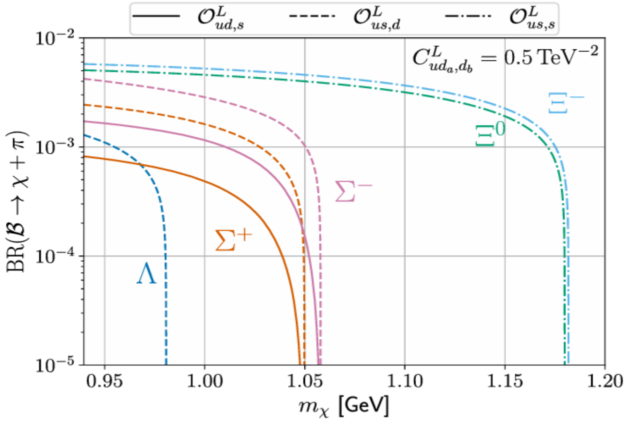
- Motivates the existence of dark baryon

- **B-Mesogenesis mechanism:** Can explain the symmetry between visible mater and antimatter and origin of DM.

- **Hyperon dark decays**



PRD **105**, 115005 (2022)

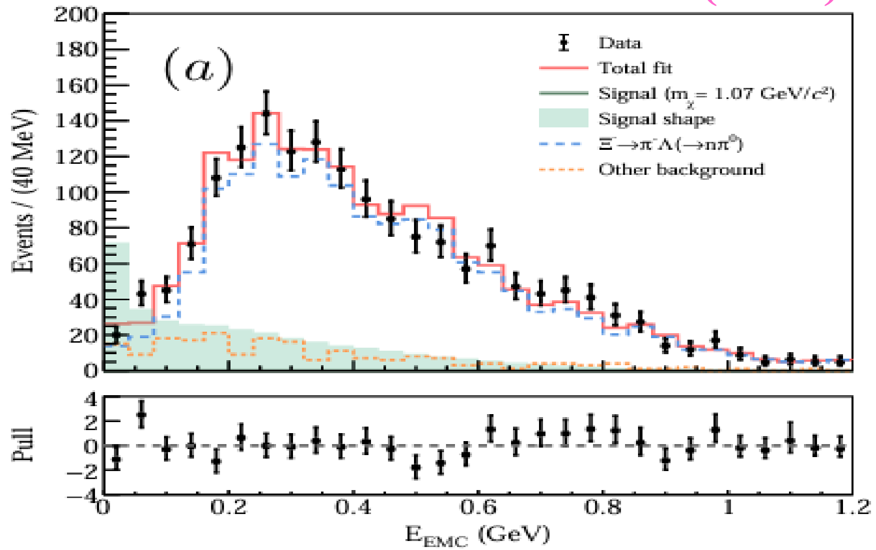


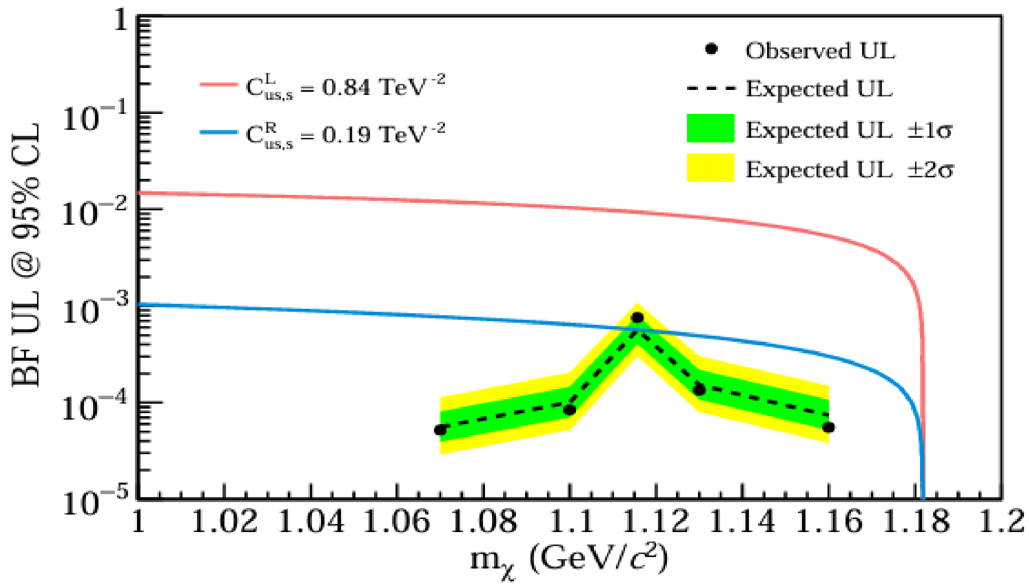
Search for dark baryon in $\Xi^- \to \pi^- \chi$

arXiv: 2505.22140 (2025)

Analysis strategy:

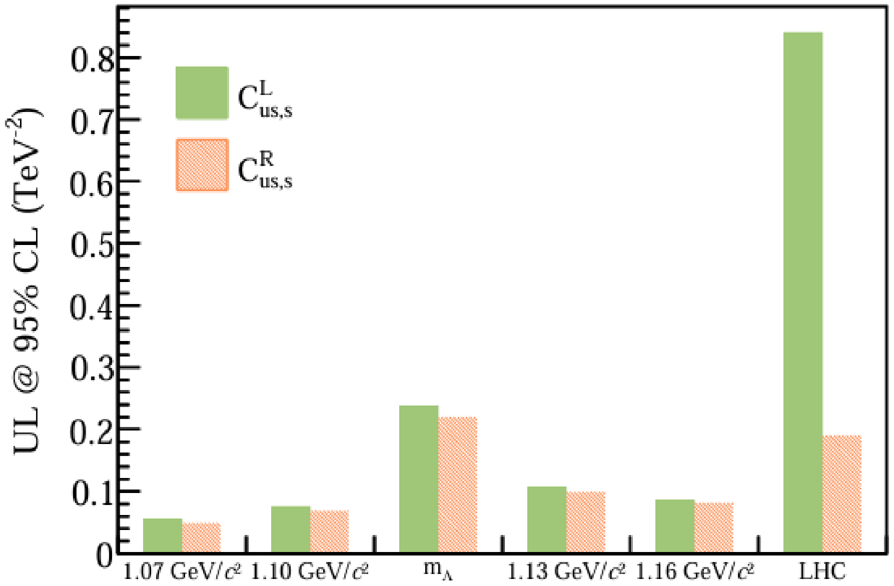
- $J/\psi \to \bar{\Xi}^+ \Xi^-$ from 10 billion J/ψ events
- Double tag method: $\bar{\Xi}^+ \to \bar{\Lambda}\pi^+$, $\bar{\Lambda} \to \bar{p}\pi^+$, $\Xi^- \to \pi^- + \chi$
- χ is the dark baryon with an invisible signature with masses of 1.07, 1.10, m_Λ, 1.13, 1.13 GeV/c^2
- The invisible signal should have EMC energy deposit peaking at zero
- No evidence of significant signal events





90% C.L. UL on $B(\Xi^- \to \pi^- + \chi)$ varies from $(4.5 - 76) \times 10^{-5}$

Corresponding Wilson coefficients C^L_{uss} and C^R_{uss} are more stringent than the previous limits from the LHC searches for the colored mediators



Search for an invisible muon philic scalar X_0 or vector X_1 via $J/\psi \to \mu^+\mu^-$+invisible

PRD 109, L031102 (2024)

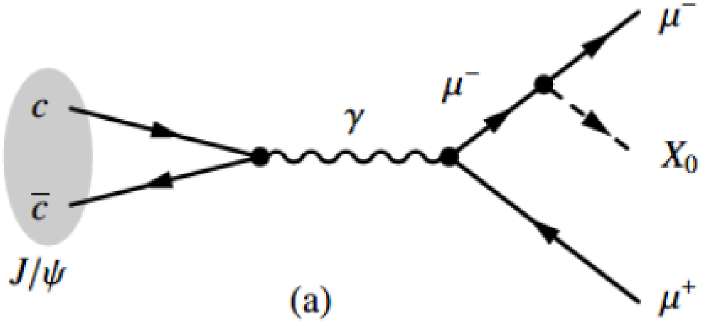
- A new type of massive vector meson X_1 or scalar boson X_0 may appear in SM extension of the anomaly free gauged U(1) or $U(1)_{L_\mu - L_\tau}$ model.
- They only couple to the second or third generations of leptons $(\mu, \nu_\mu, \tau, \nu_\tau)$ with the coupling strength $g'_{0,1}$.
- The $X_{0,1}$ can contribute to the muon anomalous magnetic moment and explain the $(g\text{-}2)_\mu$ anomaly.

$$\Delta a_\mu^{scalar} = \frac{g_0^2}{8\pi^2}\int_0^1 dx \frac{m_\mu^2(1-x)(1-x^2)}{m_\mu^2(1-x)^2 + m_{Z'}^2 x}$$

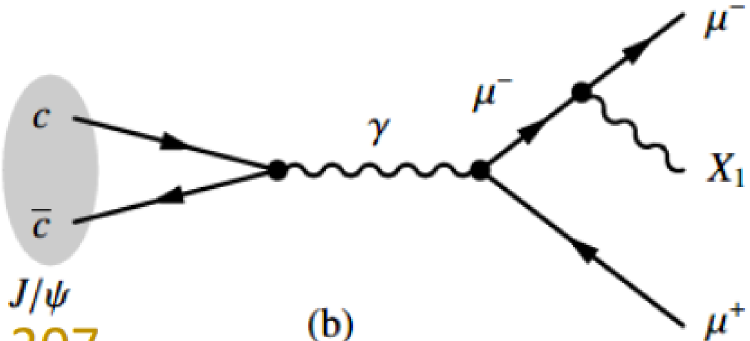
$$\Delta a_\mu^{vector} = \frac{g_1^2}{8\pi^2}\int_0^1 dx \frac{2m_\mu^2 x(1-x)^2}{m_\mu^2(1-x)^2 + m_{Z'}^2 x}$$

arXiv:1610.06587 (2016)

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



(a)



(b)

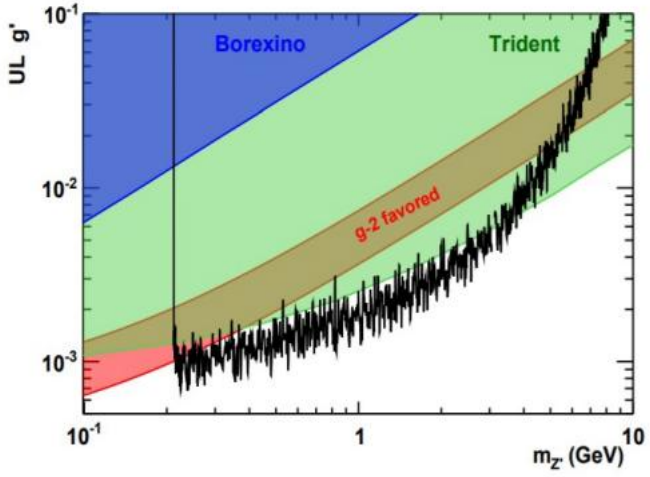
JHEP 10 (2020) 207

Search for an invisible muon philic scalar X_0 or vector X_1 via $J/\psi \to \mu^+\mu^-$+invisible

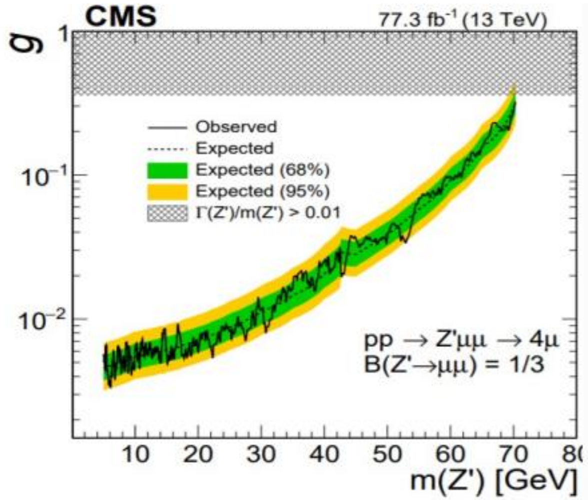
PRD 109, L031102 (2024)

- Current experimental constraints:

  - The g’ space with $Z' \to \mu^+\mu^-$

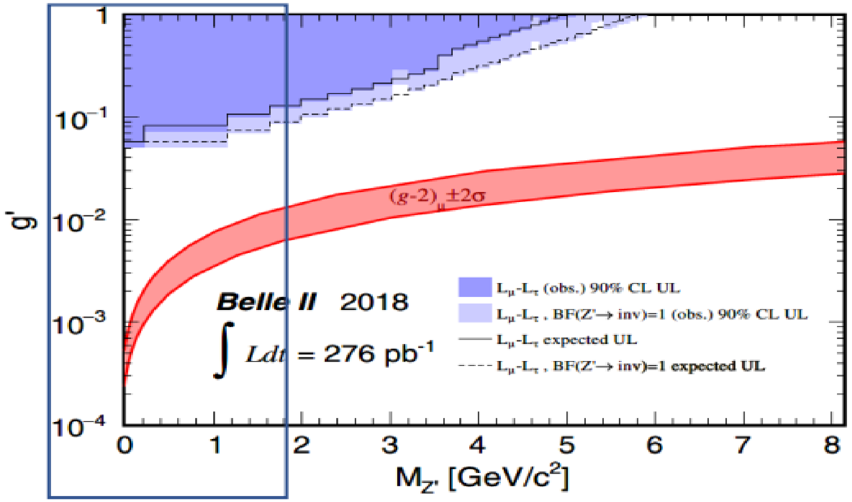


BaBar: PRD.94.011102



CMS: PLB 792, 345

  - The g’ space with $Z' \to invisible$



Belle II: PRL124 14, 141801

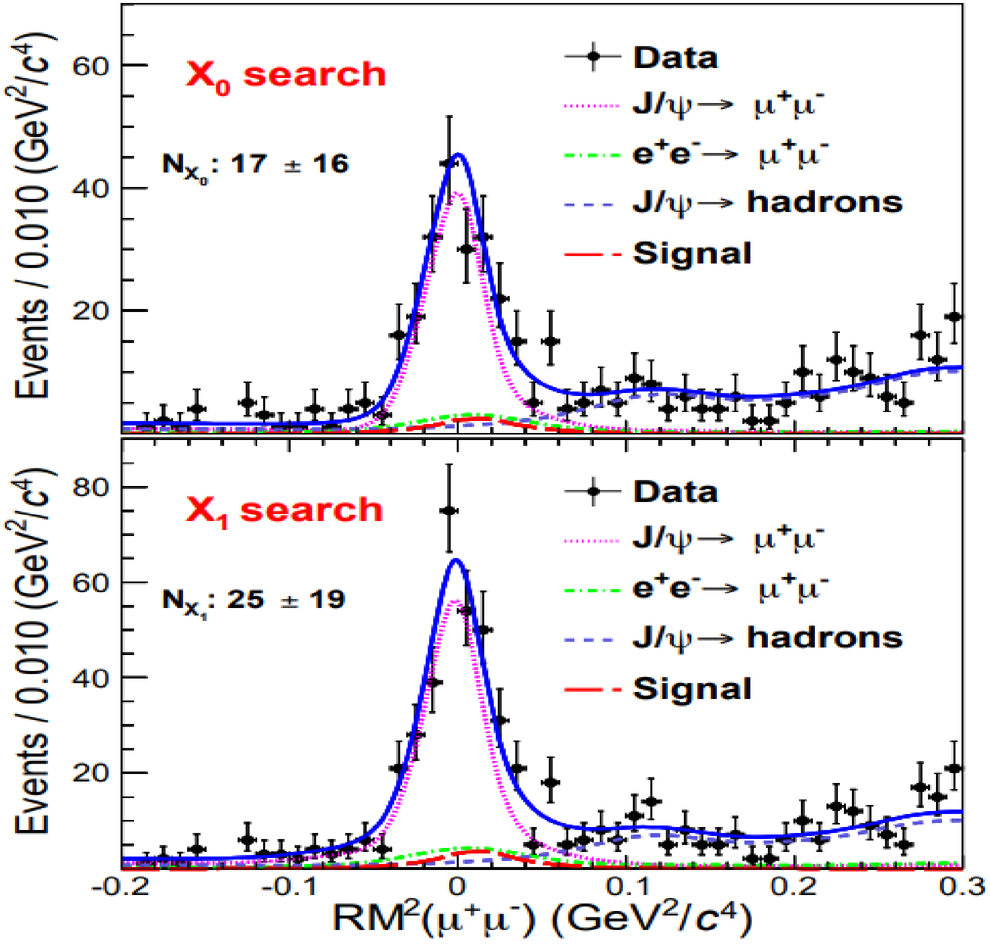
✓ BESIII can contribute to the low mass region

Search for a light muon philic scalar X_0 or vector X_1 is performed via $J/\psi \to \mu^+\mu^- X_{0,1}$ with $X_{0,1}$ invisible decays using $(8.998 \pm 0.039) \times 10^9$ J/ψ events collected by the BESIII experiment.

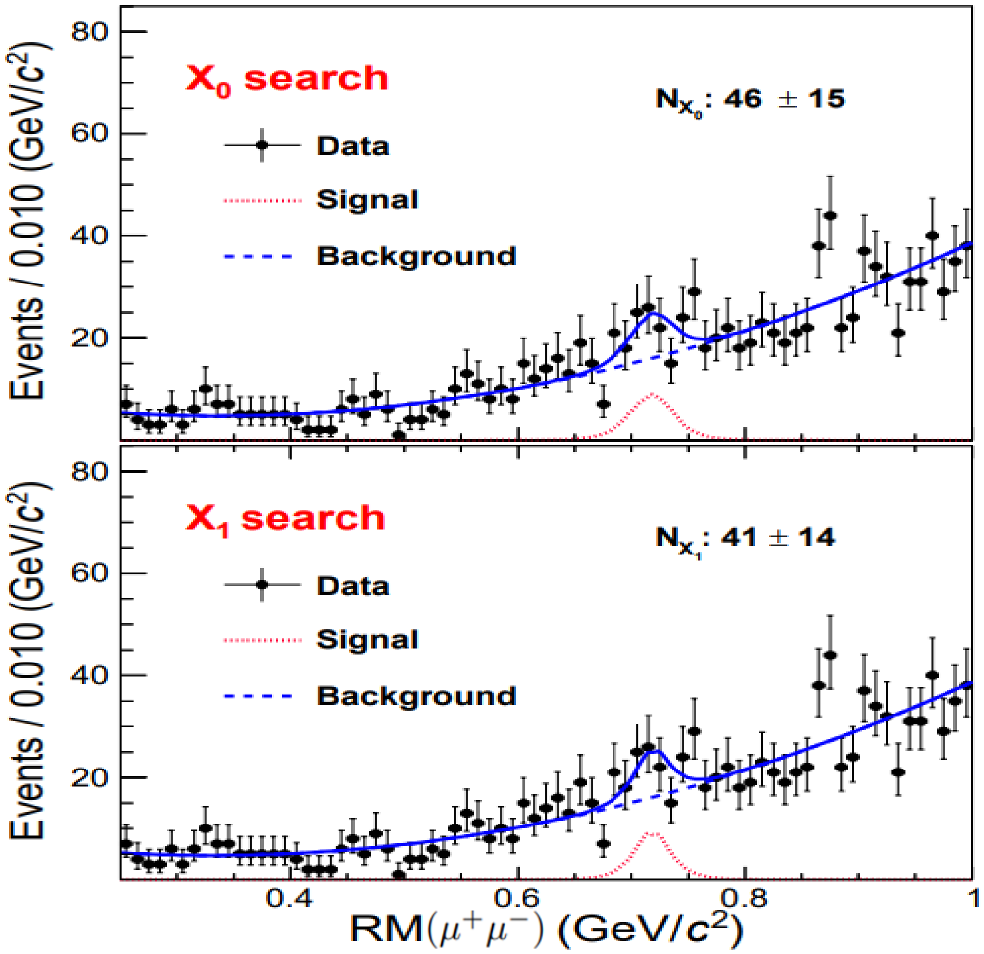
Search for an invisible muon philic scalar X_0 or vector X_1 via $J/\psi \rightarrow \mu^+\mu^-$+invisible

PRD 109, L031102 (2024)

Signal yield is extracted by performing a series of ML fits.



$$RM^2(\mu^+\mu^-) = (p_{J/\psi} - p_{\mu^+} - p_{\mu^-})^2$$



Search for an invisible muon philic scalar X_0 or vector X_1 via $J/\psi \to \mu^+\mu^-$+invisible

PRD 109, L031102 (2024)

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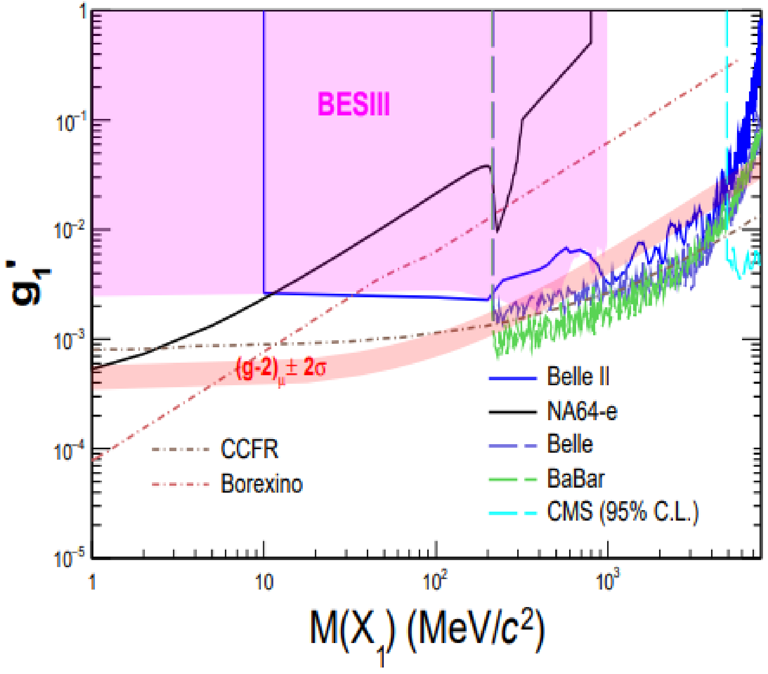
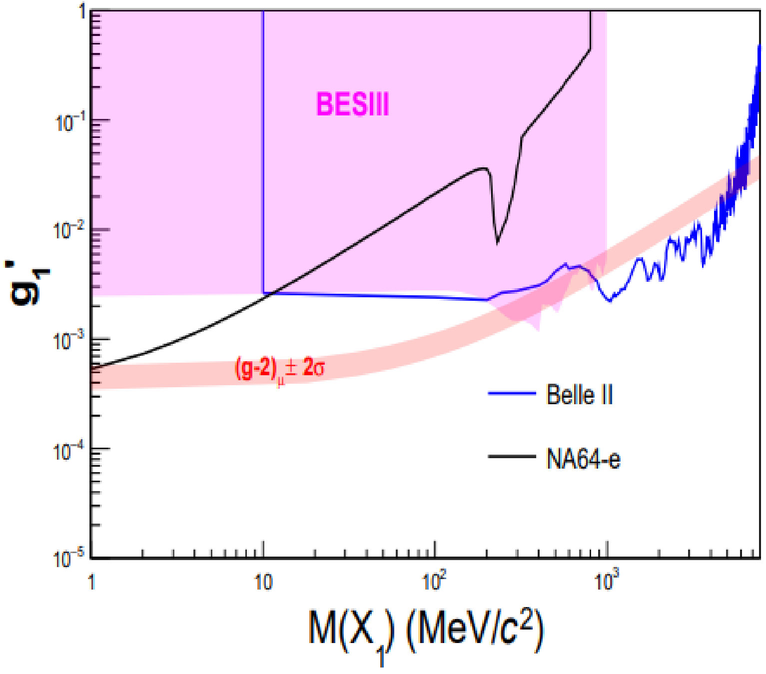
“vanilla” $L_\mu - L_\tau$ model



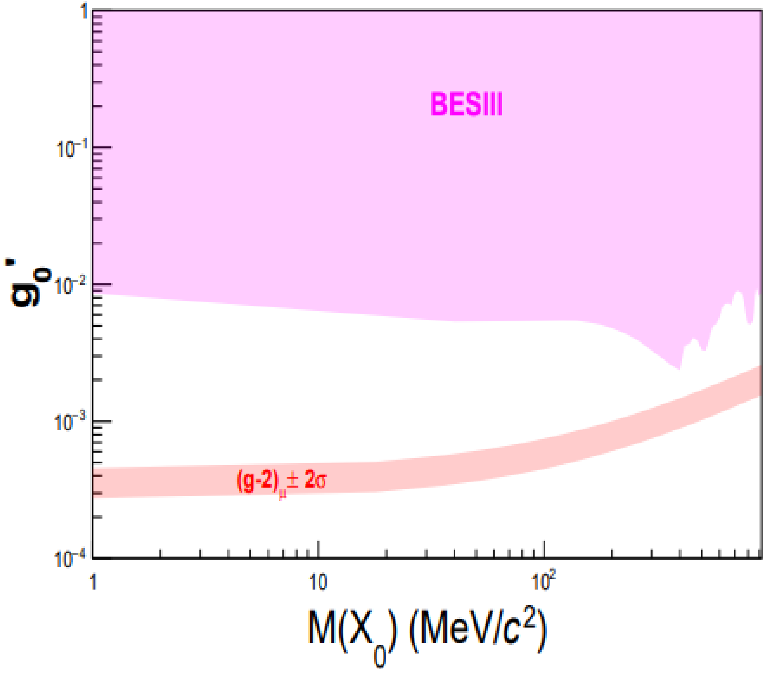
$B(X_{0,1} \to \nu\bar{\nu})$~$(33-100)\%$

“invisible” $L_\mu - L_\tau$ model



$\mathcal{B}(X_1 \to \chi\bar{\chi}) \simeq 1$

“scalar” $U(1)$ model



X_0 is long-lived with displaced decay or predominately decays to invisible particles

Summary

- Top priority is to search for new physics beyond the SM .
- BESIII plays a unique role to search for dark sector from e^+e^- collisions at the tau-charm region.
- A series of searches for invisible decays, dark photon, ALP and muon-philic particles have been performed at BESIII.
- Only null results are available so far.
- BESIII limits exclude a large fraction of the parameter space of the new physics models beyond SM.
- More results is expected to come in the near future, especially with recently collected 20 fb^{-1} of $\psi(3770)$ data.

Chin. Phys. C **44**, 040001 (2020)

Thanks!