Search for rare phenomena at BESIII

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Outline

- Motivation
- BESIII experiment
- Charmonium weak decays
  - Search for the semi-muonic charmonium decay $J/\psi \to D^- \mu^+ \nu_\mu$
  - Search for weak decays of $J/\psi \to DX$ $(X = \pi^{\pm,0}, \eta, \rho^{\pm,0})$
- Exotic particle searches
  - Search for an Axion-like particle
  - Search for invisible muon philic scalar X_0 or vector X_1 via $J/\psi \to \mu^+\mu^-$+invisible
  - Invisible decays of dark photon
  - Search for a massless dark photon in $\Lambda_c^+ \to p\gamma'$
- Summary

Motivation

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

- **But, it can't be considered to be theory of everything**

  - **Tensions with some experimental measurements:**

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

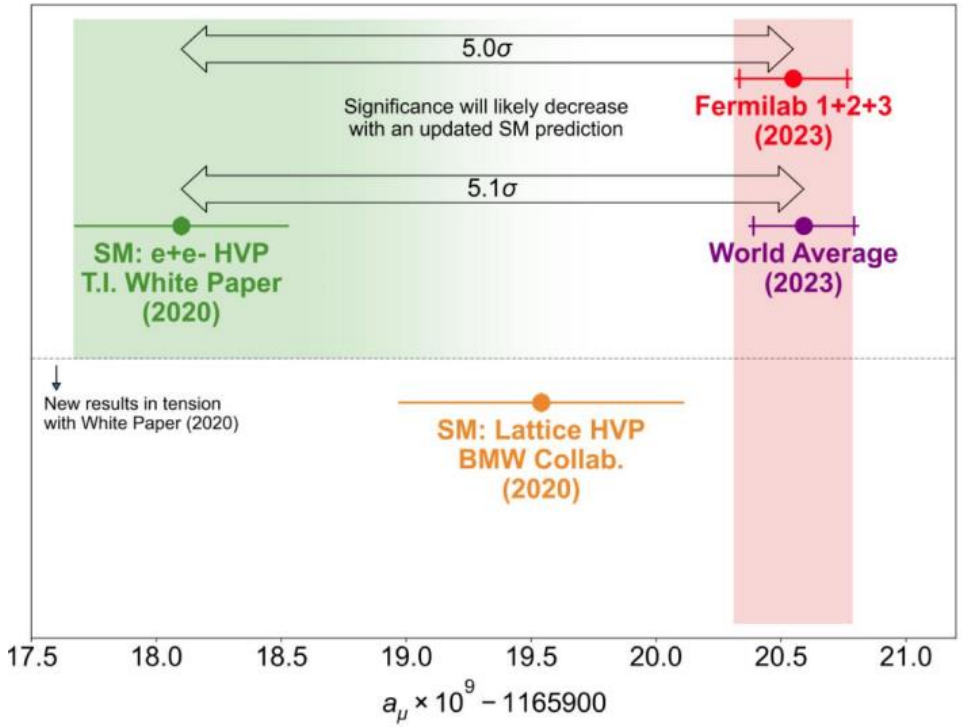
  - **Unable to explain:**

    Existence & mechanism of dark matter and dark energy

    Baryon asymmetry of the universe

    Neutrino masses and oscillations, hierarchy

Current status of anomalous magnetic moment



D. P. Aguillard, et. al. (Muon g-2 Collaboration)
arXiv:2308.06230

Real opportunity to search for new physics beyond the SM

New physics search approaches

Very rare decays

Symmetry

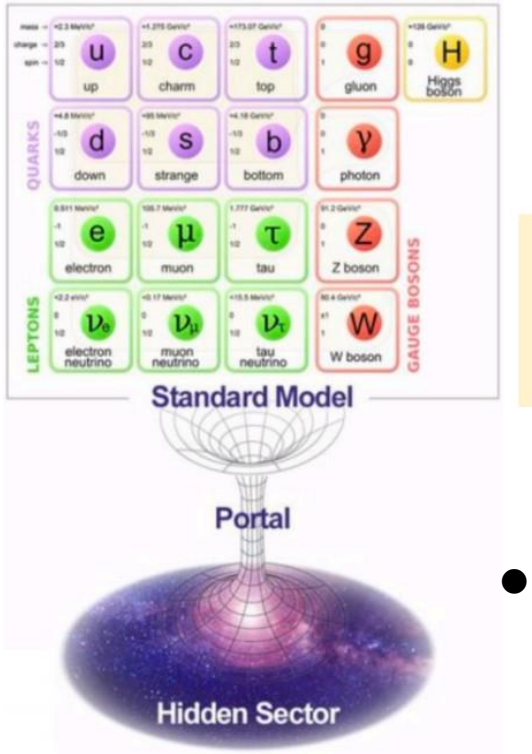
- BNV & LNV processes
- LFV processes
- Other symmetry violation

- FCNC processes
- Charmonium weak decays
- Other rare decays

Very rare

Exotic particles

- Invisible signature
- Muon philic vector/scalars
- Dark matter portals



Dark matter portals allow the connection between the SM particles with the dark matter within a 'dark matter hidden sector' model

arXiv:1311.0029 (2013)

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

A' kinetic mixing with γ, Z

Dark Higgs (mixes with SM Higgs)

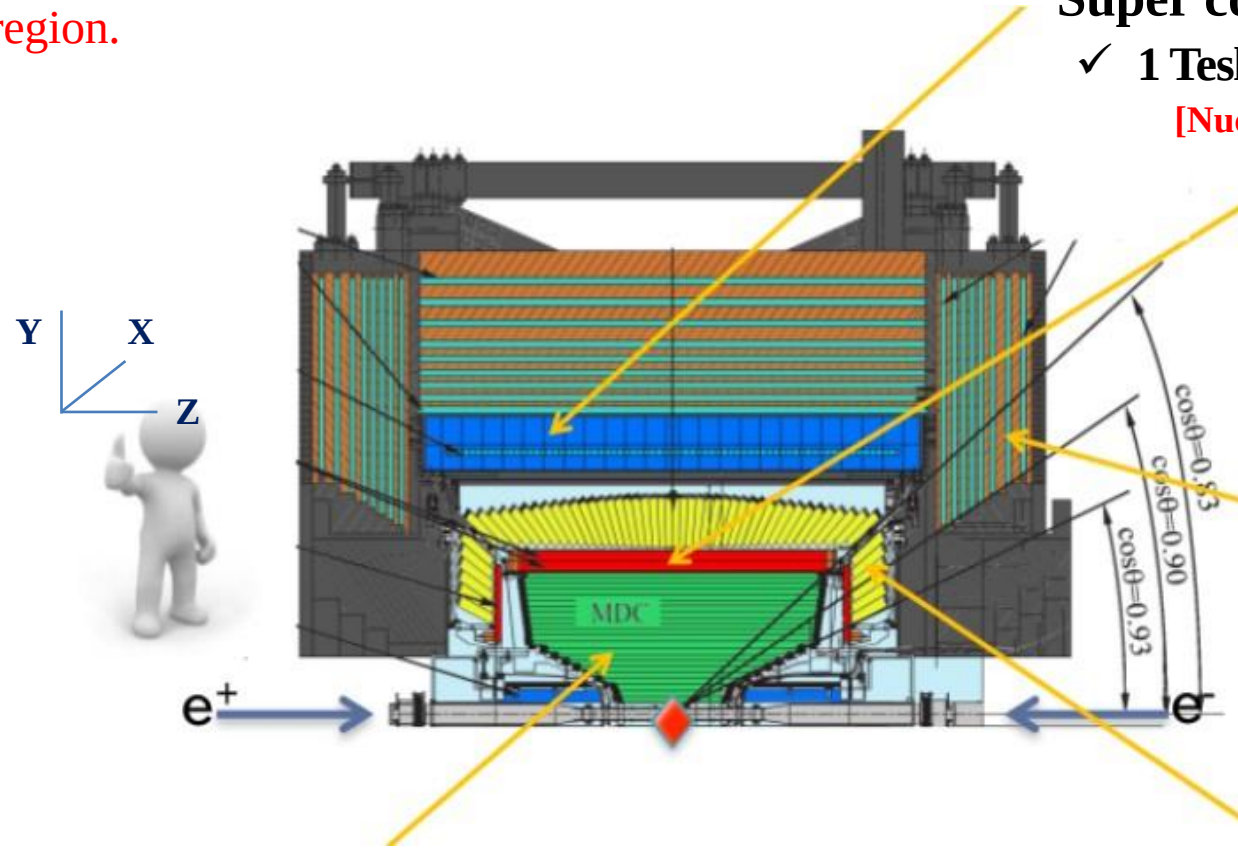
Sterile neutrino

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

A symmetric electron positron collider running at tau-charm region.



Super conducting magnet

✓ 1 Tesla

[Nucl. Instrum. Meth. A614, 345-399 (2010)]

Time of Flight (TOF)

- 2 layer plastic scintillators
- $\sigma_T \approx 68$ ps (barrel)
- $\sigma_T \approx 110$ ps (endcap) (~65 ps after upgradation with MRPC)
- Particle id

Muon system

- 9 layers of RPC
- P > 400 MeV/c
- $\delta R\phi \approx 1.4 – 1.7$ cm

Multilayer drift chamber (MDC)

- He/C_3H_8 (60/40)
- 43 layers
- Momentum resolution $\sigma_p/p \approx 0.5\%$ @ 1 GeV
- Spatial resolution $\sigma_{xy} \approx 130$ μm.

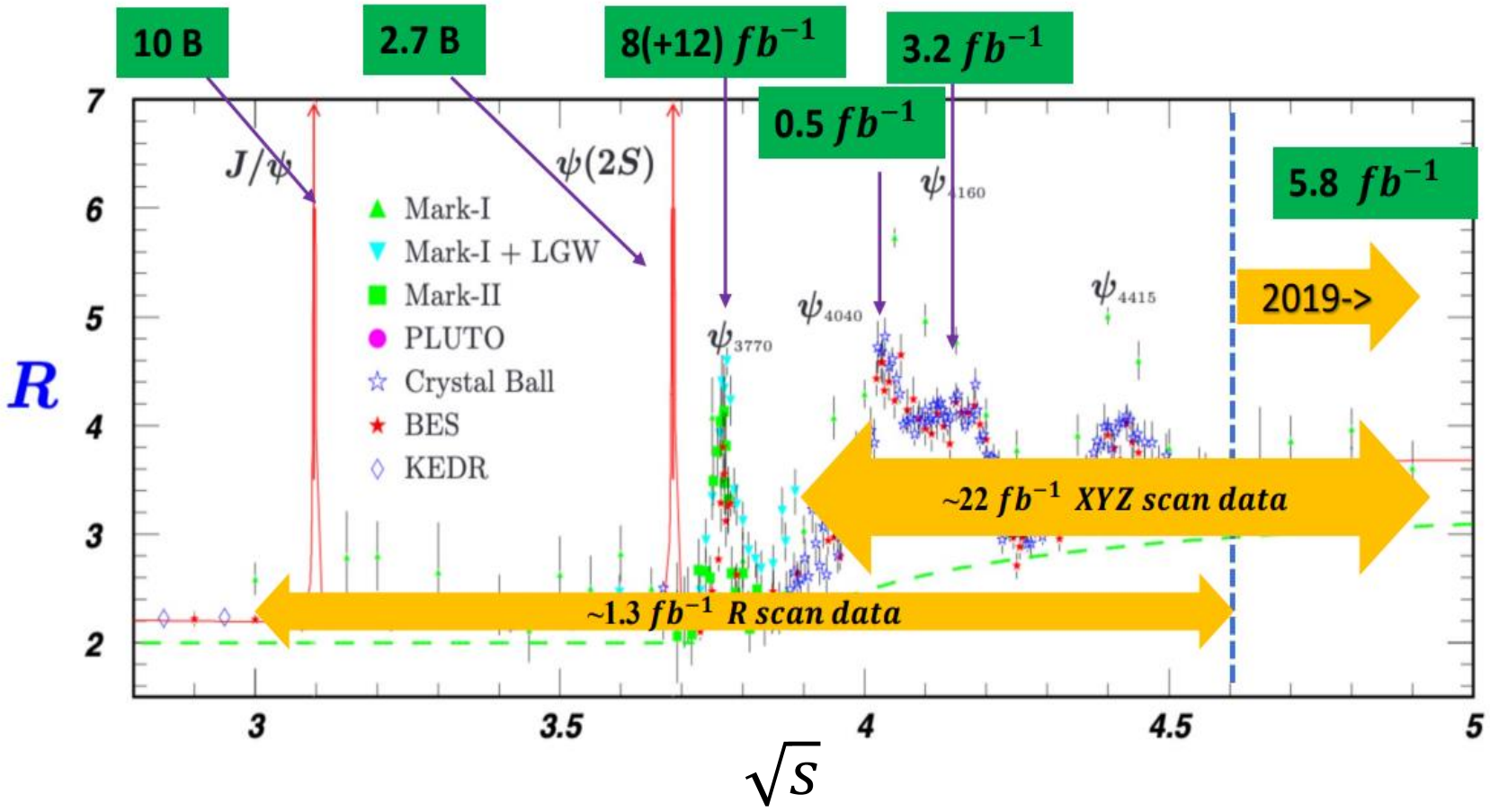
Electromagnetic calorimeter (EMC) (CsI(Tl))

→ 6240 crystals overall

- $\sigma(E)/E \approx 2.5\%$
- $\sigma_{Z,\phi}(E) \approx$ 0.5 – 0.7 cm

Will replace the inner part of the drift chamber by the three layers of CGEM detector in the coming years.

BESIII Dataset



Collected world largest data in tau-charm region

- ✓ Charmonium spectroscopy
- ✓ Charm physics
- ✓ Light hadrons
- ✓ New physics search

GOOD OPPORTUNITY TO STUDY THE LIGHT HADRON SPECTROSCOPY & SEARCH FOR NEW PHYSICS PHENOMENA!

Weak decays of J/ψ meson

$J/\psi \to D_s^- e^+ \nu_e$ Phys. Rev. D **90**, 112014 (2014)

$J/\psi \to D_s^{*-} e^+ \nu_e$ Phys. Rev. D **90**, 112014 (2014)

$J/\psi \to D^0 e^+ e^-$ Phys. Rev. D **96**, 111101(R) (2017)

$J/\psi \to D^- e^+ \nu_e$ JHEP **06**, 157 (2021)

$J/\psi \to D^- \mu^+ \nu_\mu$ arXiv:2307.02165 (2023) **(This talk)**

$J/\psi \to \bar{D}^0 X\ (X = \pi^0, \eta, \rho^0)$
$J/\psi \to D^- Y\ (\mathrm{Y} = \pi^+, \rho^+)$ arXiv:2307.07277 (2023) **(This talk)**

Charmonium weak decays

- Charmonium weak decays are allowed in SM, but highly suppressed by strong and EM decays.

- The branching fraction of inclusive weak decays $J/\psi \to D_{(s)}^{(*)} X$ ($X =$ pion or lepton-pair) is predicted to be at the level of ~ 10^{-8}

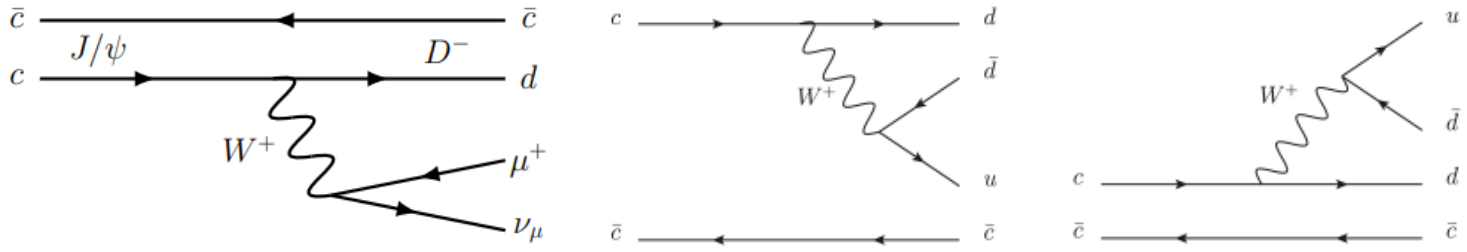
  J. Phys. G: Nucl. Part. Phys. **44**, 045004 (2017)

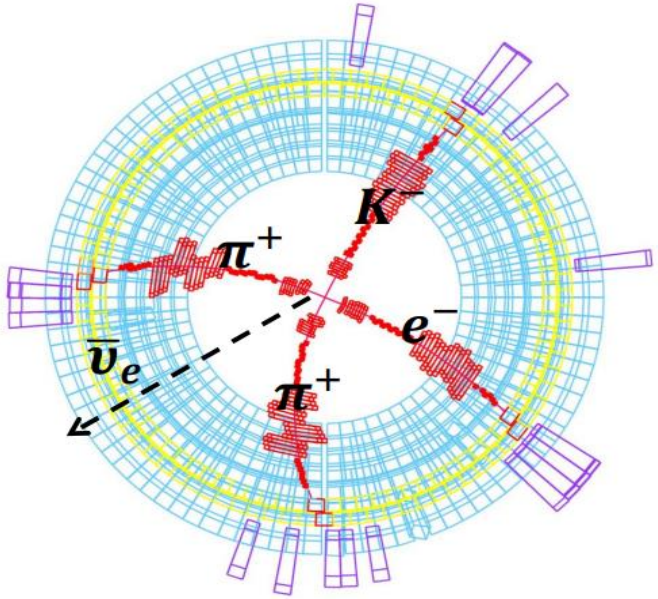
- But contribution of new physics, such as Top-color model, MSSM, two-Higgs doublet model, could enhance the branching fraction up to the level of 10^{-5}.

  PLB **345**, 483 (1995); PLB **119**, 136 (1982); PRD **15**, 1958 (1977)

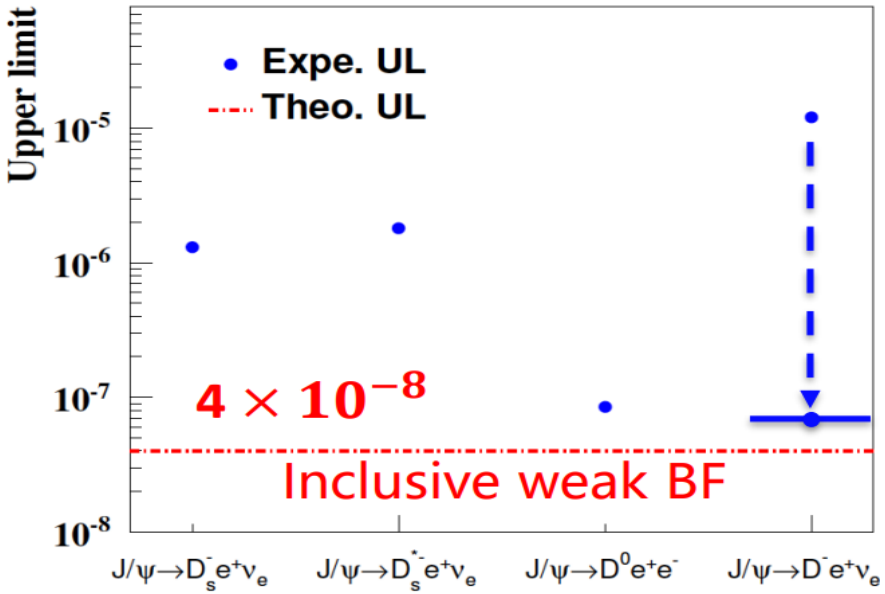
- Semi-leptonic weak decays: $\boldsymbol{J/\psi \to D^- \ell^+ \nu_\ell}$, $\boldsymbol{J/\psi \to D_s^{(*)-} \ell^+ \nu_\ell}$

- Hadronic weak decays: $\boldsymbol{J/\psi \to \bar{D}^0 X\ (X = \pi^0, \eta, \rho^0)}$ **and** $\boldsymbol{J/\psi \to D^- Y\ (Y = \pi^+, \rho^+)}$





Current experimental results

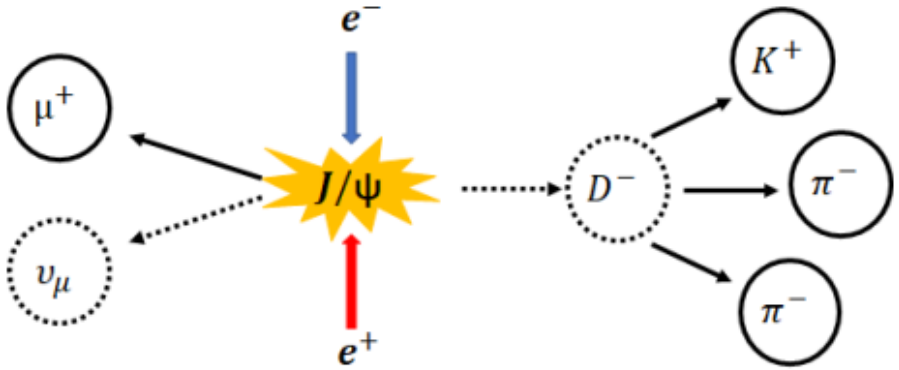


Search for the semi-muonic charmonium decay $J/\psi \to D^- \mu^+ \nu_\mu$

arXiv:2307.02165 (2023)

- Expected branching fraction of $J/\psi \to D^- \mu^+ \nu_\mu$ is at the level of 10^{-11}

  Eur. Phys. J. C **54**, 107 (2008)
  Phys. Rev. D **78**, 074012 (2008)
  Adv. HEP **2013**, 706543 (2013)
  Phys. Rev. D **92**, 074030 (2015)
  J. Phys. G: Nucl. Part. Phys. **44**, 045004 (2017)



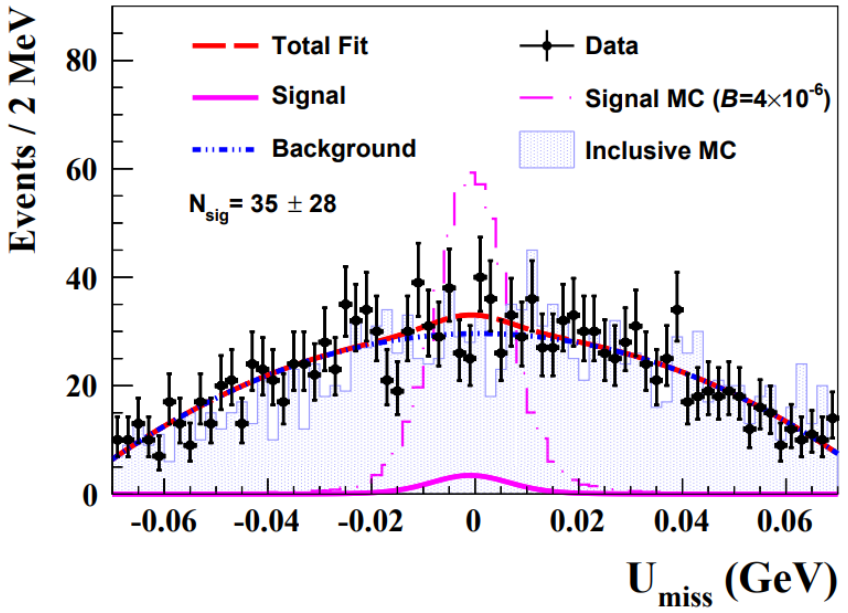
- Perform the first search for the rare semi-muonic charmomium decay $J/\psi \to D^- \mu^+ \nu_\mu$ +c.c. using 10 billion J/ψ events collected by the BESIII detector.

- Perform one-constraint (1C) fit for $D^- \to K^+ \pi^- \pi^-$ reconstruction.

- No significant signal event in found in U_{miss} distribution.

- Set an upper limit of the branching fraction at 90% CL

$$\mathcal{B}(J/\psi \to D^- \mu^+ \nu_\mu + c.c.) < 5.6 \times 10^{-7}$$



$$U_{\rm miss} = E_{\rm miss} - |\vec{P}_{\rm miss}|c$$

$$E_{\rm miss} = E_{J/\psi} - E_{D^-} - E_{\mu^+}$$

$$|\vec{P}_{\rm miss}| = |\vec{0} - \vec{P}_{D^-} - \vec{P}_{\mu^+}|$$

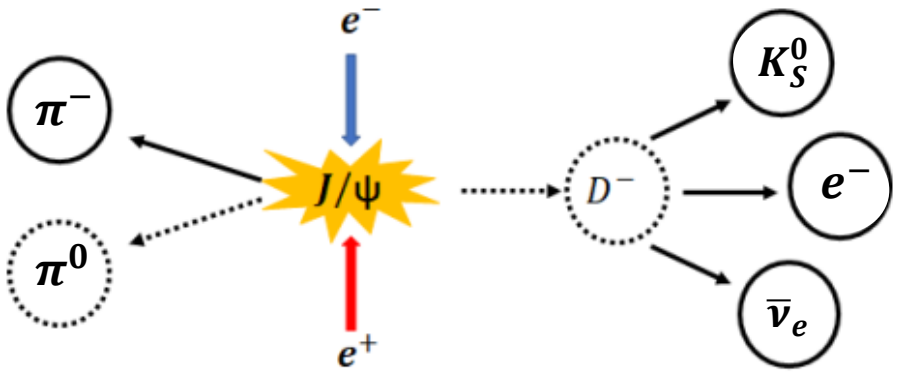
Dominant backgrounds:

$J/\psi \to K^+\pi^-\pi^+\pi^-(\pi^0)$
$J/\psi \to K^+K^-\pi^+\pi^-$
$J/\psi \to \pi^+\pi^-\pi^+\pi^-\pi^0$
$J/\psi \to K^+\pi^-\pi^+\pi^- K_L$

Search for weak decays of $J/\psi \to DX$ ($X = \pi^{\pm,0}, \eta, \rho^{\pm,0}$)

- The 10 billion of BESIII J/ψ data has also been utilized to search for weak decays $J/\psi \to \bar{D}^0 X$ $(X = \pi^0, \eta, \rho^0)$ and $J/\psi \to D^- Y$ (Y $= \pi^+, \rho^+$).

arXiv:2310.07277 (2023)

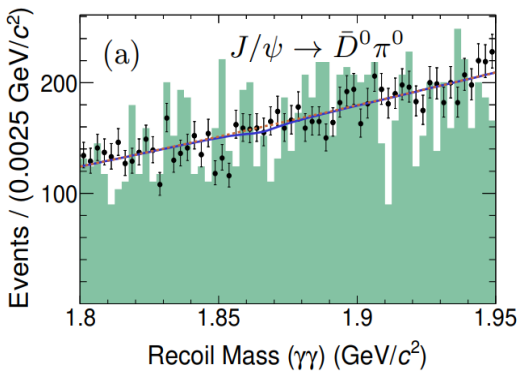


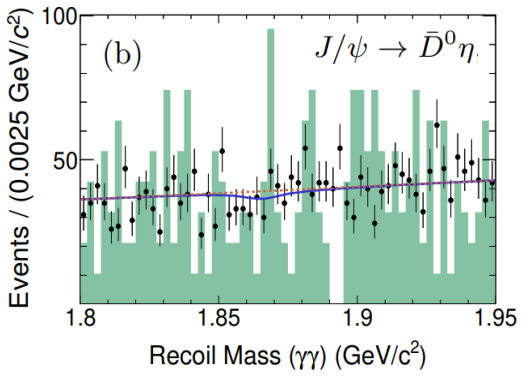
- Semi-leptonic modes of reconstructed D candidates:

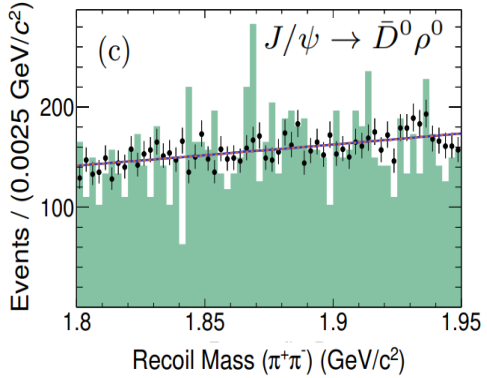
$$\bar{D}^0 \to K^+ e^- \bar{\nu}_e \qquad D^- \to K_S^0 e^- \bar{\nu}_e$$

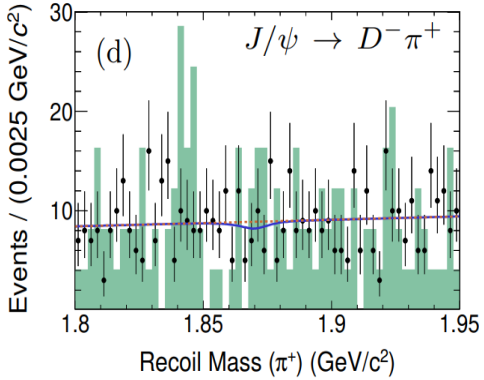
- Perform one-constraint (1C) fit for $\pi^0/\eta \to \gamma\gamma$ reconstruction.

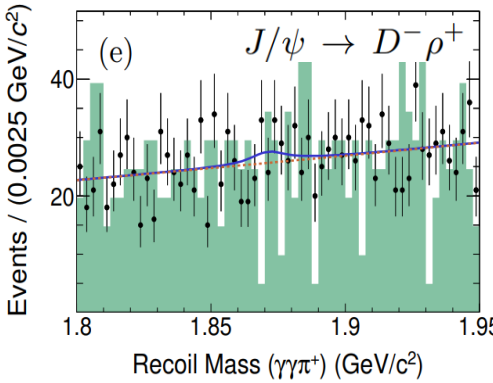
- No evidence of significant signal events in accepted candidates to the recoiling mass spectra









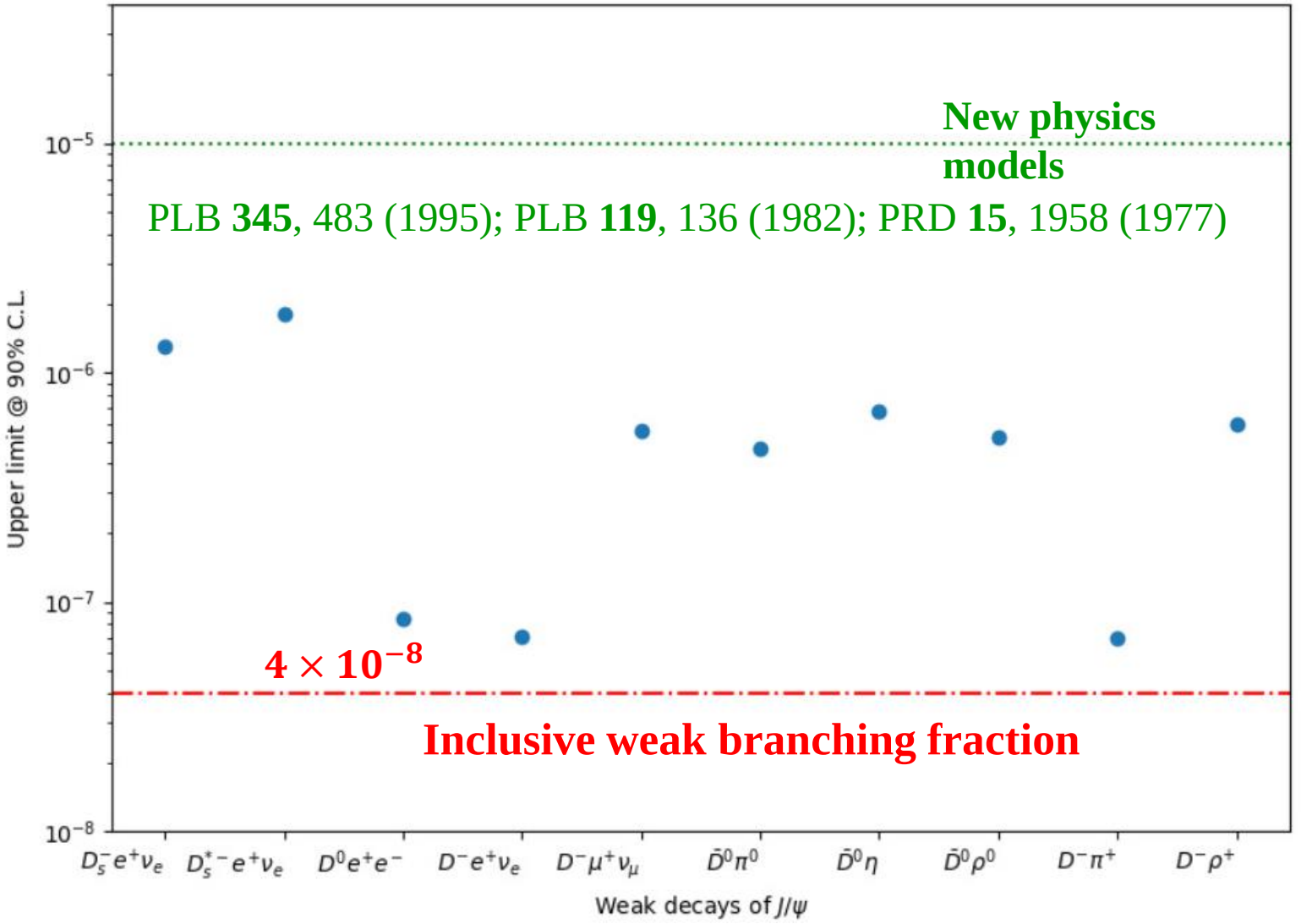


- Set 90% CL upper limits on branching fractions

$$\mathcal{B}(J/\psi \to \bar{D}^0\pi^0 + c.c.) < 4.7 \times 10^{-7} \qquad \mathcal{B}(J/\psi \to \bar{D}^0\eta + c.c.) < 6.8 \times 10^{-7} \qquad \mathcal{B}(J/\psi \to \bar{D}^0\rho^0 + c.c.) < 5.2 \times 10^{-7}$$

$$\mathcal{B}(J/\psi \to D^-\pi^+ + c.c.) < 7.0 \times 10^{-8} \qquad \mathcal{B}(J/\psi \to D^-\rho^+ + c.c.) < 6.0 \times 10^{-7}$$

Status of J/ψ weak decays after new BESIII results



Exclude large fraction of the parameter space of the new physics models.

Future J/ψ data to be collected by super tau-charm factory may prove or disprove the SM predictions.

Exotic particles searches at BESIII

Dark Matter portals

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

a) With $\psi(2S)$ data

Phys. Lett. B **838**, 137698 (2023)

b) With J/ψ data

Preliminary result (**This talk**)

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

Visible (di-muon) decay

PRD **105**, 012008 (2022)

PRD **93**, 052005 (2016)

PRD **85**, 092012 (2012)

invisible decay

PRD **101**, 112005 (2020)

Dark photon

$J/\psi \to U\eta(')$ decay

PRD **99**, 012013 (2019)

PRD **99**, 012006 (2019)

PRD **102**, 052005 (2020)

ISR process

PLB **774**, 252 (2017) (visible)

PLB **839**, 137785 (2023) (invisible)

(**This talk**)

Fully invisible decays

Invisible decays of Λ baryon

PRD **105**, L071102 (2022)

Invisible decays of ω/ϕ mesons

PRD **98**, 032001 (2018)

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 massless dark photon

PRD **106**, 072008 (2022) (**This talk**)

Search for heavy Majorana neutrino

PRD **99**, 112002 (2019)

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 $(g-2)_\mu$ anomaly.

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

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

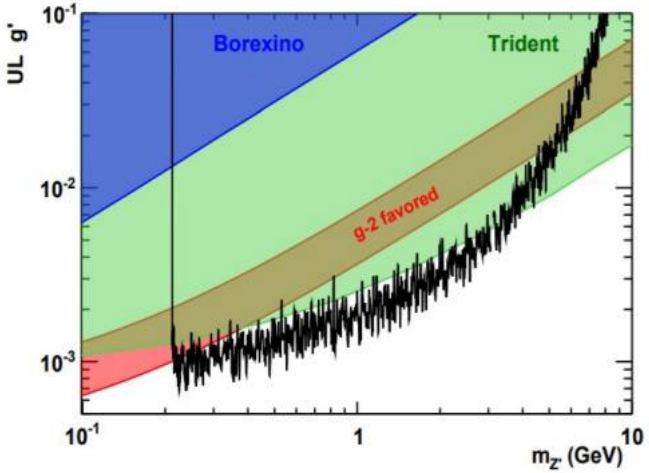
arXiv:1610.06587 (2016)

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

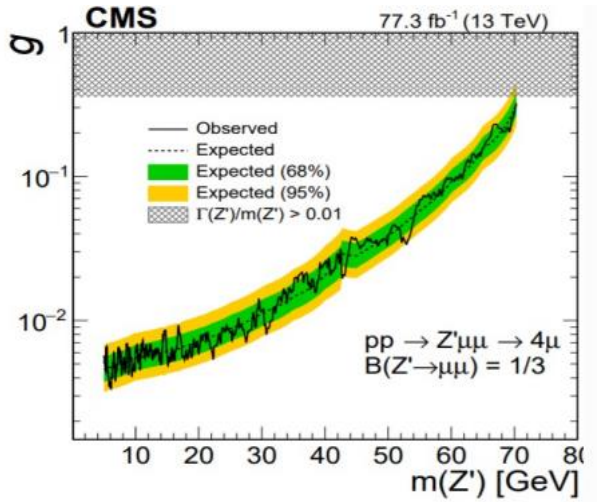
JHEP 10 (2020) 207

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 $Z' \to \mu^+\mu^-$

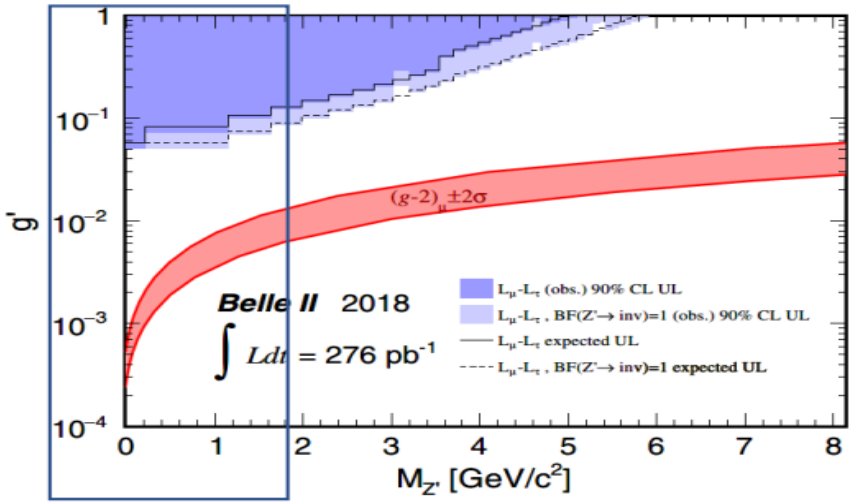


BaBar: PRD.94.011102



CMS: PLB 792, 345

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



Belle II: PRL124 14, 141801

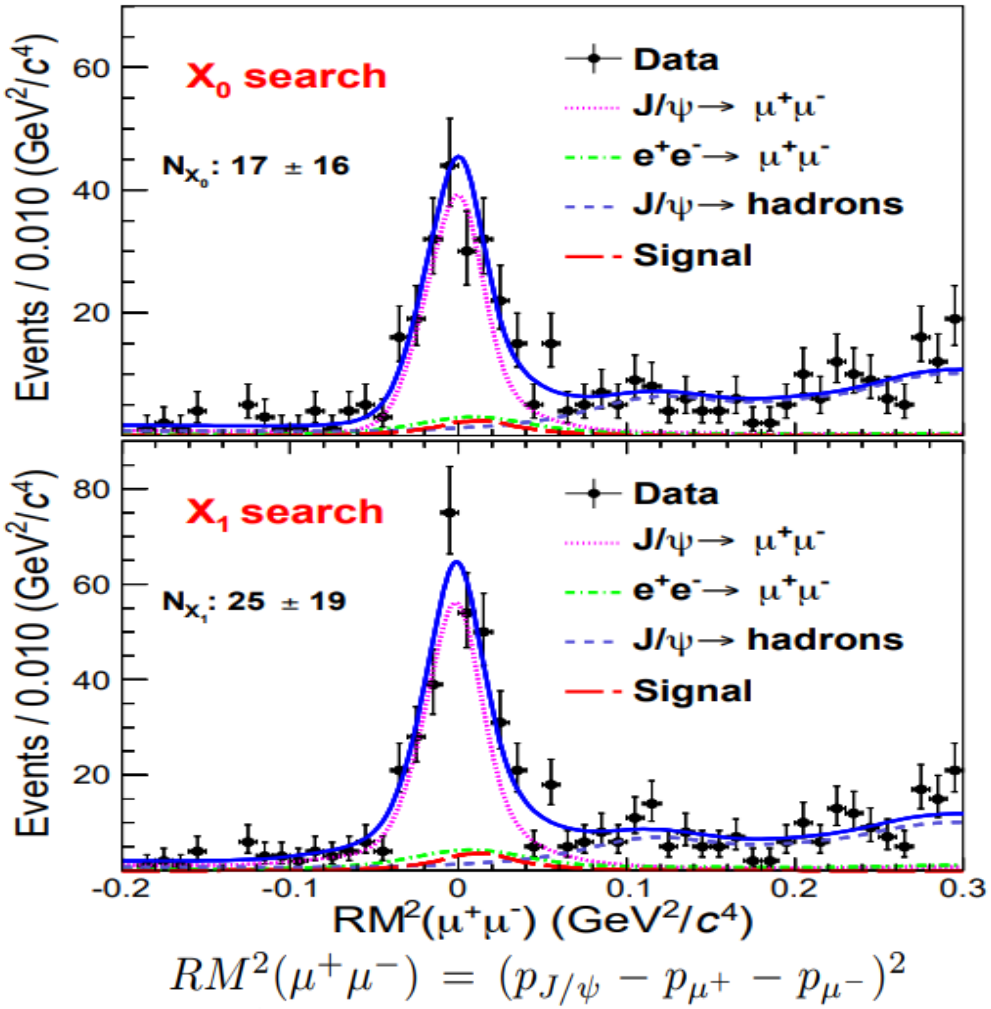
✓ BESIII can contribute to the low mass region

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 $J/\psi \to \mu^+\mu^-$+invisible

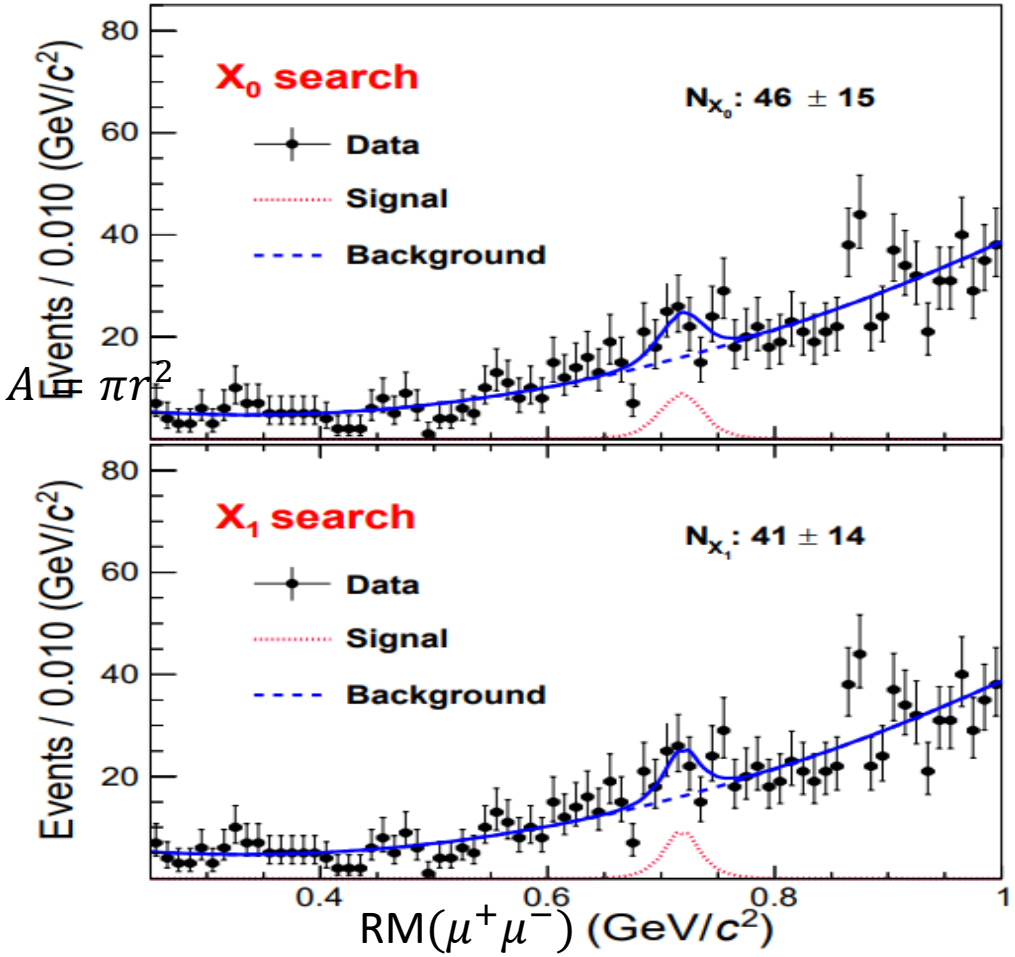
PRD 109, L031102 (2024)

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



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

$A = \pi r^2$



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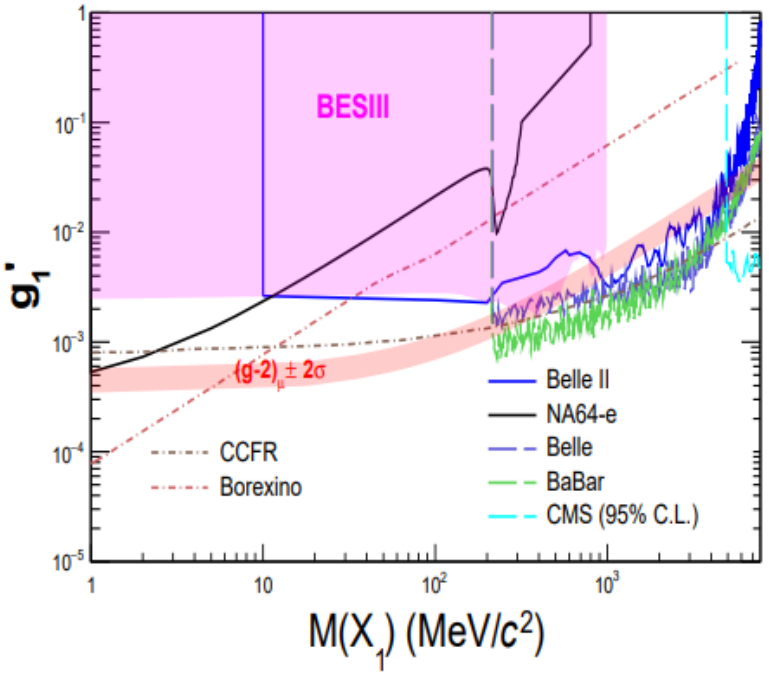
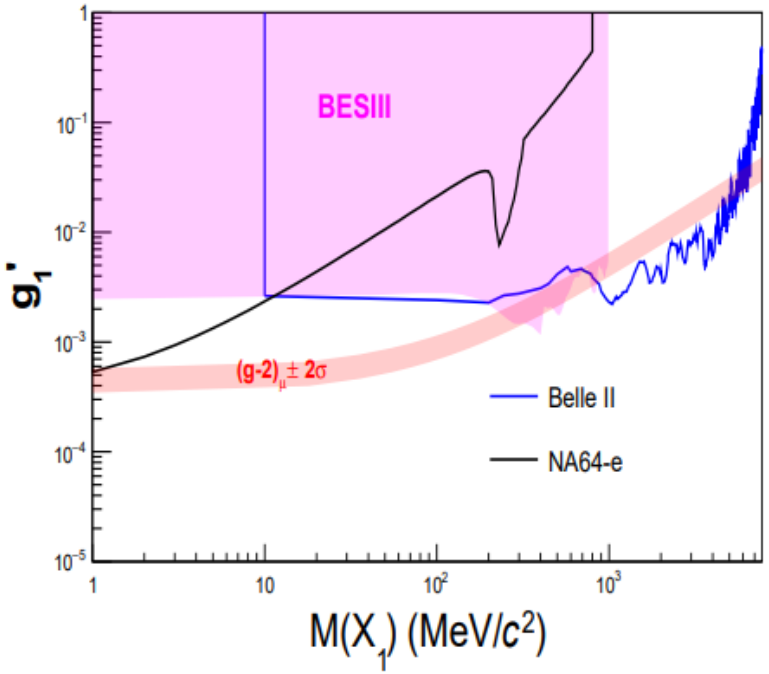
"vanilla" $L_\mu - L_\tau$ model



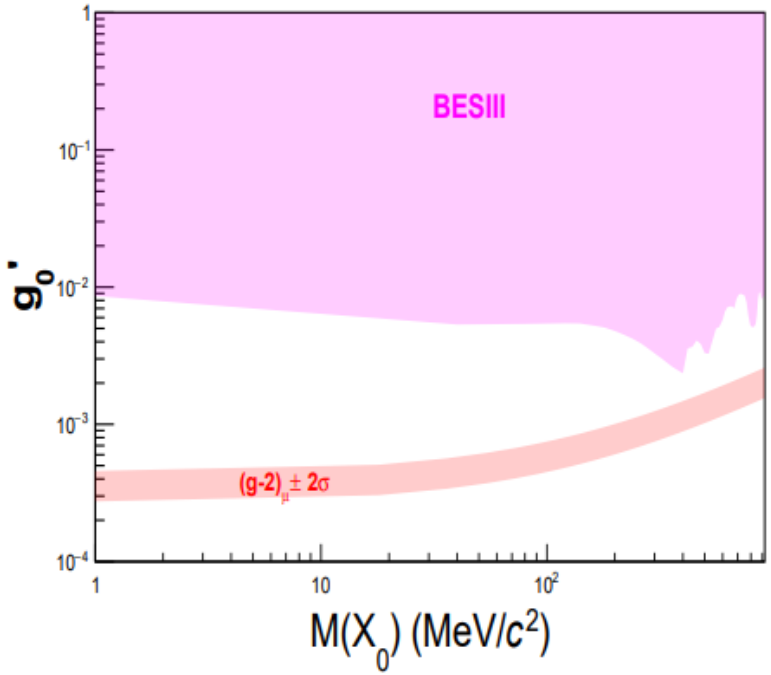
$B(X_{0,1} \to \nu\bar{\nu})$~(33 − 100)%

"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

Search for an Axion-like particle

BESIII
Preliminary

An Axion

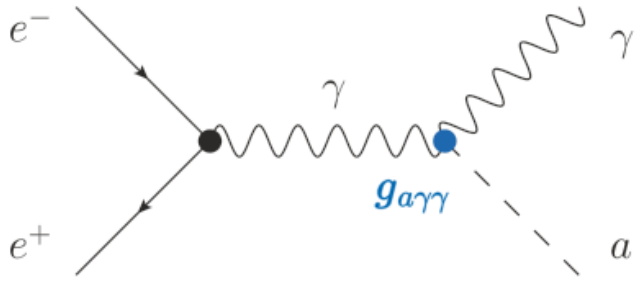
- is a pseudo-scalar particle
- introduced by the spontaneous breaking of Peccei-Quinn symmetry to solve the strong CP problem of the QCD

  Phys. Rev. Lett. **40**, 223 (1978); Phys. Rev. Lett. **40**, 279 (1978)

  Phys. Rev. Lett. **38**, 1440 (1977); Phys. Rev. D **16**, 1791 (1977)
- An Axion-like particle (ALP) is predicted by many models beyond the SM and proposed to be a cold DM candidate.
- couples to a pair of photons with ALP photon coupling $g_{a\gamma\gamma}$
- Experimental bounds on $g_{a\gamma\gamma}$ with m_a range of MeV/c^2 – GeV/c^2 mainly come from e$^+$e$^-$ collider experiments

  Phys. Lett. B 753, 482 (2016)

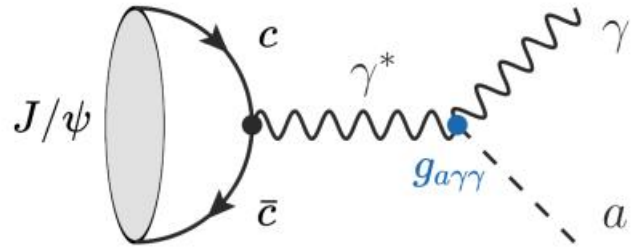
ALP-Strahlung process



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

Radiative decay process

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

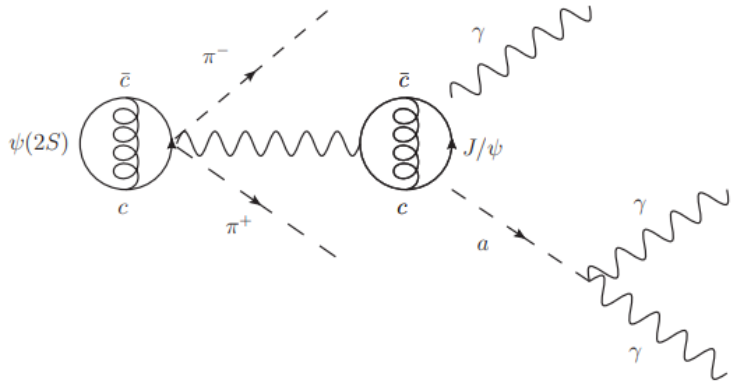


JHEP **06**, 091 385 (2019)

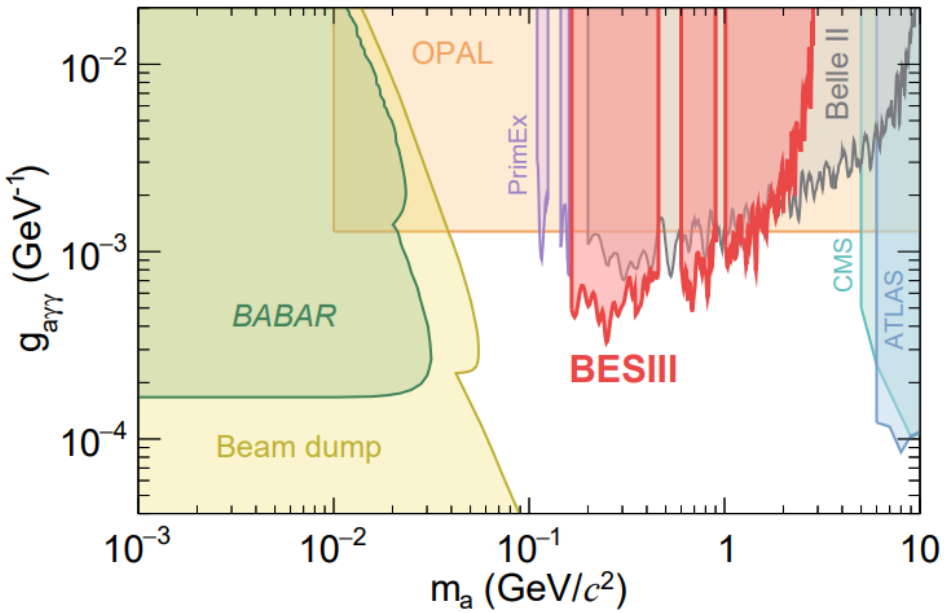
$$\mathcal{B}(J/\psi \to \gamma a) = \frac{m_{J/\psi}^2}{32\pi\alpha} g_{a\gamma\gamma}^2 \left(1-\frac{m_a^2}{m_{J/\psi}^2}\right)^3 \mathcal{B}(J/\psi \to e^+e^-)$$

Axion-like particle search with $\psi(2S)$ data

- Using 2.7 billion $\psi(2S)$ data, BESIII has set one of best limits on $g_{a\gamma\gamma}$ via $J/\psi \to \gamma a$



Phys. Lett. B **838**, 137678 (2023)



- The limits can be further improved with 10 billion of BESIII J/ψ data, which can include both radiative $J/\psi \to \gamma a$ and ALP-Strahlung process $e^+e^- \to \gamma a$.

Expected pollution of ALP-Strahlung process $e^+e^- \to \gamma a$ in J/ψ data

Cross-section of radiative process: $\sigma_a^{rad} = \frac{N_{J/\psi}}{L_{J/\psi}} \cdot \mathcal{B}(J/\psi \to \gamma a)$

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

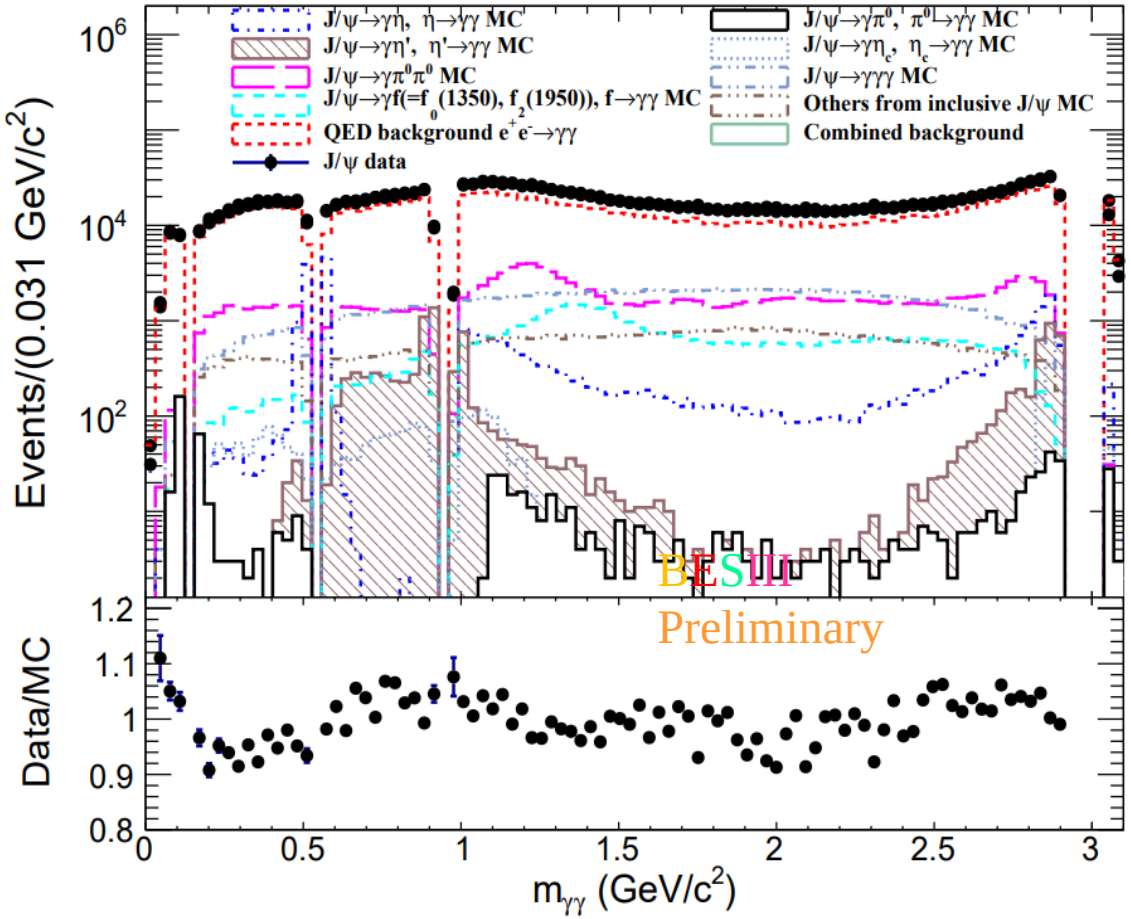
σ_a/σ_a^{rad} is calculated to be 0.044. (To be considered as systematic uncertainty)

Search for an Axion-like particle

BESIII
Preliminary

- Select at least three photon candidates in the EMC barrel region
- A four-constraint (4C) kinematic fit is performed to improve the mass resolution.
- Important selection criteria:
  - EMC time difference between two photons: $-500 < \Delta t < 500$ ns
  - $\chi^2_{4C} < 30$
  - $\chi^2_{4C}(3\gamma) < \chi^2_{4C}(n\gamma)$ (n=2,3,4)
  - Energy difference between third and first (second) photons > -1.46 (-1.41) GeV
  - Absolute value of azimuthal angle difference between third and first photons larger than 1 radian.

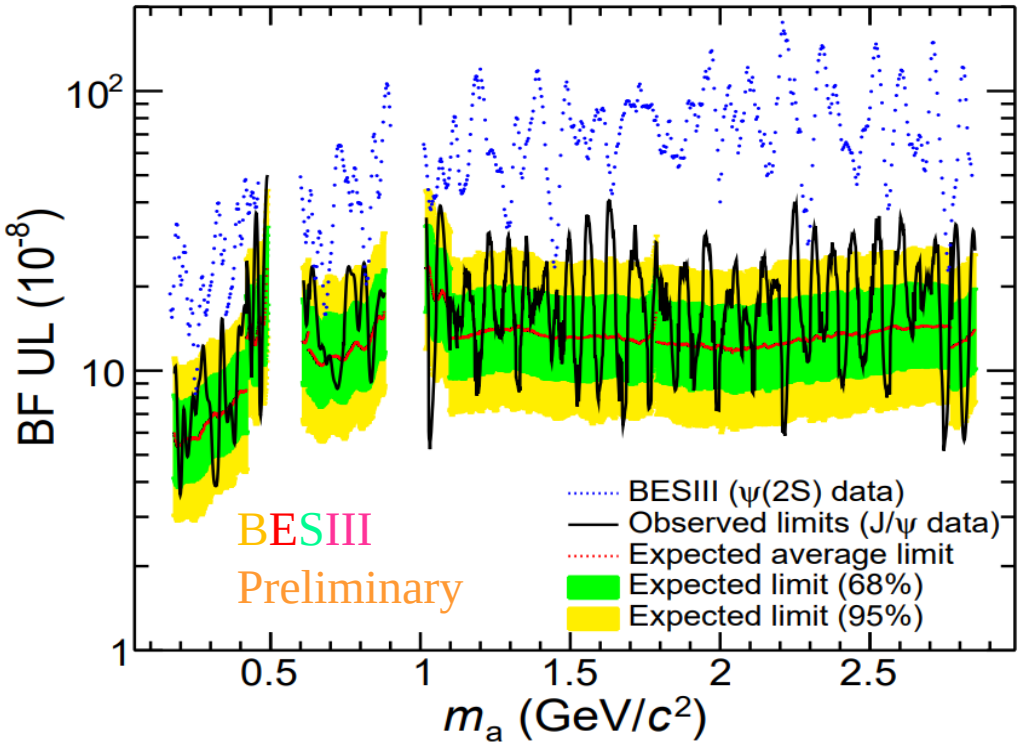
Di-photon invariant mass spectrum with all the three combinations of photons after vetoing the $J/\psi \to \gamma P$ ($P = \pi^0, \eta, \eta', \eta_c$) backgrounds



Search for an Axion-like particle

BESIII
Preliminary

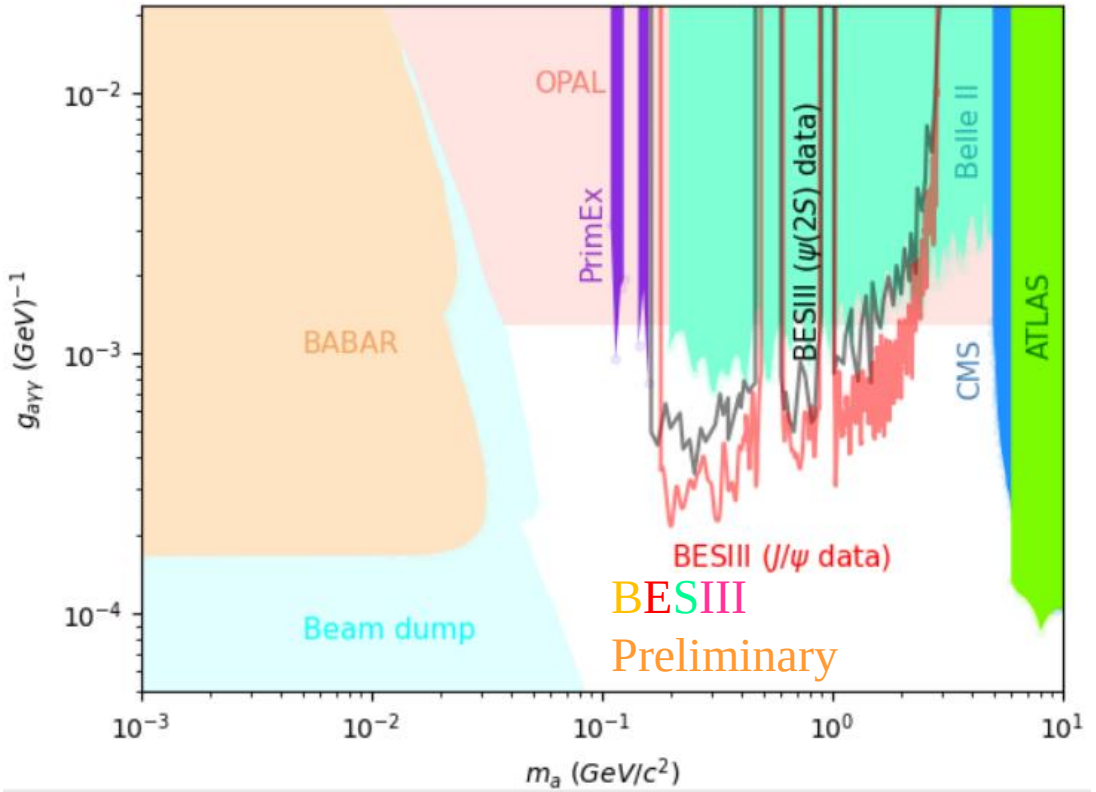
95% Confidence level upper limits on product branching fractions



New BESIII measurement has 8-9 times improvement than the previous BESIII measurement

arXiv:2308.15486 (2023)

95% Confidence level upper limits on ALP-photon coupling



New BESIII measurement has an improvement by a factor of 3 (5) over previous BESIII (Belle-II) measurement.

Phys. Lett. B **838**, 137678 (2023)

Phys. Rev. Lett. **125**, 161806 (2020)

Invisible decays of dark photon

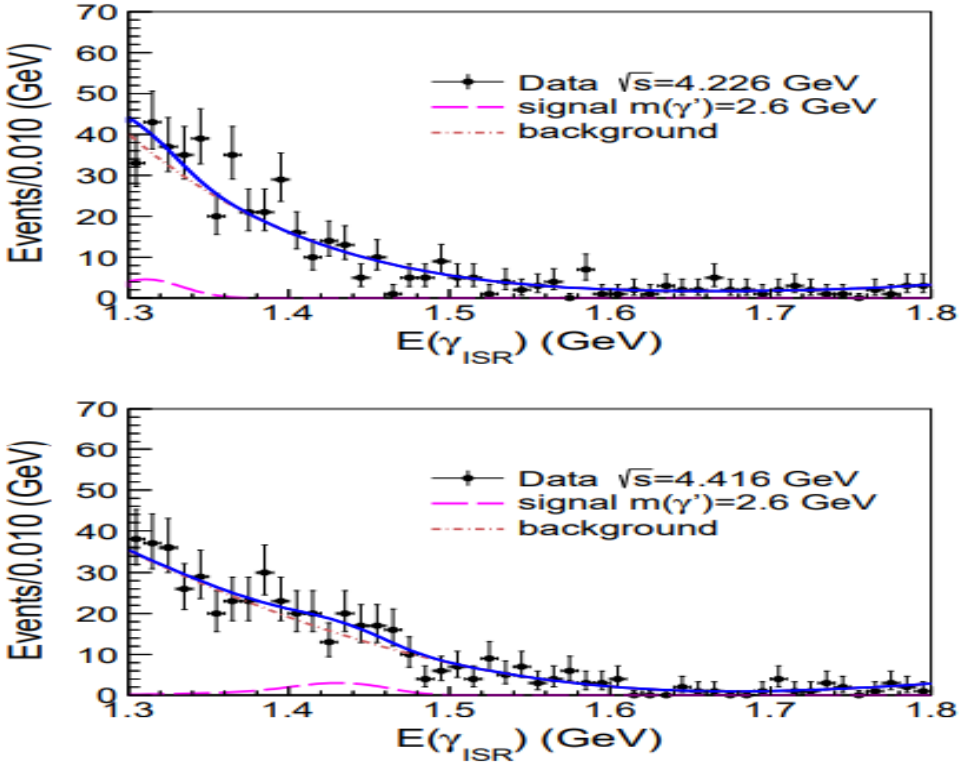
- This search is based on 14.9 fb^{-1} of e^+e^- annihilation data taken at center-of-mass (CM) energies from 4.13 to 4.60 GeV.

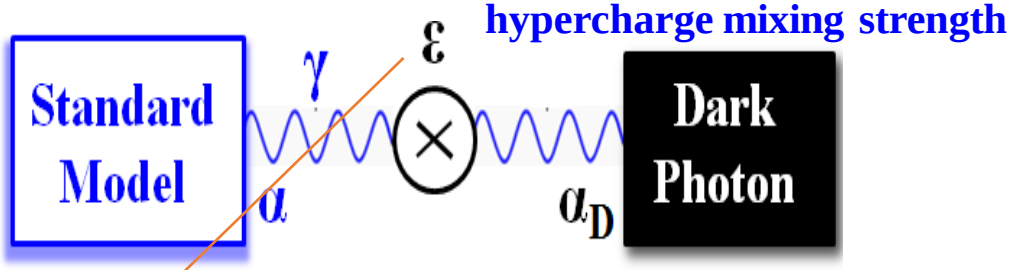
PLB 839, 137785 (2023)

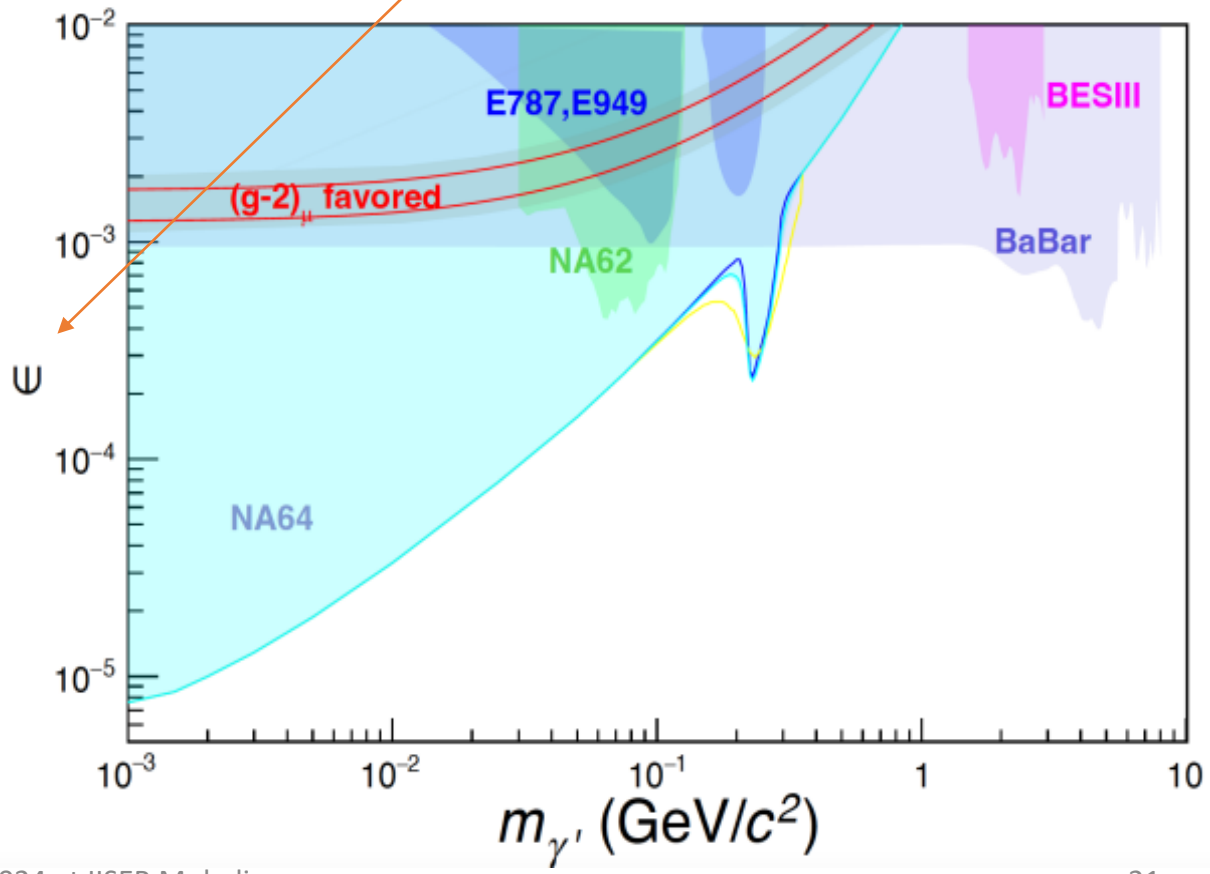
Dark photon search is explored via Initial-State-Radiation (ISR) production ($e^+e^- \to \gamma_{ISR}\gamma'$), where γ_{ISR} is an ISR photon.

Energy of monochromatic photon:

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







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

PRD **106**, 072008 (2022)

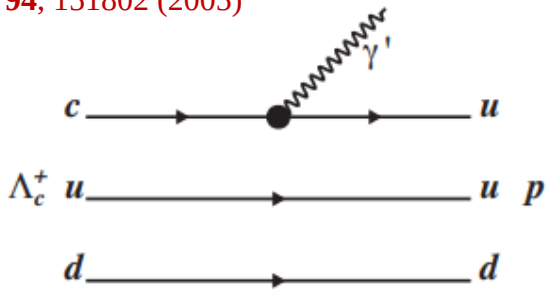
- A massless dark photon γ' is predicted by the BSM via spontaneously broken of Abelian group $U(1)_D$.

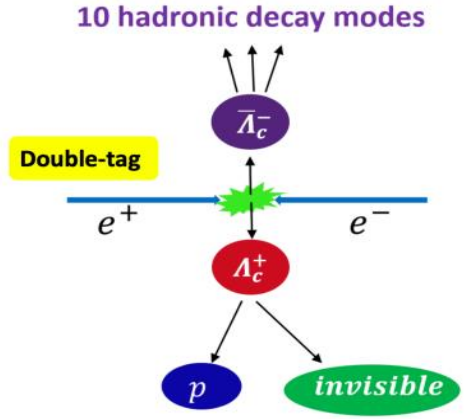
B. Holdom, Phys. Lett. B **166**, 196 (1986)
B. A. Dobrescu, Phys. Rev. Lett. **94**, 151802 (2005)

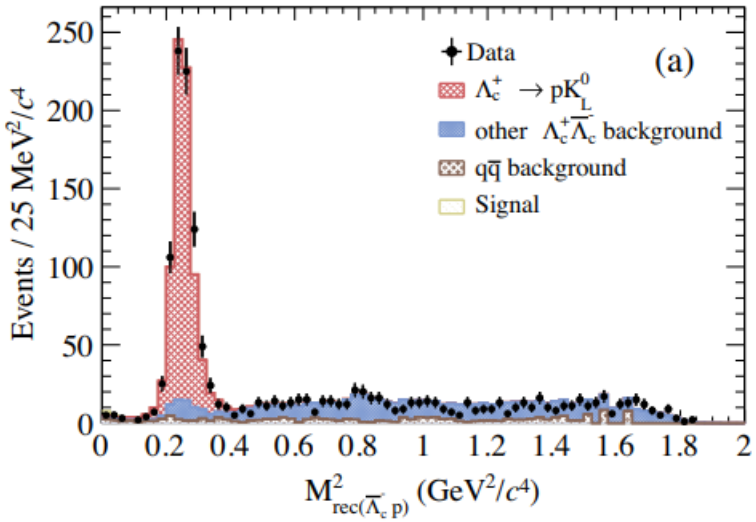
- Massless dark photon γ' may enhance the branching fractions of flavor changing neutral current (FCNC) decays, which are highly suppressed in charm-sector

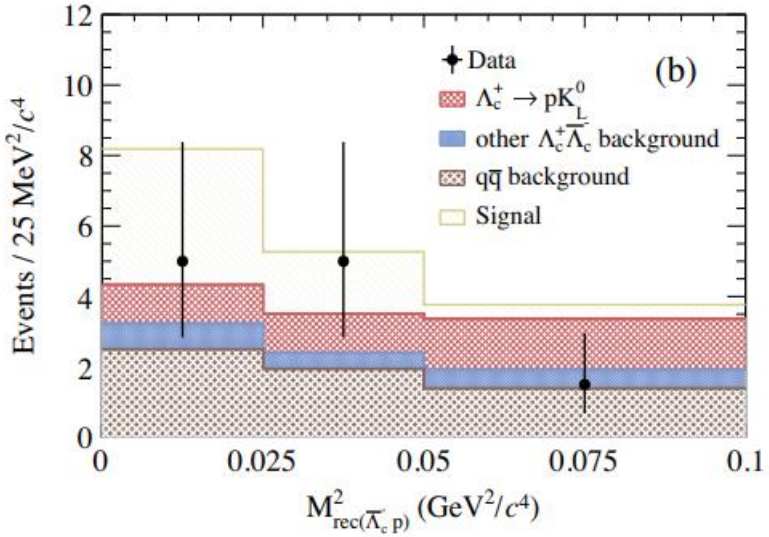
S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D **2**, 1285 (1970).

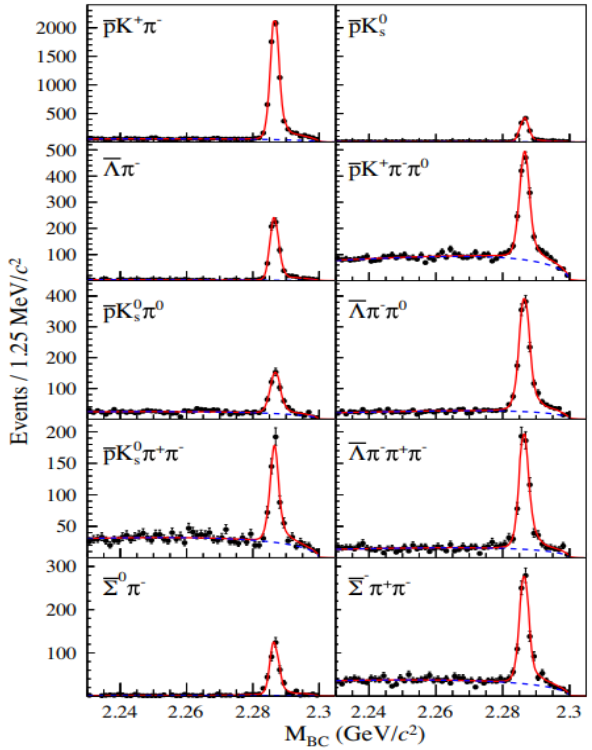
- Search for a massless dark photon is conducted using 4.5 fb^{-1} of data collected at CM energies between 4.6 and 4.699 GeV .











90% C.L. upper limit $\mathcal{B}(\Lambda_c^+ \to p\gamma') < 8 \times 10^{-5}$

Summary

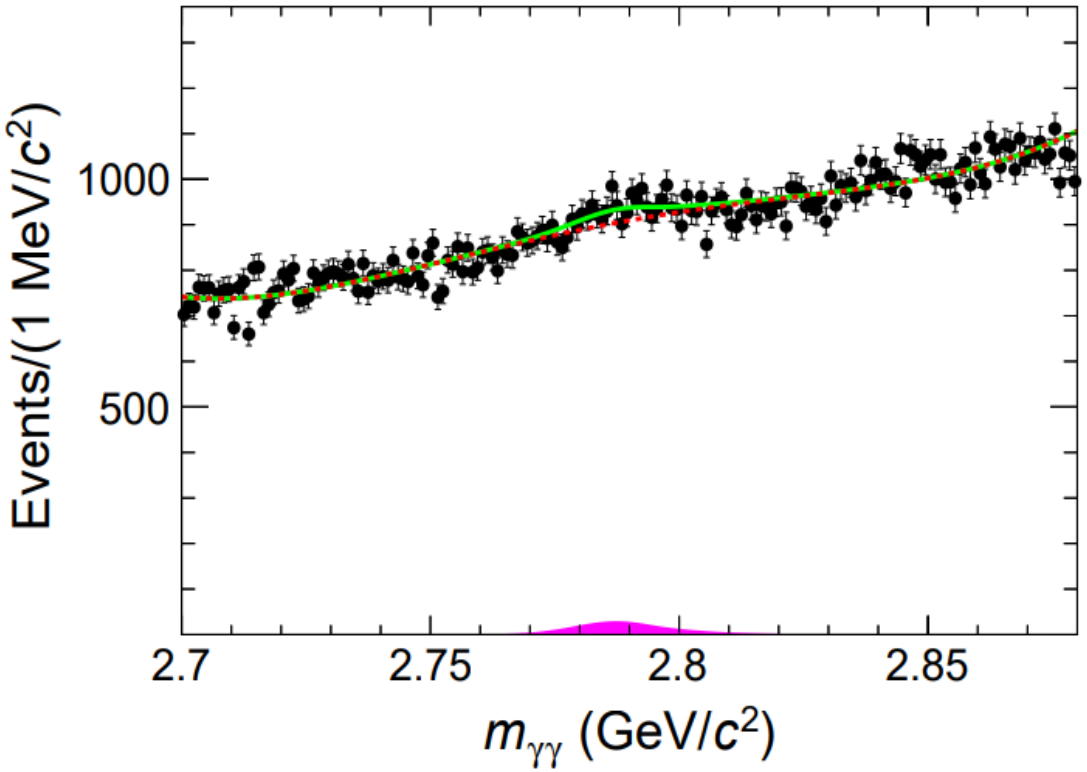
- Rare decays of charmonium mesons are sensitive to new physics beyond the SM.
- Recent BESIII results related to the weak J/ψ decays are consistent with the SM predictions.
- Future J/ψ data of super tau-charm factory may prove or disprove the SM prediction of the weak decays of charmonum mesons.
- BESIII has set one of most stringent limits on Axion-photon coupling in the range of [0.18, 2.8] GeV.
- BESIII has also put the competitive exclusion limits on other dark matter scenarios.
- More results is expected to come in the near future, especially with recently collected 20 fb^{-1} of $\psi(3770)$ data.

Thanks!

Search for an Axion-like particle

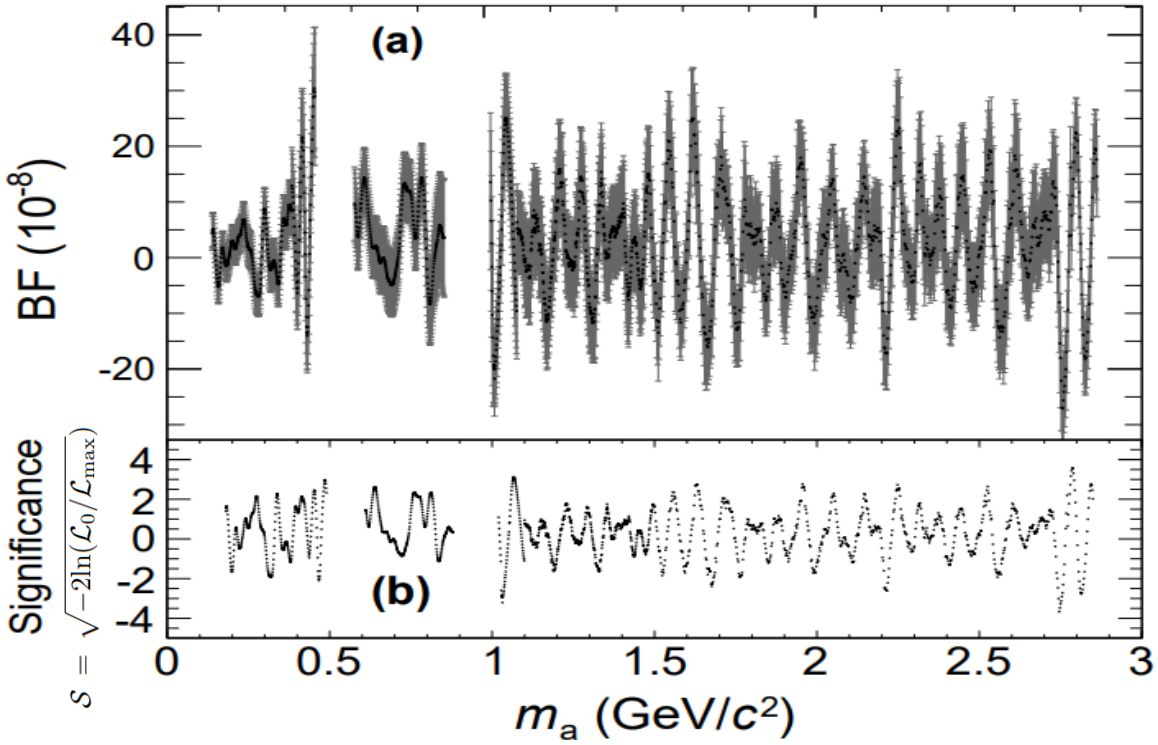
BESIII
Preliminary

Signal yield is extracted by performing a series of maximum likelihood (ML) fit to the di-photon invariant mass($m_{\gamma\gamma}$) spectrum



Product branching fraction (BF) versus m_a

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



Maximum local significance = 3.5σ

Corresponding global significance = 1.6σ

No evidence of axion-like particle production.