



BESIII

Recent results of new physics searches at BESIII

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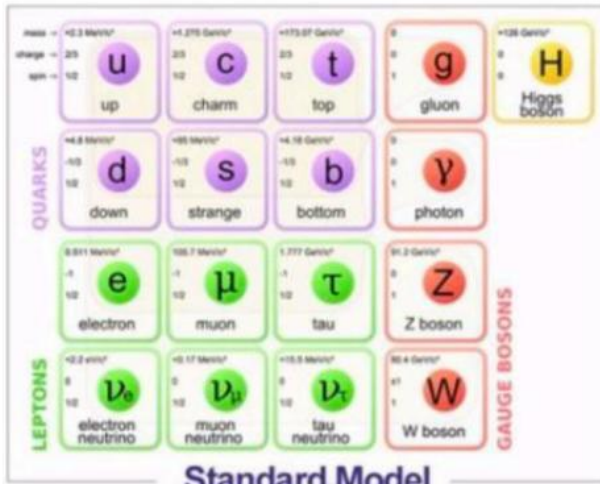
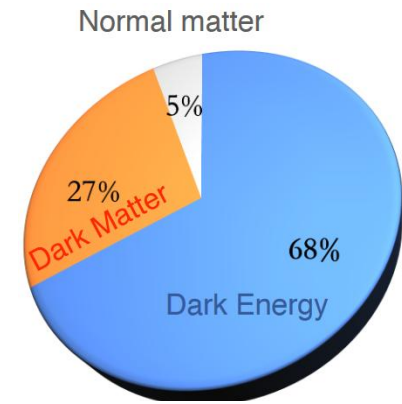


Outline

- Introduction
- BESIII experiment
- Search for muonphilic vector/scalar
- Search for axion-like particles
- Search for dark photons
- Study of symmetry violation
- Summary and outlook

Dark matter interacting with SM

- Amounts 27% of the total matter density of the universe
- Not interact with strong and electromagnetic interactions
- Explain the features of astrophysical observations



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

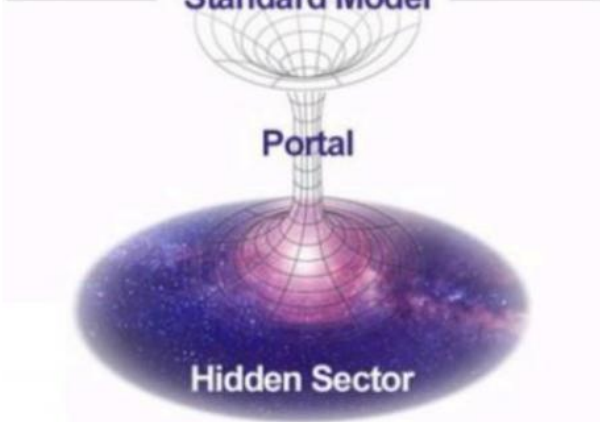
A' kinetic mixing with γ, Z

Dark Higgs (mixes with SM Higgs)

Sterile neutrino

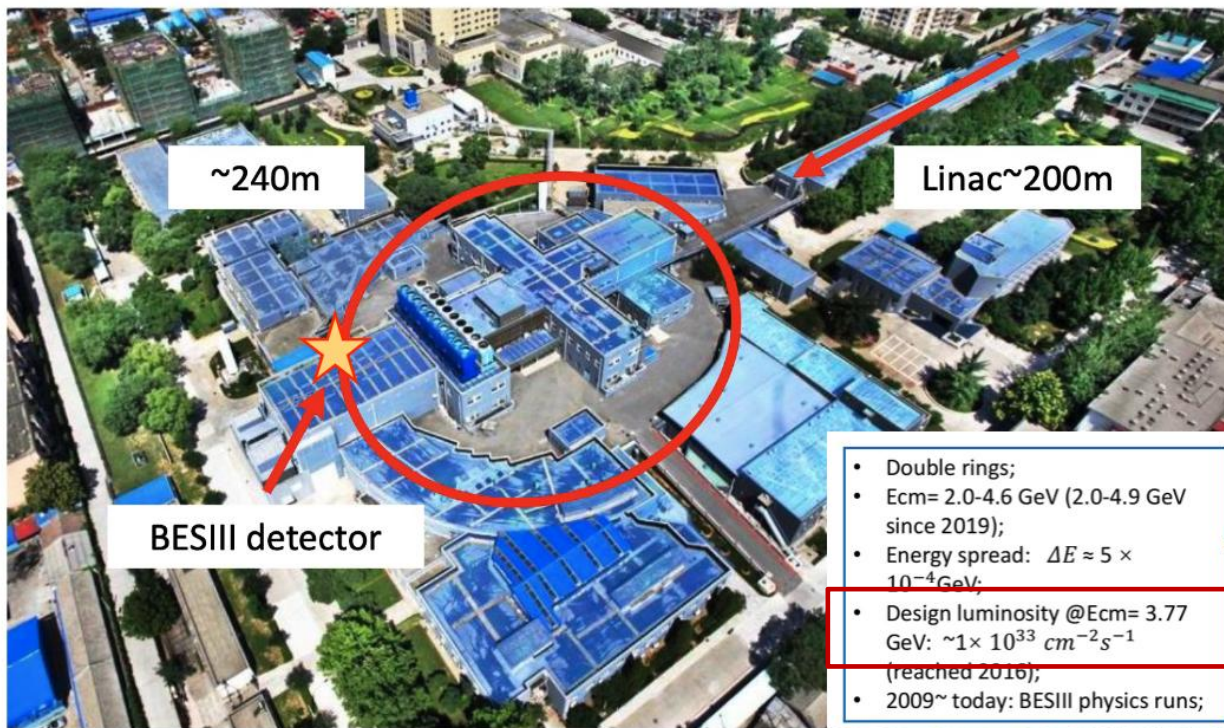
Axion, coupling to DM [arxiv:1311.0029](https://arxiv.org/abs/1311.0029)

- Dark matter has not seen yet in particle physics experiments
- One of the simplest models is “DM hidden sector” that allows the coupling between DM and SM particles via the so called “portals”
- “Portal” interactions are accessible by high intensity e+e- collider experiments, such as BESIII experiment, if their masses are a few GeV

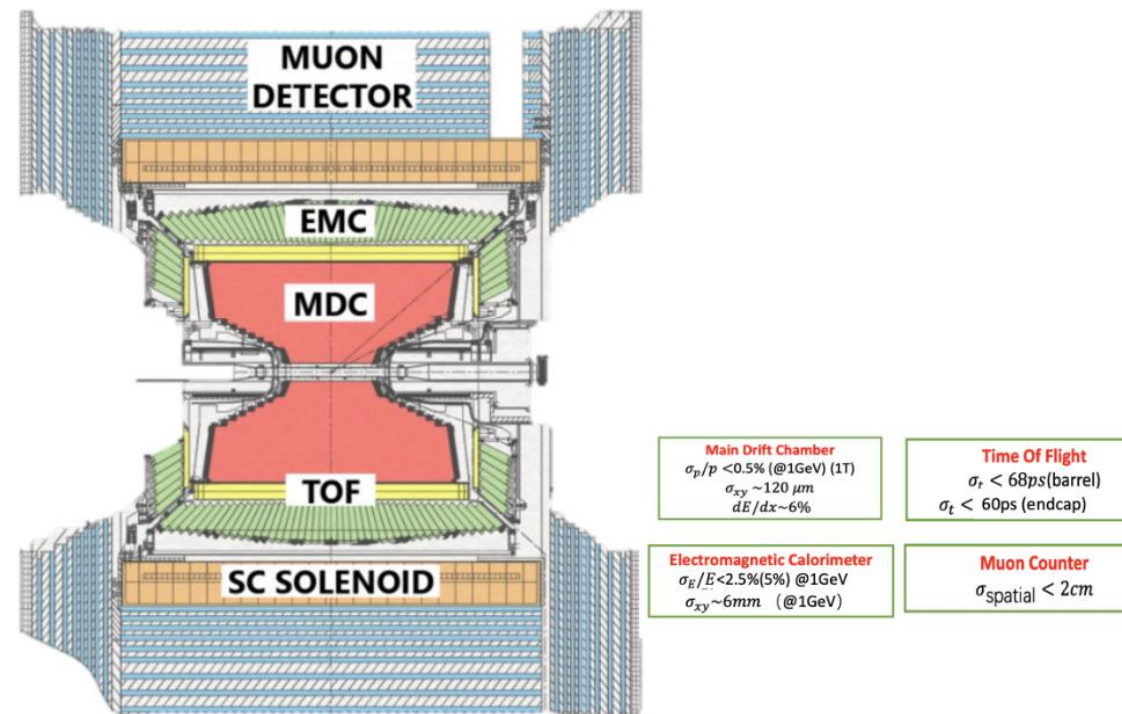


BESIII experiment

Beijing Electron-Positron Collider II

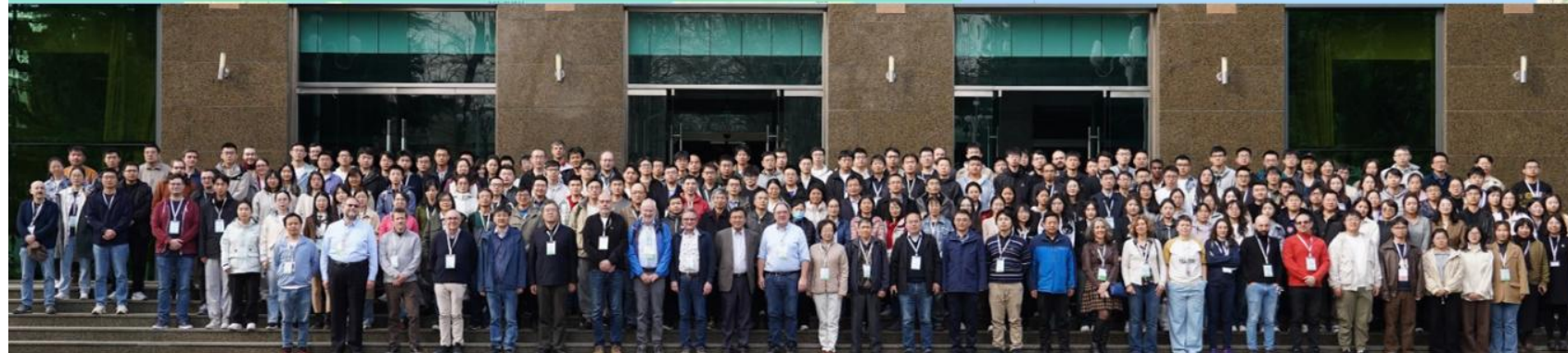
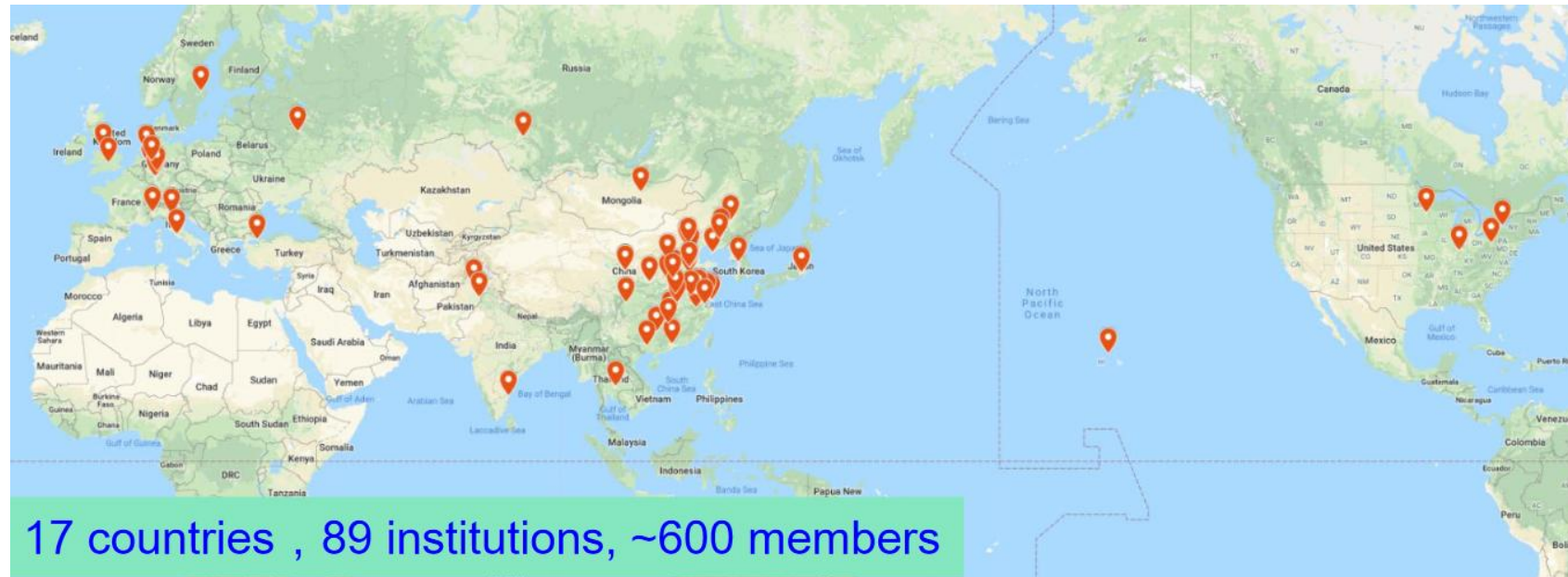


Beijing Spectrometer III



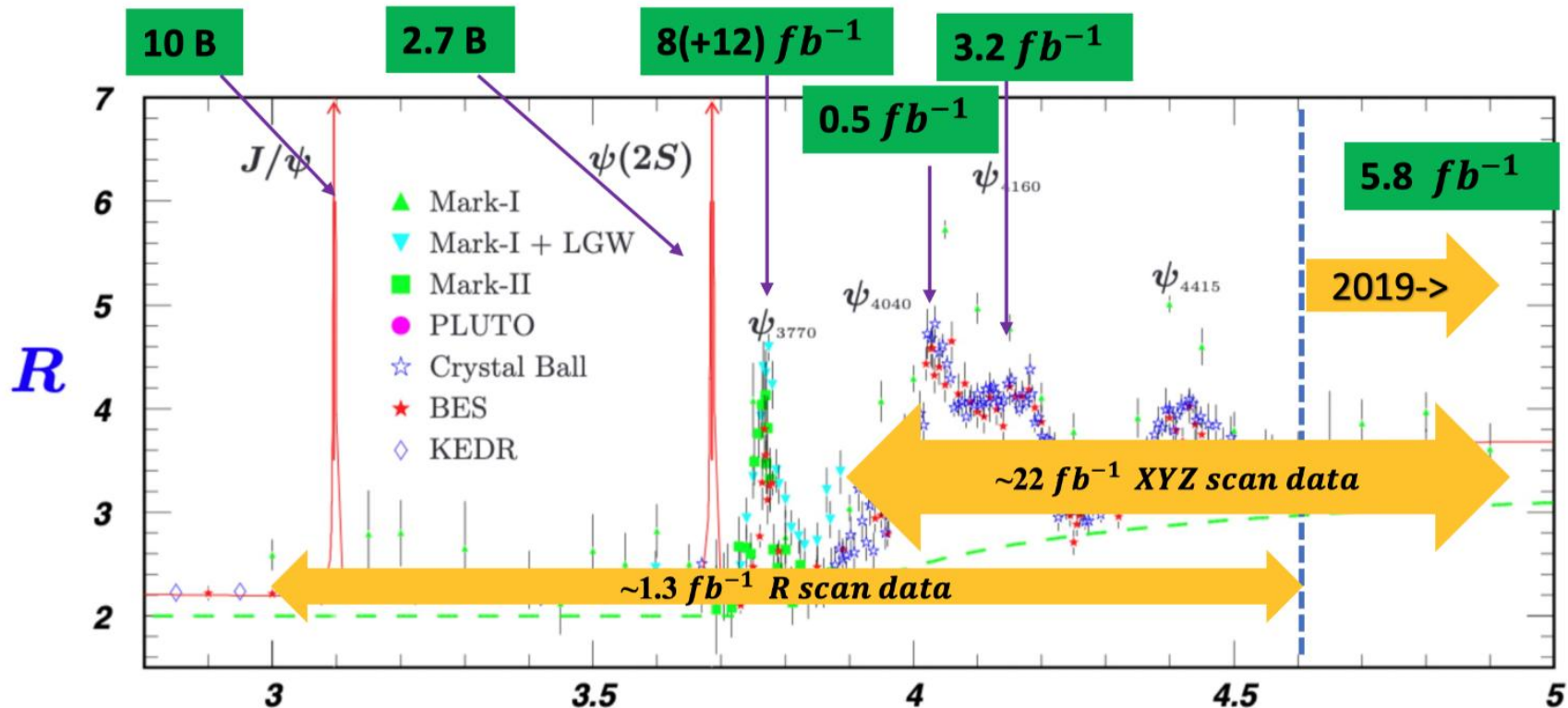
A symmetric e^+e^- collider running at tau-charm (2-5 GeV) region

BESIII collaboration



BESIII data sets

- World's largest data samples in tau-charm region
- 10 billion J/ψ , 2.7 billion $\psi(3686)$ and 20 fb^{-1} $\psi(3770)$ on threshold



- Charmonium
- XYZs
- Charm physics
- Light hadron
- Tau physics
- New physics

Search for new physics at BESIII

• Exotic particles

- Muonphilic vector/scalars
- Invisible processes
- Dark matter portals

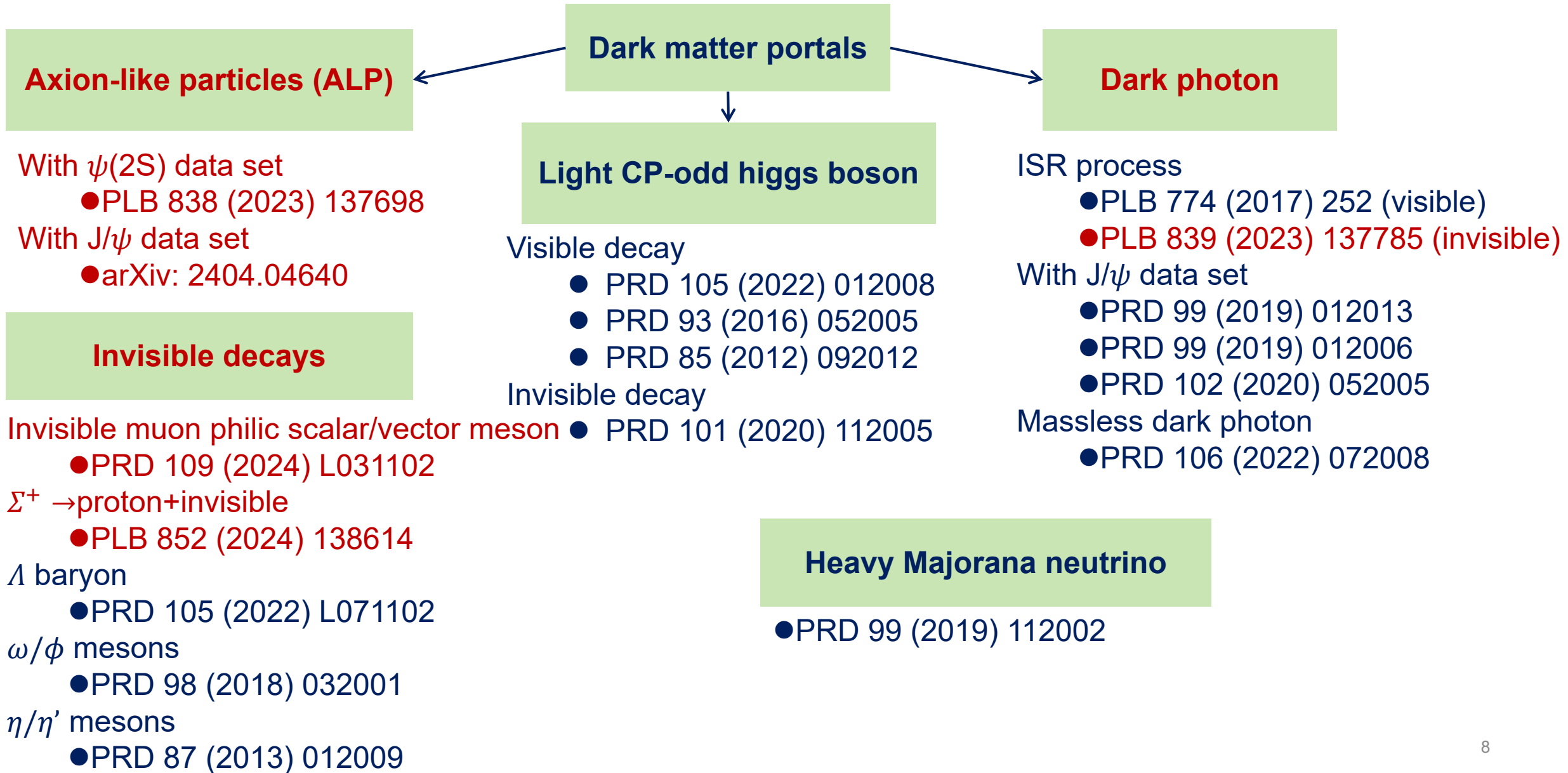
• (Very) Rare decays

- Charmonium weak decays
 - JHEP 01 (2024) 126
- Charm FCNC
 - arxiv:2404.05973 (accepted by PRL)

• Symmetry violation

- BNV/LNV processes
 - PRL 131 (2023) 121801
 - PRD 108 (2023) 012006
 - arXiv:2308.05490
- cLFV processes
 - SCPMA 66 (2023) 221011

Exotic particles search at BESIII



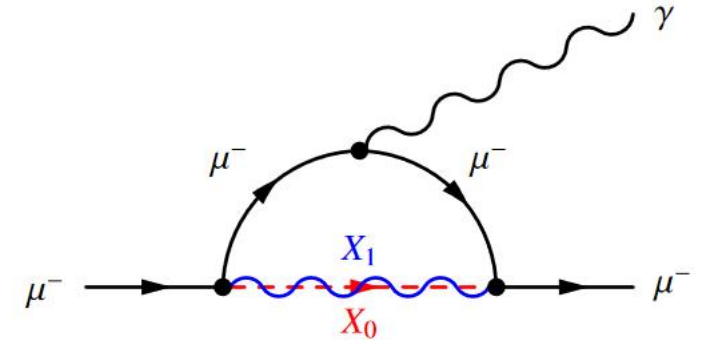
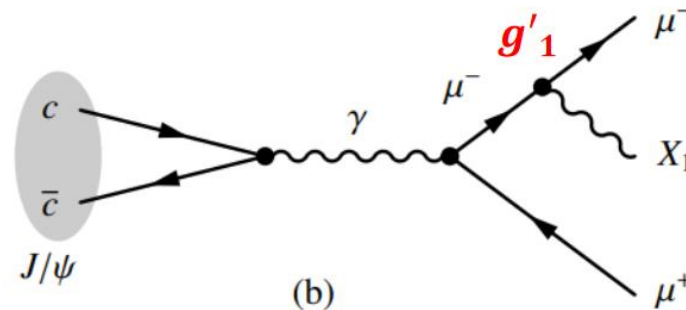
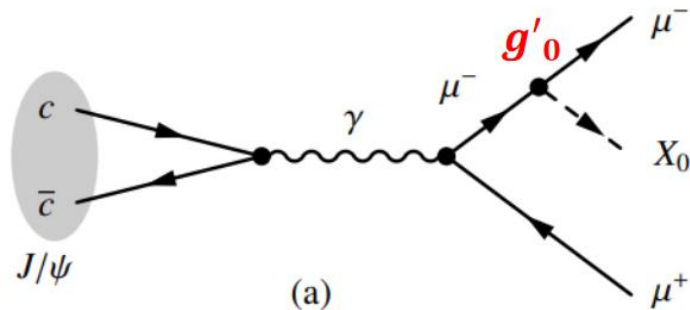
Muonphilic scalar/vector $X_{0/1}$

- Proposed as an explanation to the $(g - 2)_\mu$ anomaly
- A minimal extension of $U(1)$ group is added to the SM
- $U(1)_{L_\mu - L_\tau}$ model:

a massive scalar X_0 or vector X_1 boson couples only with the 2nd and 3rd generation leptons

$$\mathcal{L}_\mu^{\text{scalar}} = -g_0 X_0 \bar{\mu} \mu, \quad \mathcal{L}_\mu^{\text{vector}} = -g_1 X_1 \bar{\mu} \gamma \mu$$

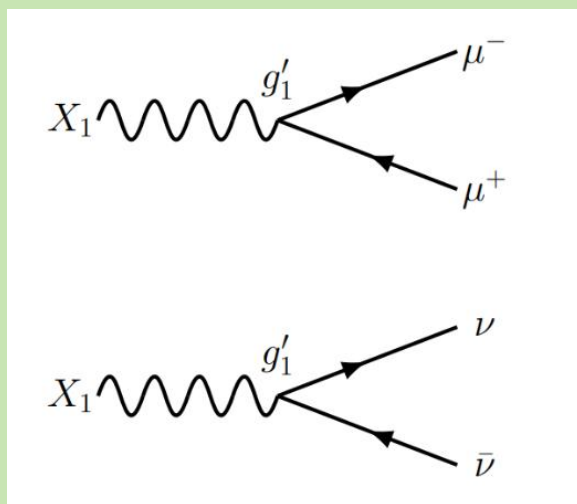
- Can be studied with $J/\psi \rightarrow \mu^+ \mu^- X_{0/1}$



JHEP 10 (2020) 207

Three model scenarios

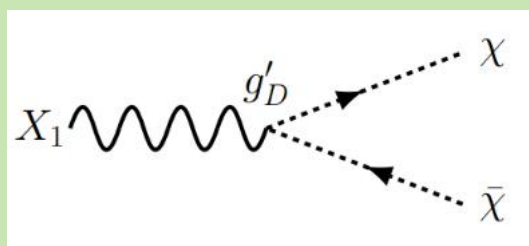
“Vanilla” $L_\mu - L_\tau$ model



X_1 only couples to SM particles

$$BF(X_1 \rightarrow \nu\nu) \sim (33 - 100)\%$$

Invisible $L_\mu - L_\tau$ model



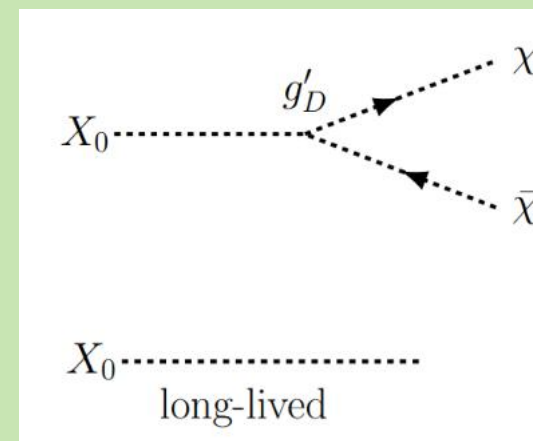
Dark matter particle χ couples to X_1 with strength g'_D

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

$$g'_D \gg g_1$$

$$BF(X_1 \rightarrow \chi\bar{\chi}) \sim 100\%$$

Scalar $U(1)$ model



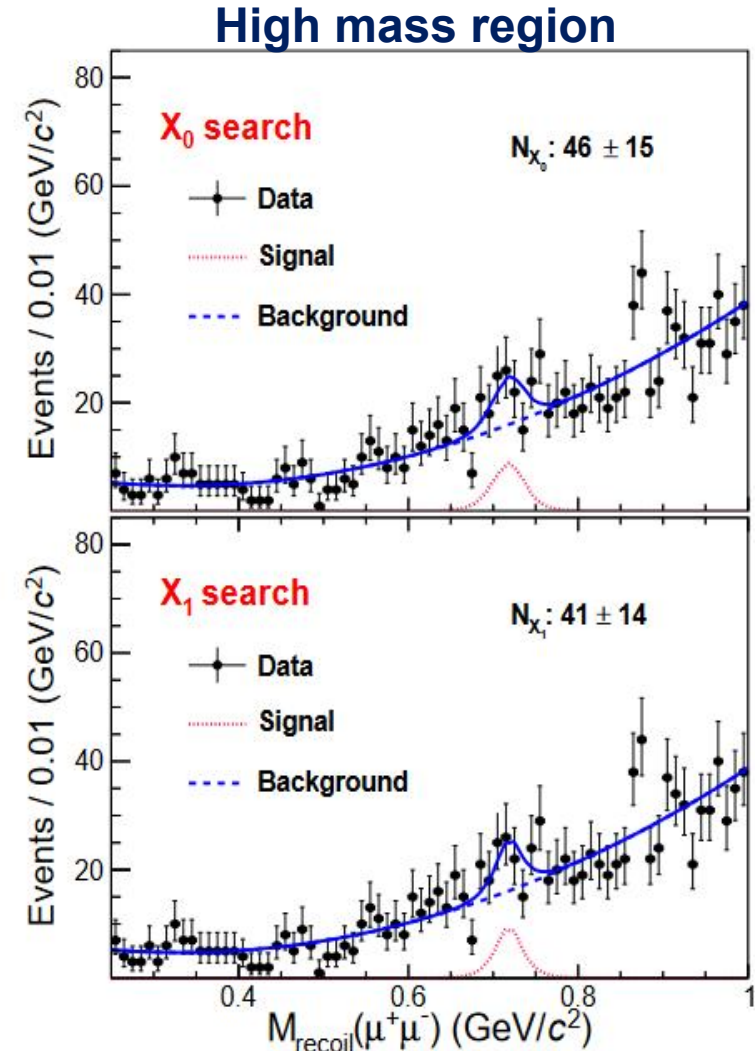
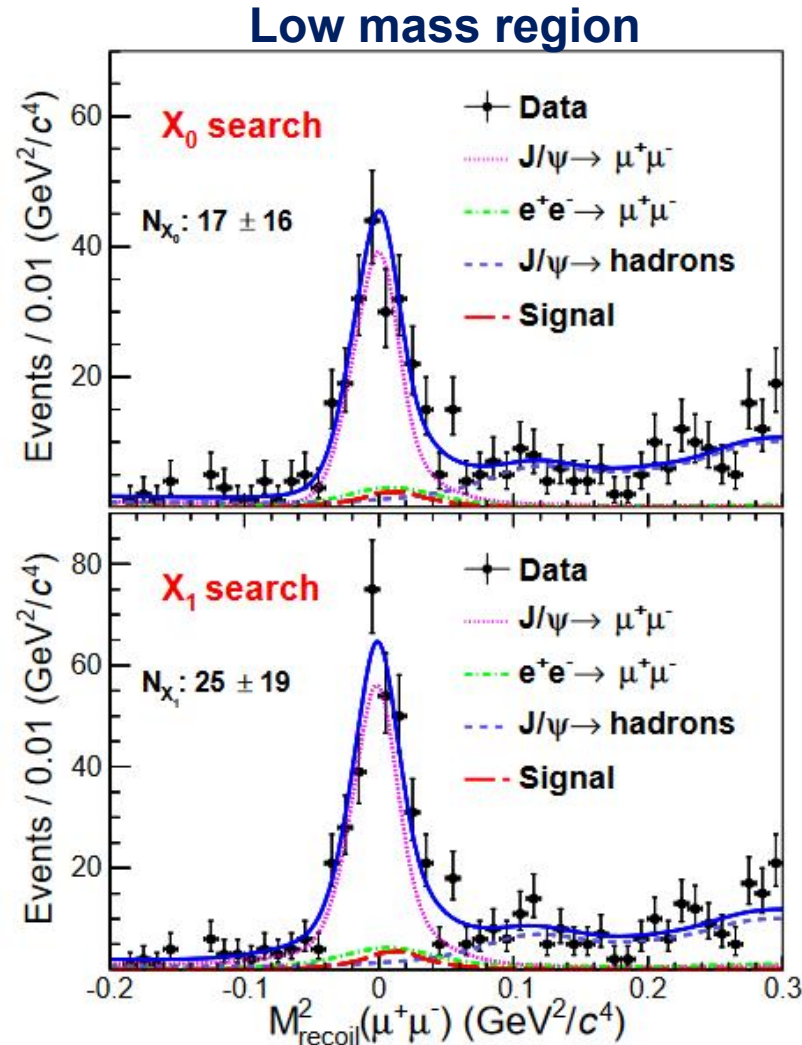
Dark matter particle χ couples to X_0 with strength g'_D
 X_0 is long lived or only decays to invisible final states

Search for $J/\psi \rightarrow \mu^+ \mu^- X_{0/1}$

Search for $X_{0/1}$ in the mass region 1 MeV - 1 GeV

No evidence for the signals of $X_{0/1}$ invisible decay

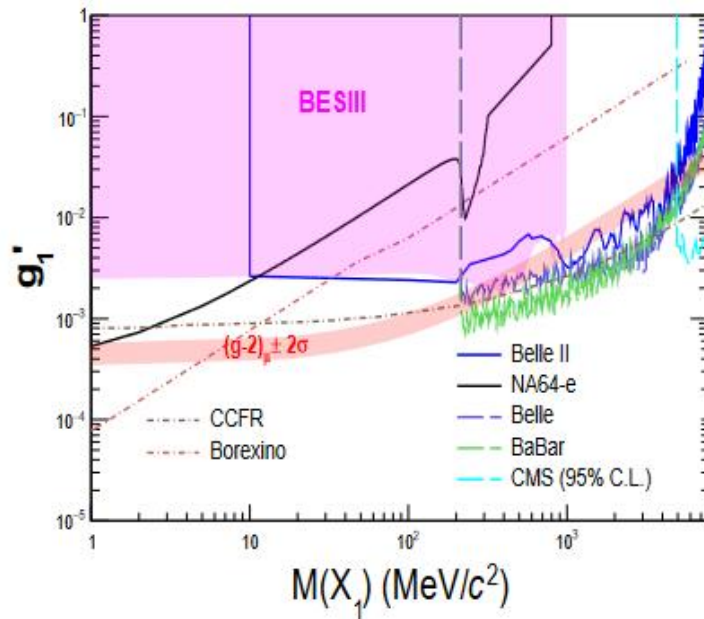
Maximum local significance is 2.5σ at $0.72 \text{ GeV}/c^2$



Upper limits on the couplings

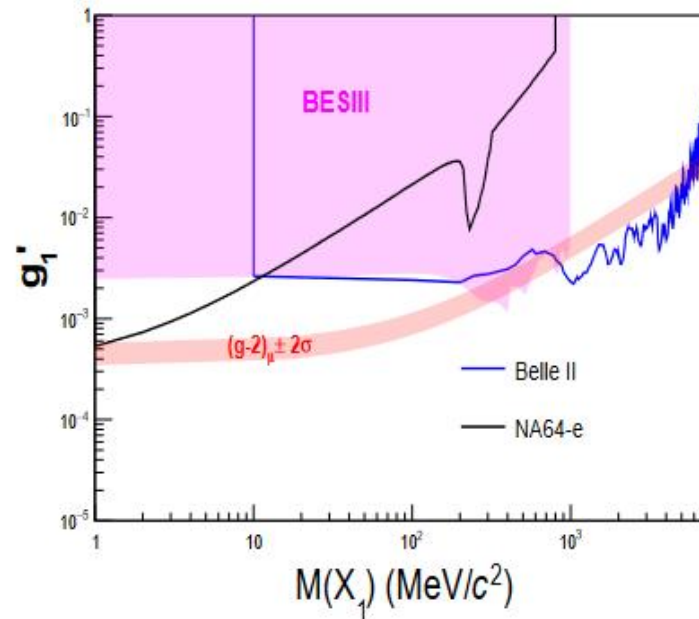
PRD (2024) 109, L031102

“vanilla” $L_\mu - L_\tau$ model



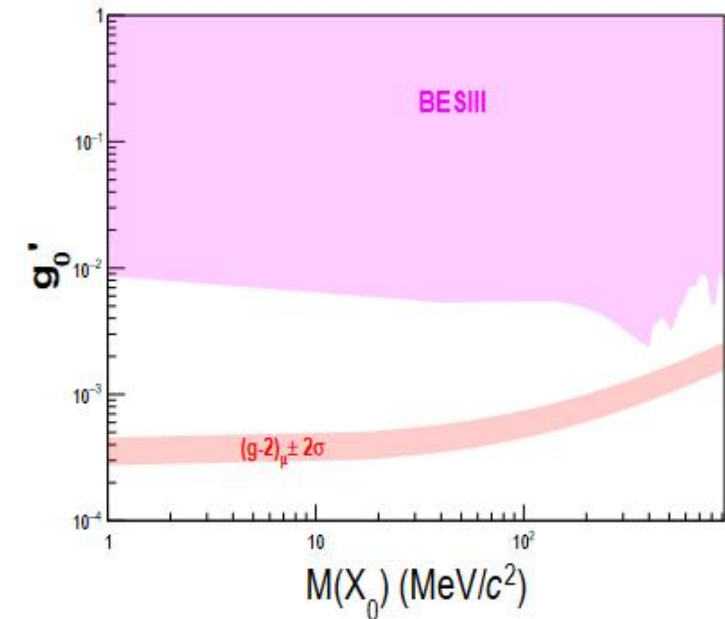
BESIII, BelleII, NA64-e: $X_1 \rightarrow \nu\nu$
 BABAR, CMS, Belle: $X_1 \rightarrow \mu^+\mu^-$

“invisible” $L_\mu - L_\tau$ model



BESIII provides best sensitivity
 in $200-860 \text{ MeV}/c^2$

“scalar” $U(1)$ model



BESIII perform the first direct
 search for the scalar

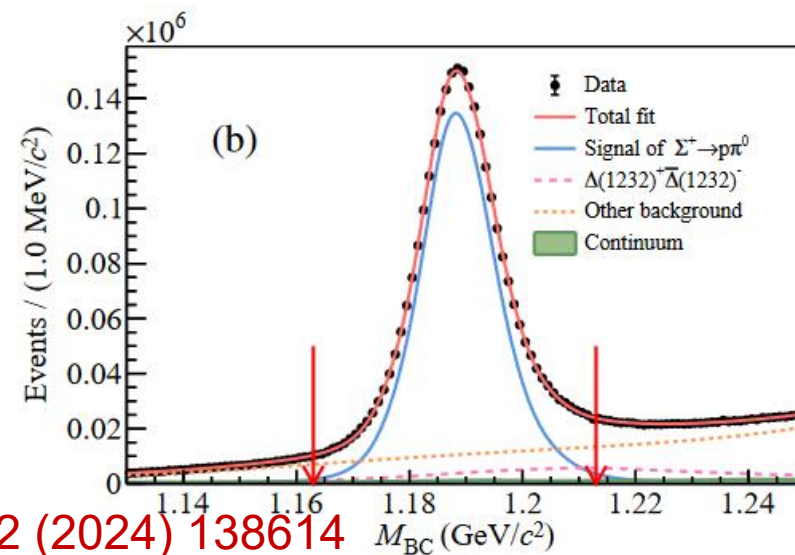
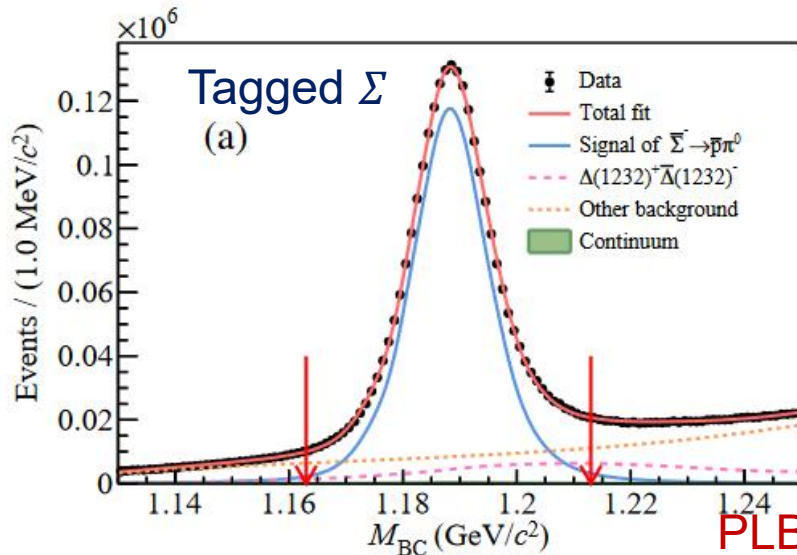
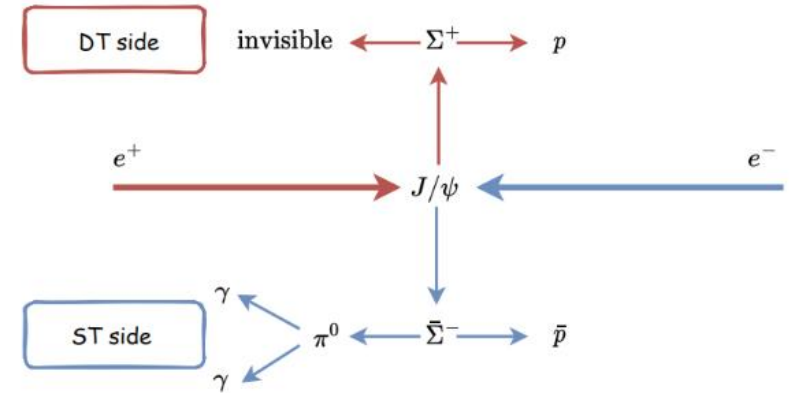
Search for $\Sigma^+ \rightarrow \text{proton} + \text{invisible}$

- Multiple new physics effects can enter the signal decay

- FCNC process $s \rightarrow d\nu\nu$
- Massless dark photon, QCD axion...

- 10 million pairs of $\Sigma^+ \bar{\Sigma}^-$ are produced
(10 billion J/ψ decays)

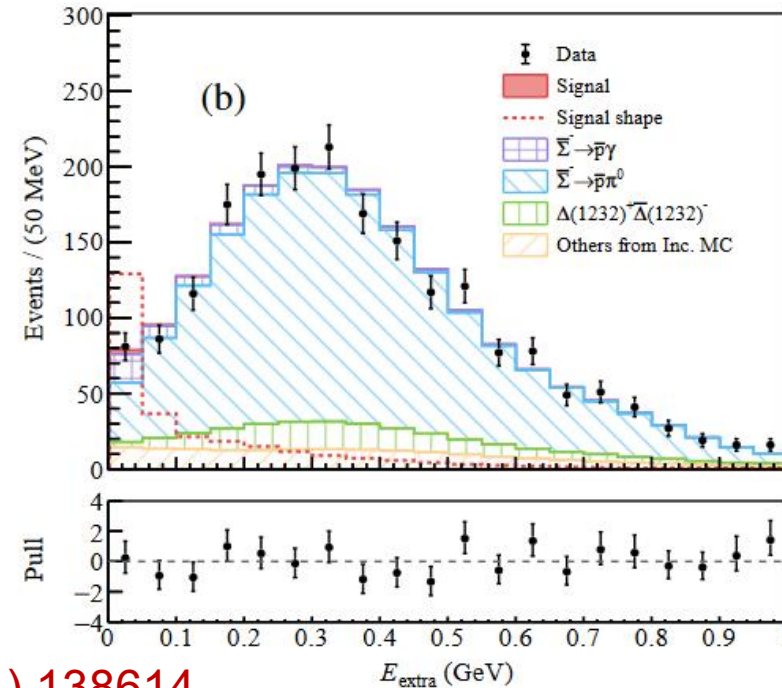
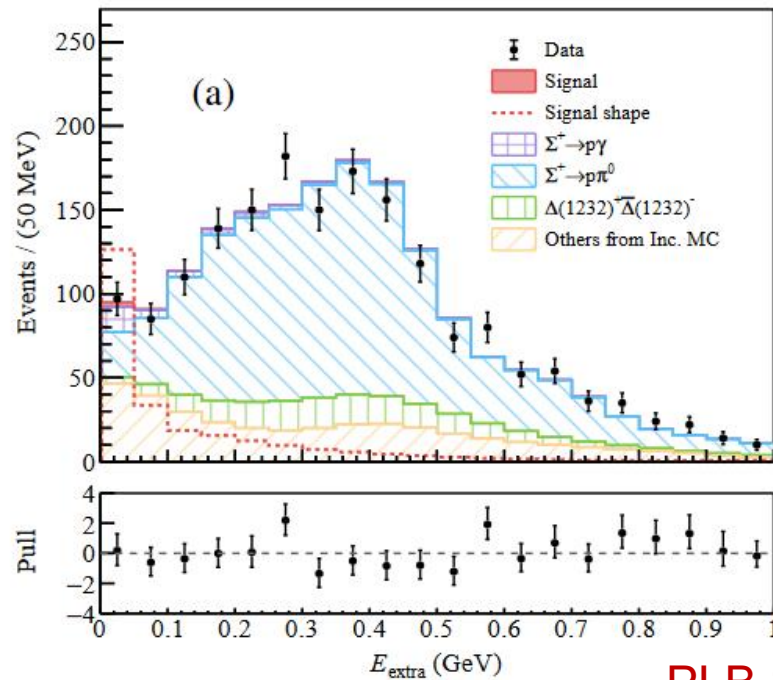
- Enables studies of decays with “missing” particles by tagging one $\Sigma \rightarrow p\pi$



PLB 852 (2024) 138614

Search for $\Sigma^+ \rightarrow \text{proton} + \text{invisible}$

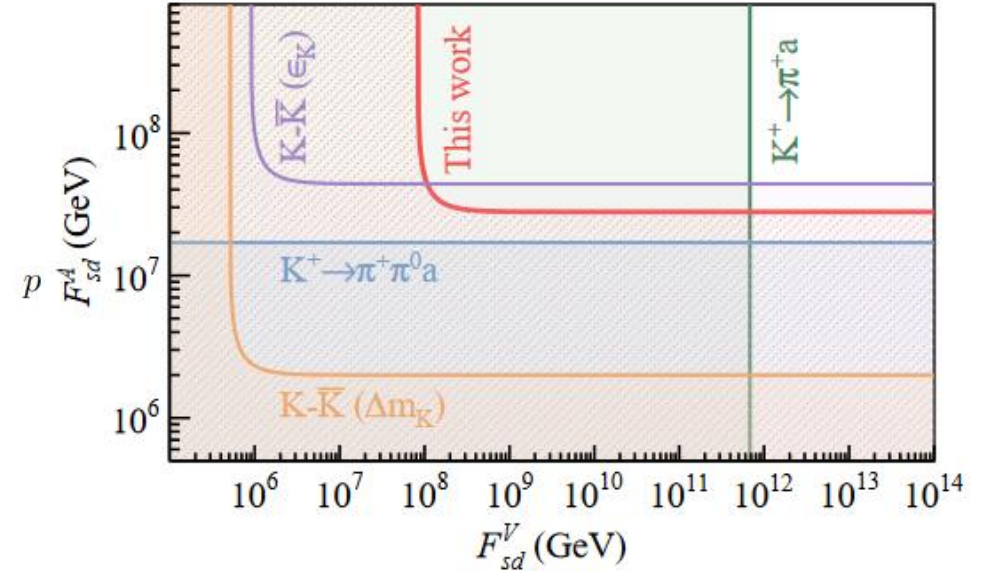
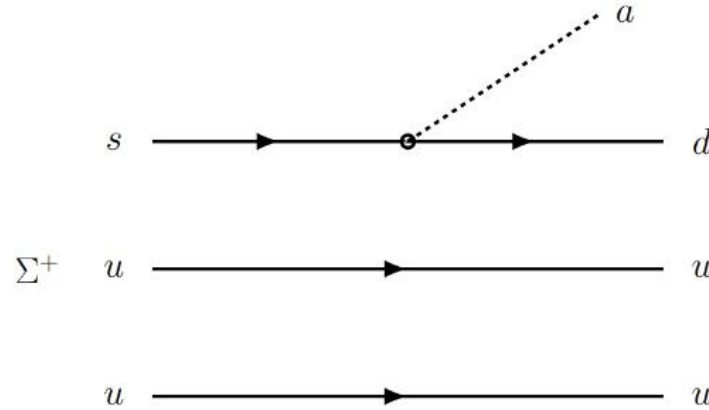
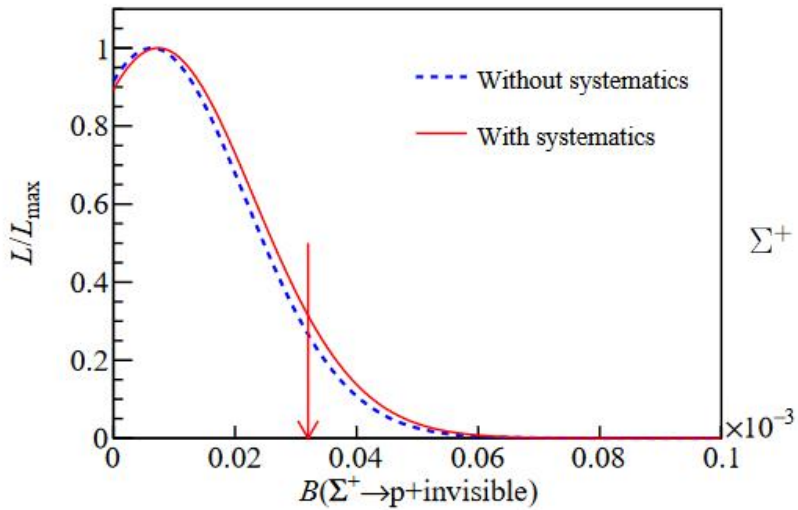
- Count the energy deposit in electro-magnetic calorimeter
- A unique method at electron-positron colliders



PLB 852 (2024) 138614

- Anti-protons are more likely to interact with detector materials, causing the energy deposit larger than proton
- Requires data-driven method to model the background

Search for $\Sigma^+ \rightarrow \text{proton} + \text{invisible}$



PLB 852 (2024) 138614

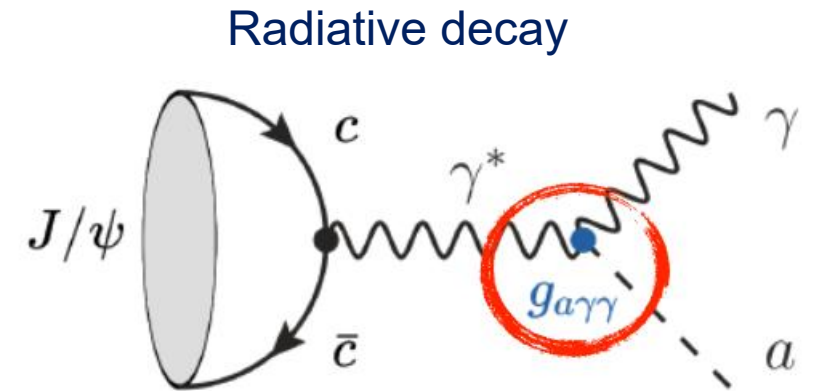
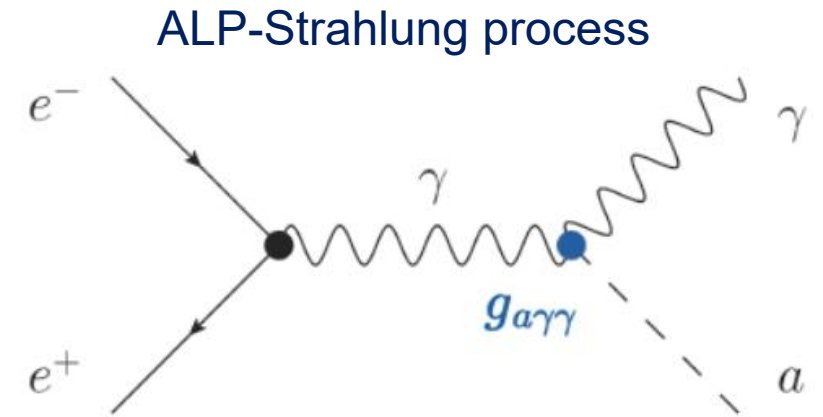
$$\Gamma(\Sigma^+ \rightarrow pa) = \frac{M_{\Sigma^+}^3}{16\pi} \left(1 - \frac{M_p^2}{M_{\Sigma^+}^2}\right)^3 \left(\frac{(-1)^2}{|F_{sd}^V|^2} + \frac{0.34^2}{|F_{sd}^A|^2}\right)$$

PRD 102 (2020) 015023

- First upper limit of the decay branching fraction is reported ($< 3.2 \times 10^{-5}$ at 90% CL.)
- Complements other searches for the **QCD axion** with tiny mass (< 1 eV) and long lifetime (PLB 169 (1986) 73), also constraints massless dark photon models

Search for an axion-like particle

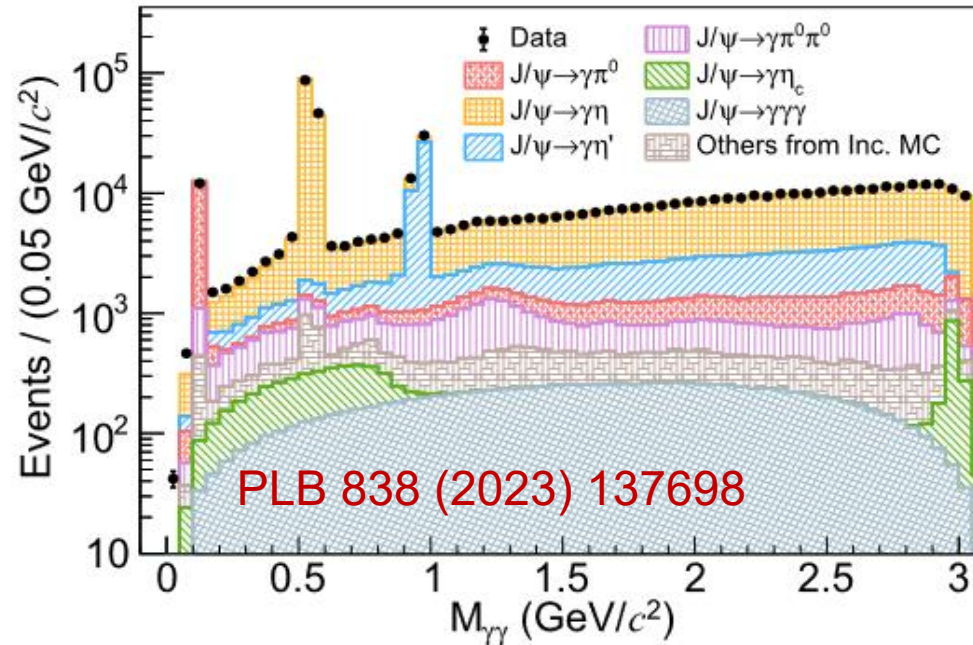
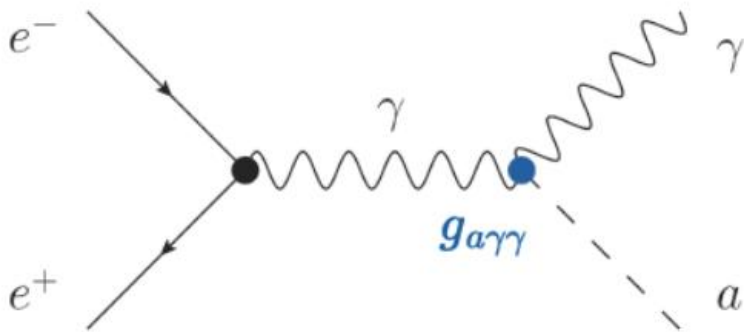
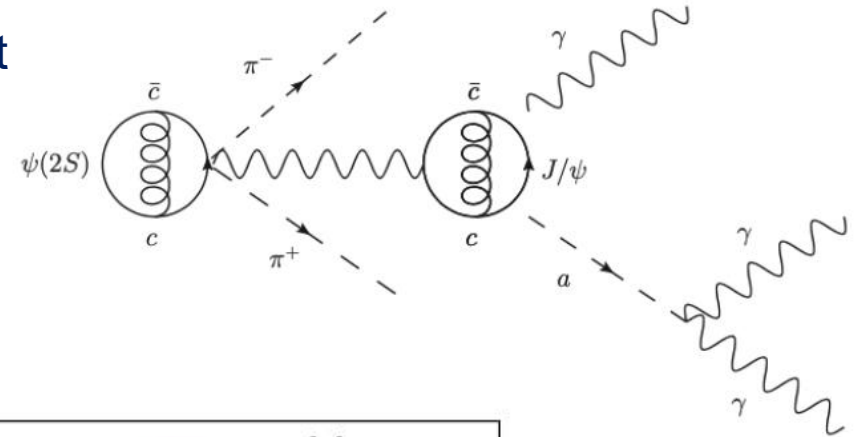
- An axion-like particle (ALP)
 - is a pseudo-scalar particle
 - introduced by the spontaneous breaking of Peccei-Quinn symmetry to solve the strong CP problem of the QCD
 - Phys. Rev. Lett. 40, 223 (1978); Phys. Rev. Lett. 40, 279 (1978)
 - Phys. Rev. Lett. 38, 1440 (1977); Phys. Rev. D 16, 1791 (1977)
 - predicted by many models beyond the SM and proposed to be a **cold DM candidate**
 - 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 $\text{MeV}/c^2 - \text{GeV}/c^2$, **mainly constrained by e^+e^- colliders**
 - Phys. Lett. B 753, 482 (2016)



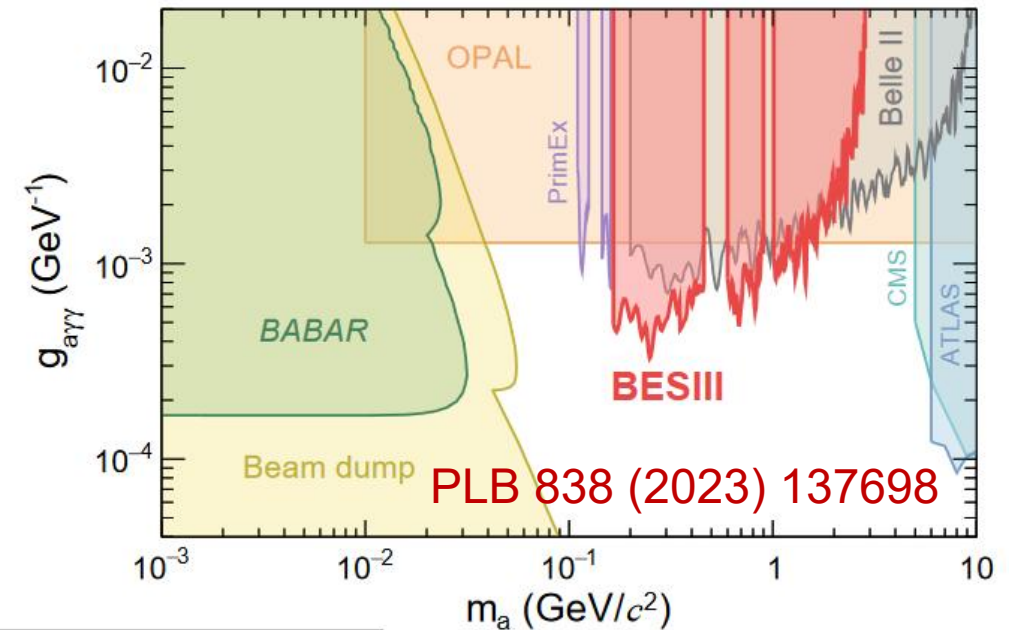
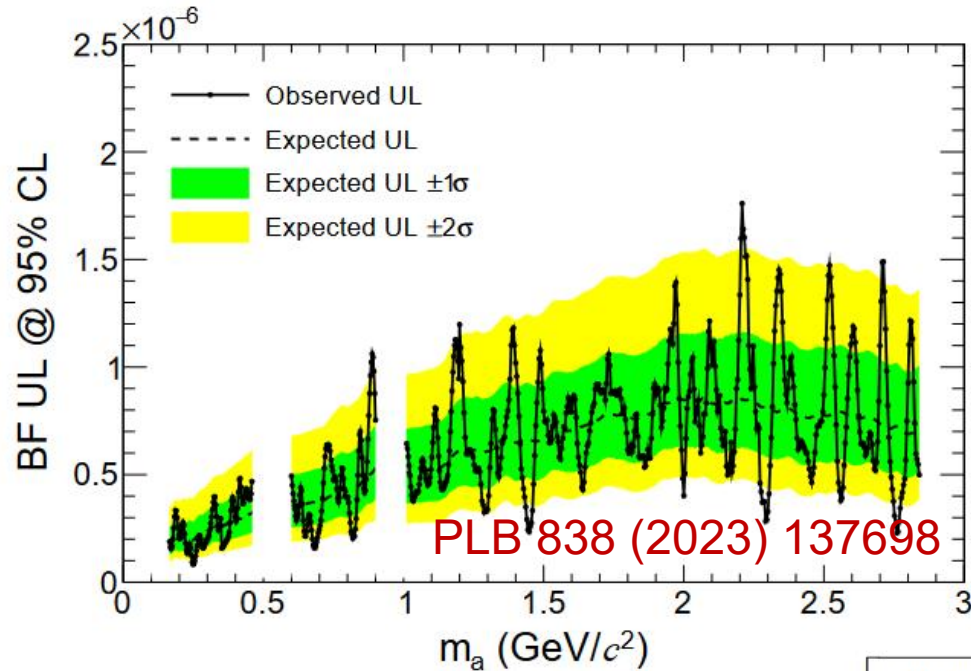
JHEP 06 (2019) 091

Search for ALP with $\psi(2S)$ data

- Using 2.7 billion $\psi(2S)$ data, BESIII has set one of the best limits on $g_{a\gamma\gamma}$ via $J/\psi \rightarrow \gamma a(\rightarrow \gamma\gamma)$
- Can avoid the pollution of non-resonant production and QED background



Search for ALP with $\psi(2S)$ data

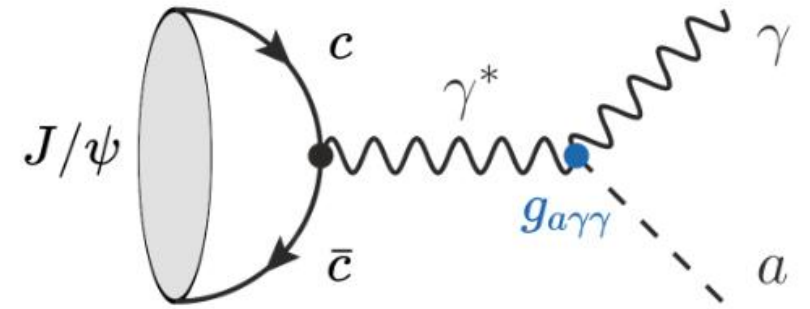


$$g_{a\gamma\gamma} = \sqrt{\frac{\mathcal{B}(J/\psi \rightarrow \gamma a)}{\mathcal{B}(J/\psi \rightarrow e^+e^-)} \left(1 - \frac{m_a^2}{m_{J/\psi}^2}\right)^{-3} \frac{32\pi\alpha_{em}}{m_{J/\psi}^2}}$$

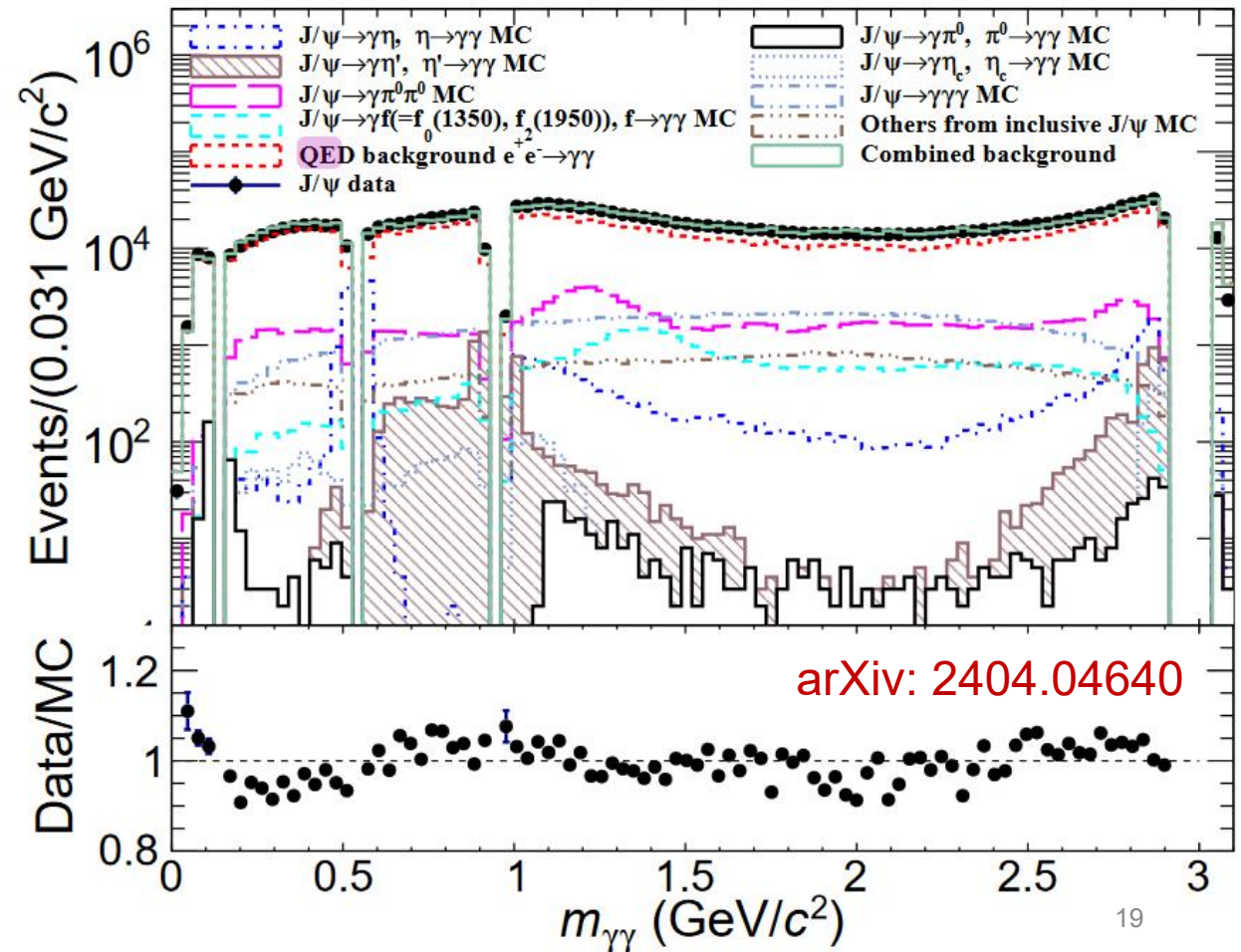
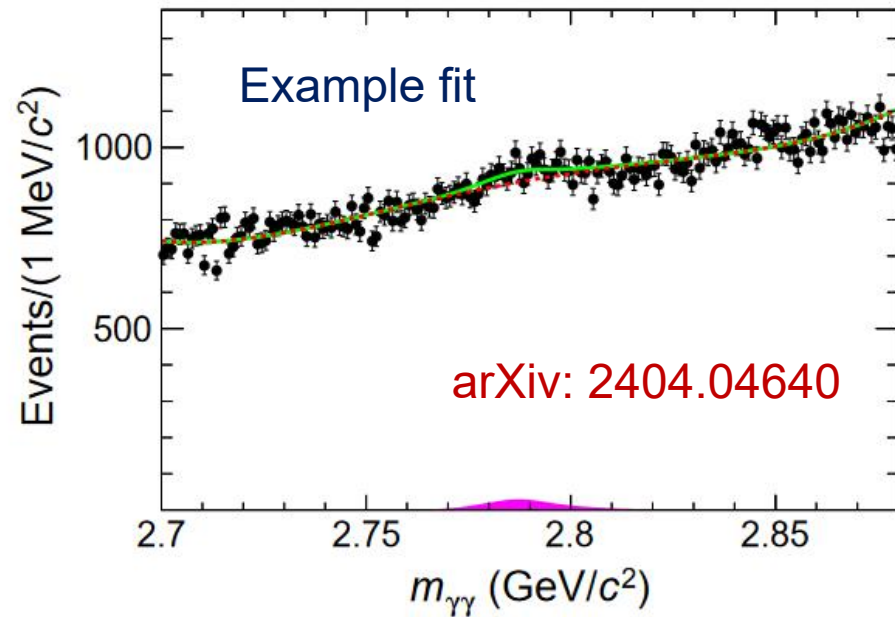
- Limits at $10^{-6} - 10^{-8}/\text{GeV}$ level
- Most stringent constraints on $g_{a\gamma\gamma}$ in the m_a range $[0.165, 1.468] \text{ GeV}/c^2$ up-to-date
- Can be further improved with 10 billion of BESIII J/ψ data, which can include both radiative $J/\psi \rightarrow \gamma a$ and ALP-strahlung process $e^+e^- \rightarrow \gamma a$

Expected pollution of ALP-strahlung process $e^+e^- \rightarrow \gamma a$ in $J/\psi \rightarrow \gamma a$

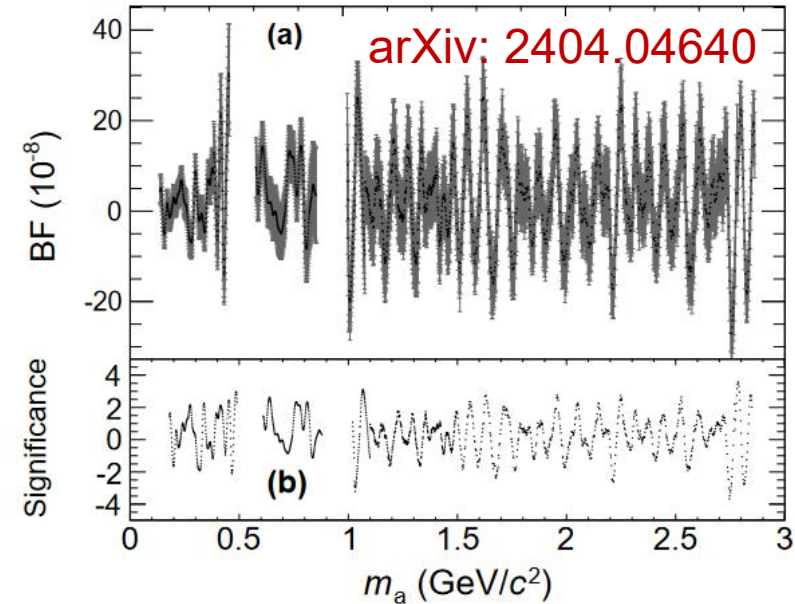
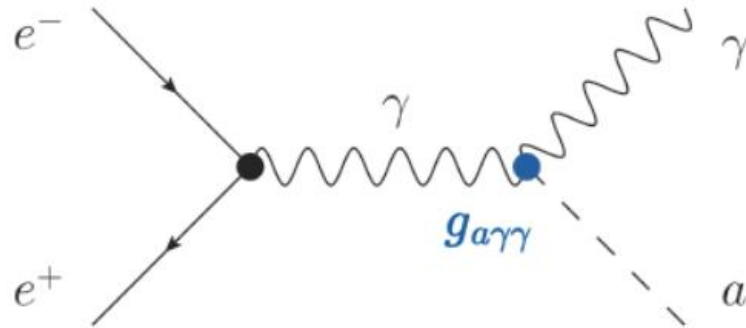
Search for ALP with J/ψ data



- Using 10 billion J/ψ data, BESIII has the best limits on $g_{a\gamma\gamma}$ via $J/\psi \rightarrow \gamma a (\rightarrow \gamma\gamma)$
- Huge but flat QED background (estimated with continuum data), found to have minimal effect on signal



Search for ALP with J/ψ data



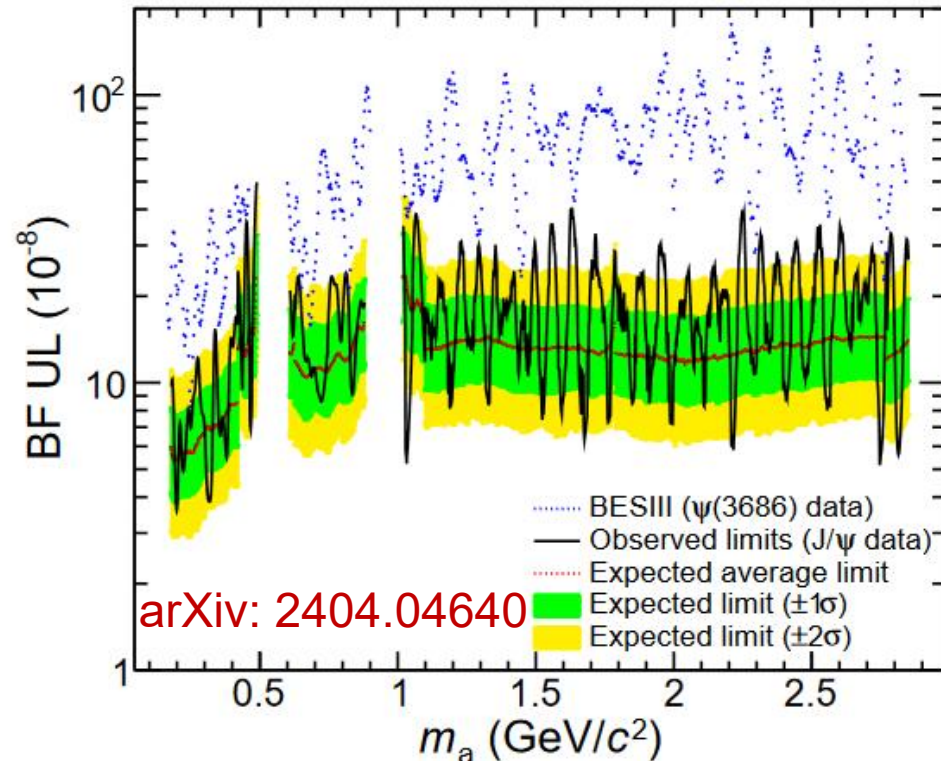
- Background of ALP-Strahlung process is estimated with $\sigma_a^{rad} = \frac{N_{J/\psi}}{L_{J/\psi}} \cdot \mathcal{B}(J/\psi \rightarrow \gamma a)$ and taken as a systematic uncertainty of 4.4%

- Uncertainty associated with the fit model is estimated by varying the parameterized PDFs of signal and background, which is 9.2%

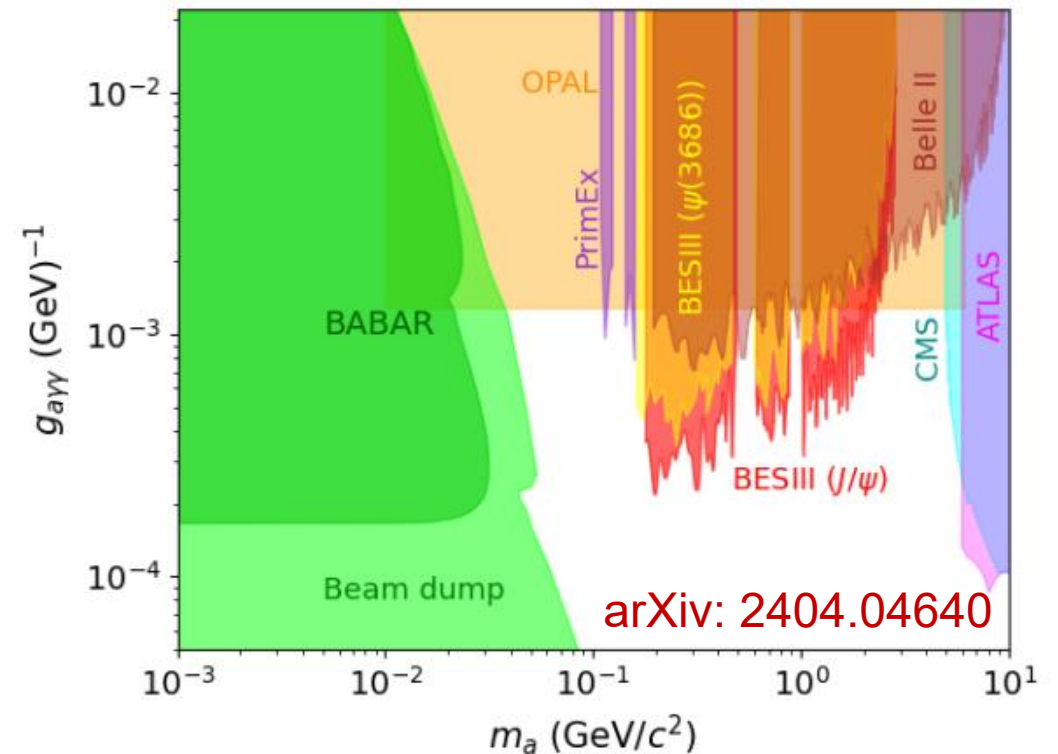
- At a given mass point $m_a = 2.786 \text{ GeV}/c^2$, the global significance is 1.6sigma → no significant signal has been found

Search for ALP with J/ψ data

95% Confidence level ULs on product branching fraction



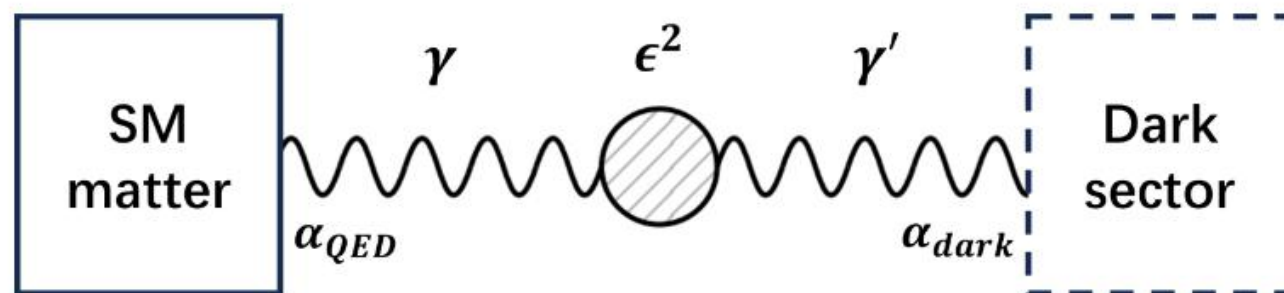
95% Confidence level ULs on ALP-photon coupling



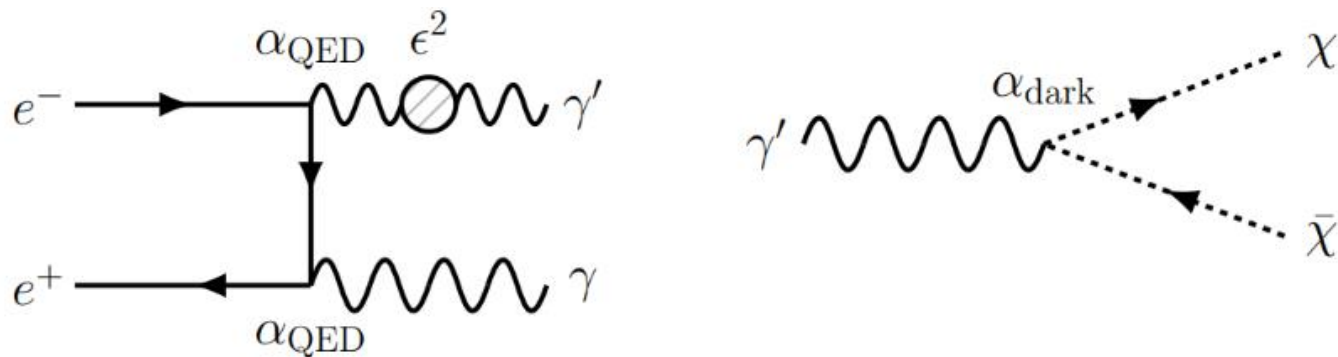
These results supersede the previous BESIII (Belle-II) search by 3 (5) times
Phys. Lett. B 838, 137678 (2023); Phys. Rev. Lett. 125, 161806 (2020)

Search for massive dark photon

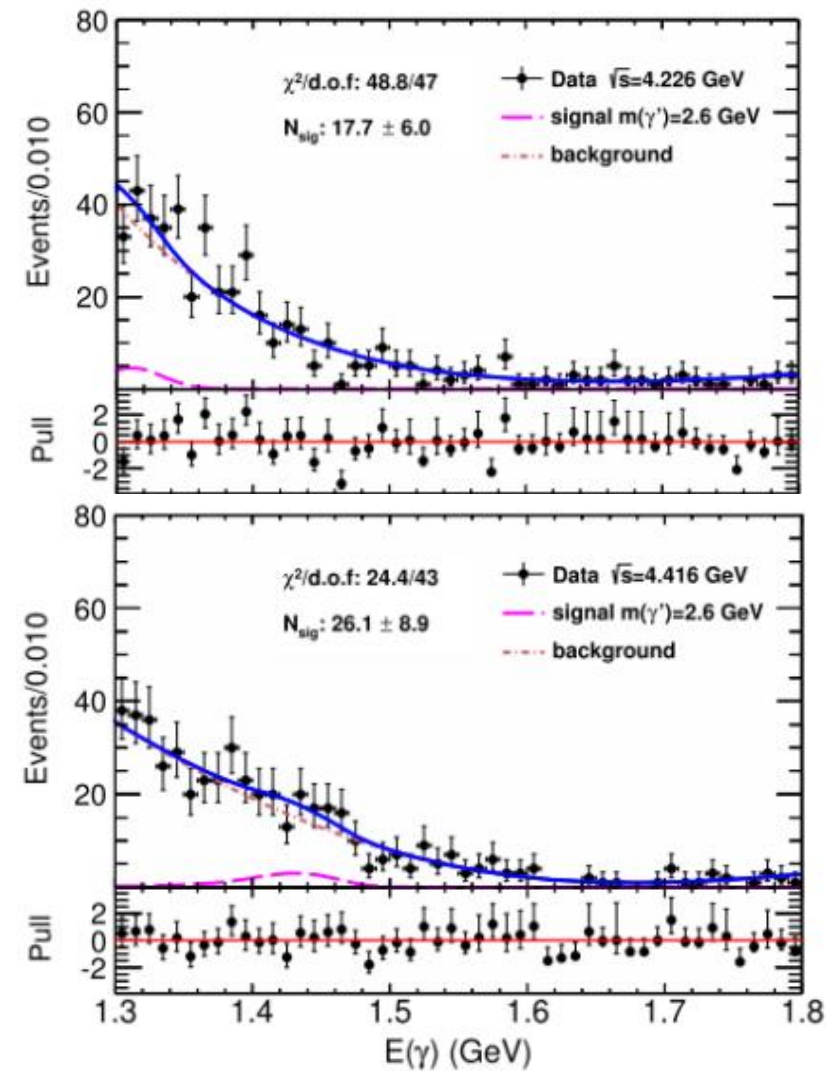
- Extra gauge group $U(1)_D$
 - The associated gauge boson is the dark photon
 - Massive if the symmetry is spontaneously broken
- Dark photon has a kinetic mixing with the SM photon $\frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu}$
- Effective coupling strength with SM matter $e\epsilon$
- Can be produced in any process by replacing the SM photon



Search for massive dark photon in $e^+ e^- \rightarrow \gamma \gamma'$



- γ' predominantly decays to $\chi\bar{\chi}$ if $m_\chi < m_{\gamma'}/2$
- Search for a peak in the SM γ energy spectrum $E_\gamma = \frac{s - m_{\gamma'}^2}{2\sqrt{s}}$
- 14.9 fb^{-1} data samples between $\sqrt{s}=4.13\text{-}4.60$ GeV
- Scan of $m_{\gamma'}$ in [1.5, 2.9] GeV
- Maximum global significance is 2.2σ

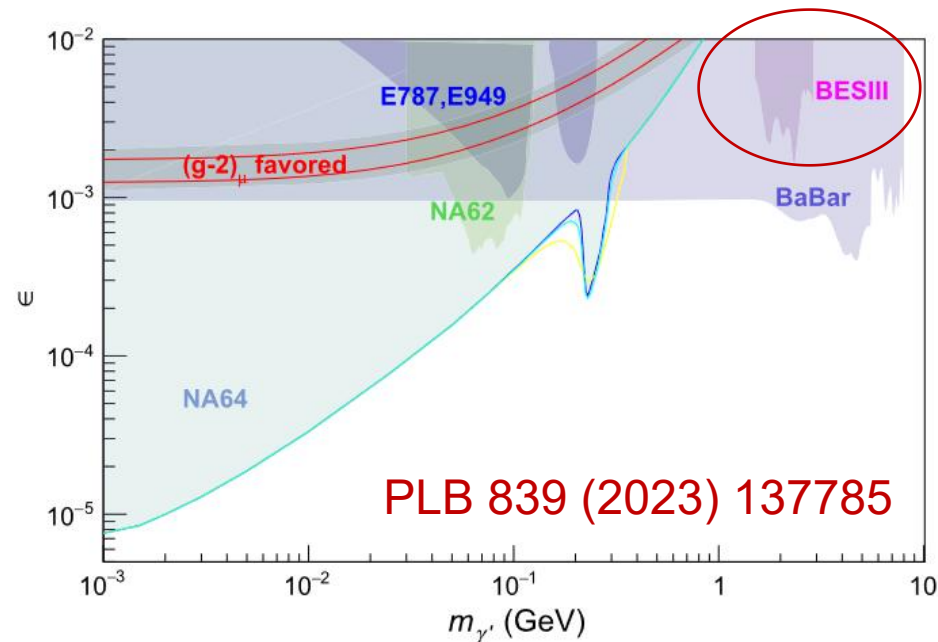


Constraint on mixing parameter ϵ

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

PRD 80 (2009) 015003

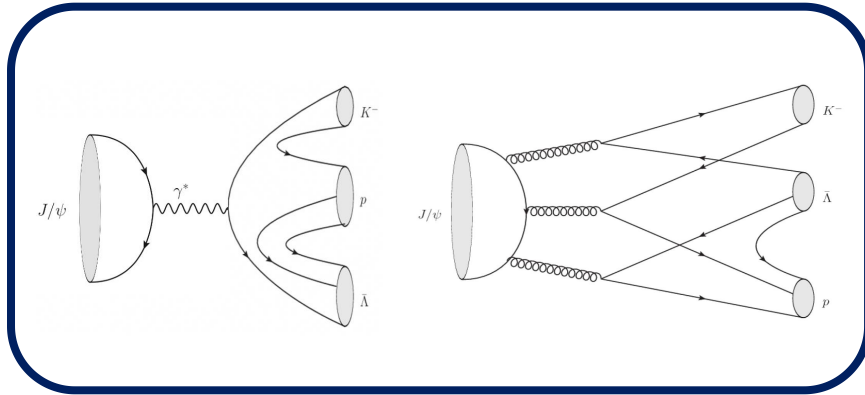
$\cos\theta_c$ is the cut on γ polar angle



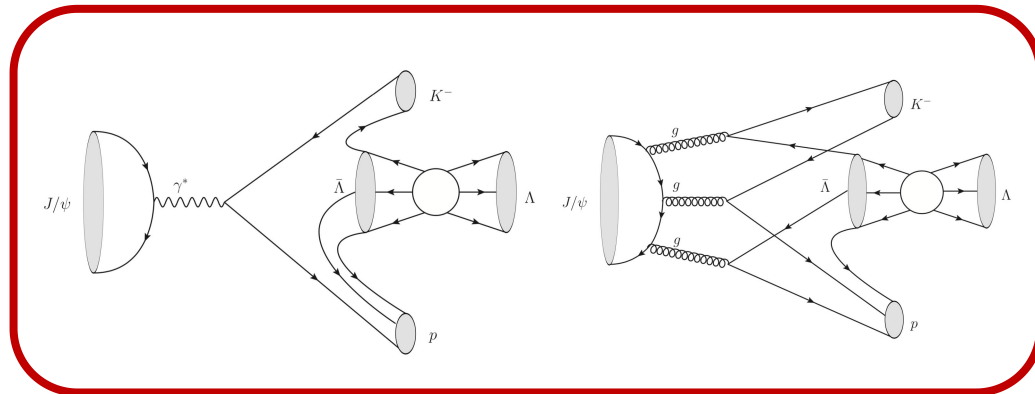
BESIII will produce more competitive constraints with 20 fb^{-1} data at 3.773 GeV

Search for $\Lambda\bar{\Lambda}$ oscillation

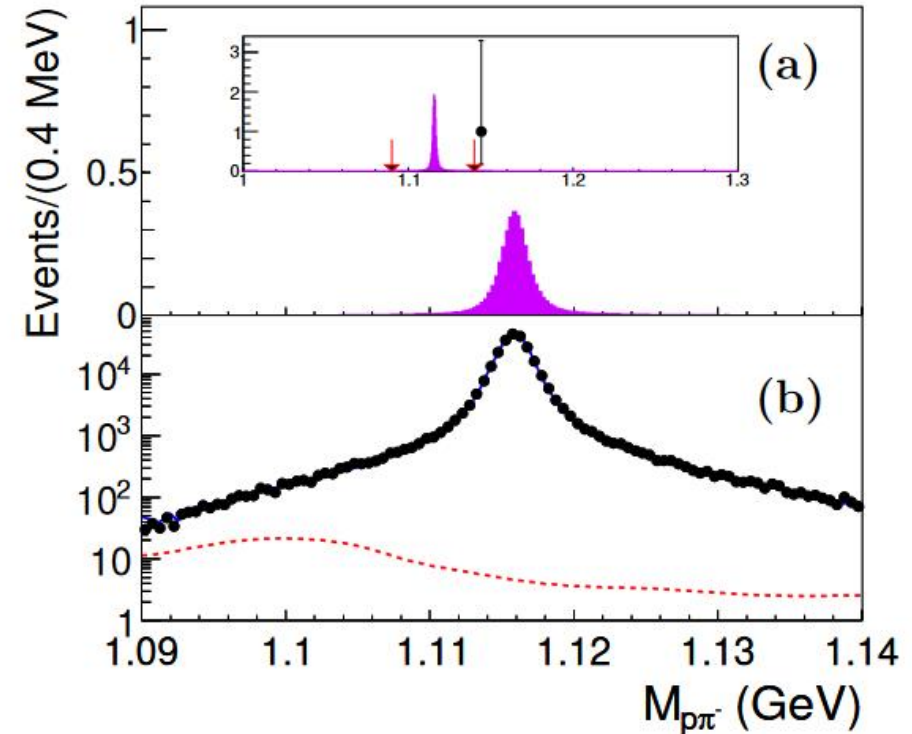
PRL 131 (2023) 121801



Right Sign Channel
 $J/\psi \rightarrow pK^- \bar{\Lambda} \rightarrow pK^- (\bar{p}\pi^+)$



Wrong Sign Channel
 $J/\psi \rightarrow pK^- \Lambda \rightarrow pK^- (p\pi^-)$

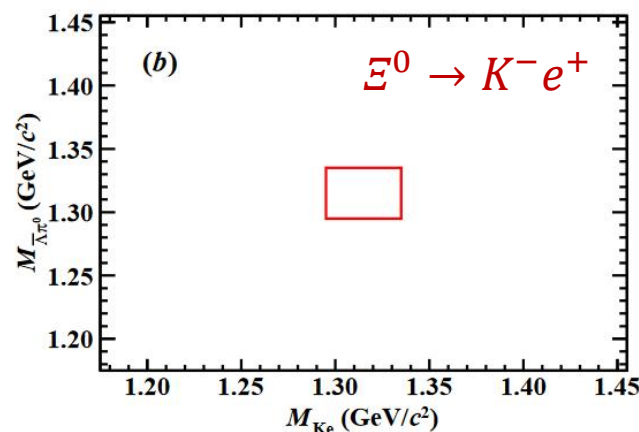
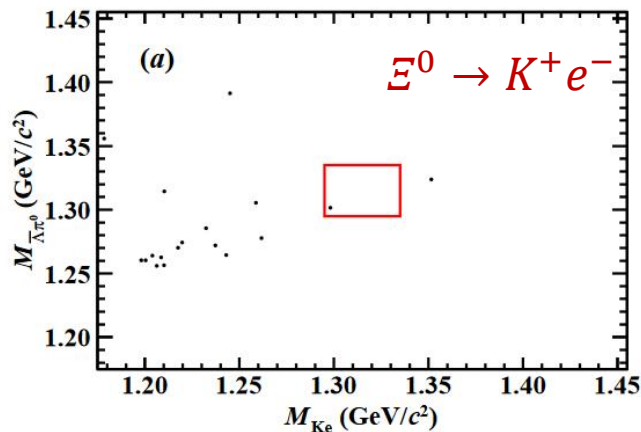
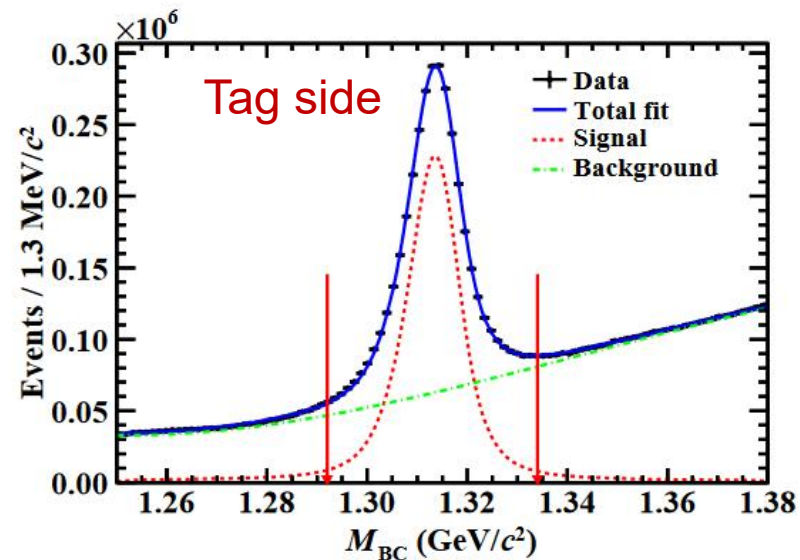
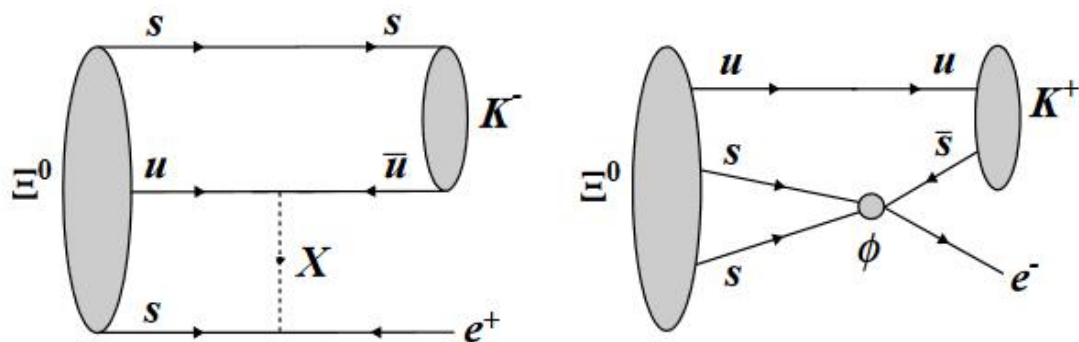


$$\delta m_{\Lambda\bar{\Lambda}} < 3.8 \times 10^{-18} \text{ GeV}$$

$$\tau_{\text{osc}} > 1.7 \times 10^{-7} \text{ s}$$

- BNV process contains a second generation quark
- Complements to $n\bar{n}$ oscillation studies

Search for $\Delta(B - L)=2$ process

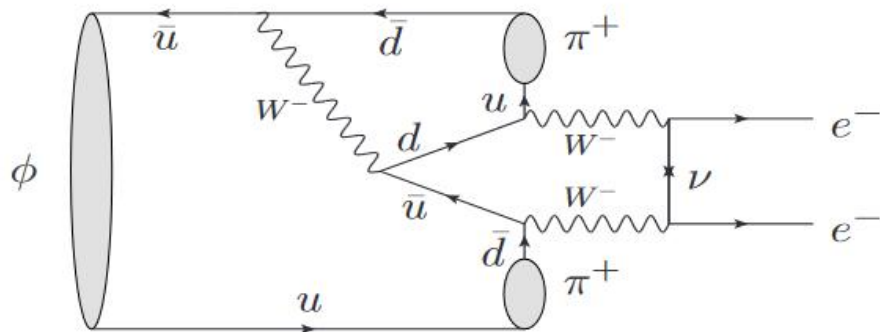


Double tag method with $J/\psi \rightarrow \Xi^0 \bar{\Xi}^0$ decays
background free!

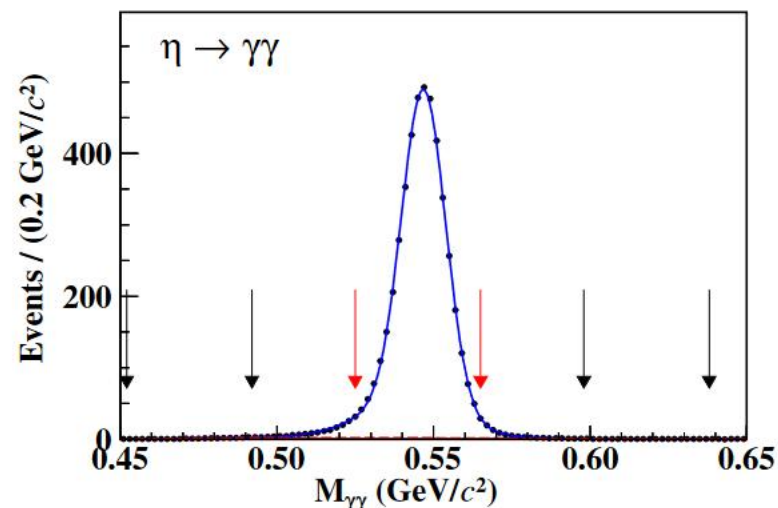
PRD 108 (2023) 012006

- First search, BF upper limits of $K^+ e^- / K^- e^+$ are $3.6/1.9 \times 10^{-6}$

Search for LNV process

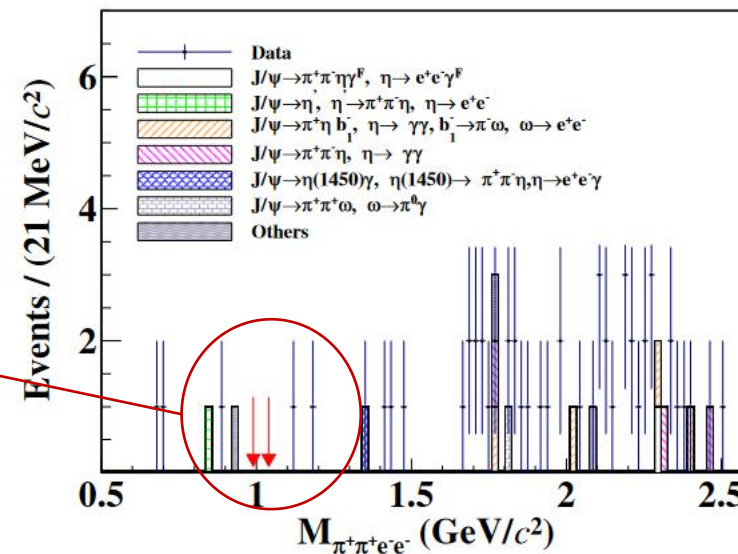
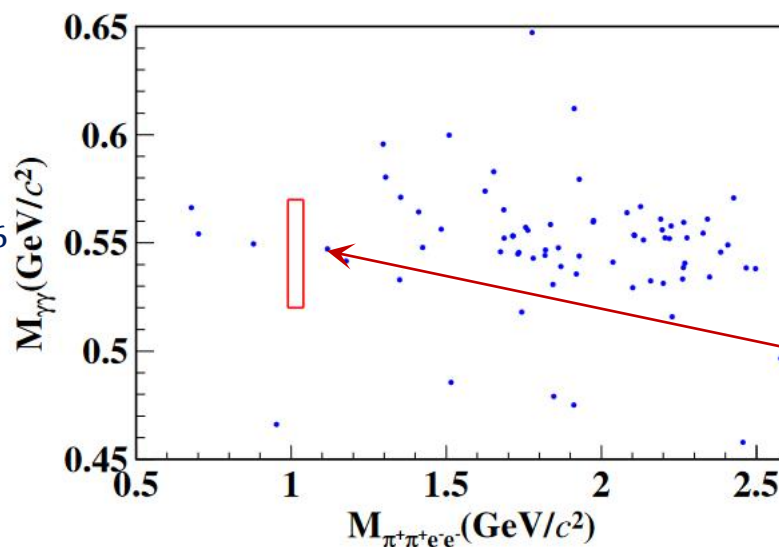


Decay diagram in the scenario of Majorana neutrino

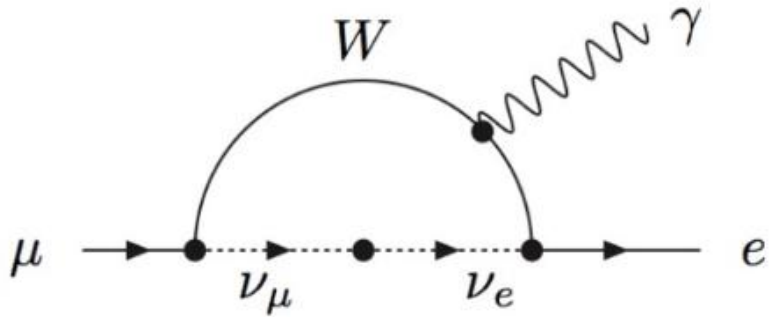


Tag $\eta \rightarrow \gamma\gamma$ in $J/\psi \rightarrow \phi\eta$ decays,
Search for $\phi \rightarrow \pi^+\pi^+e^-e^-$ in the recoiling side
use $\phi \rightarrow K^+K^-$ as reference channel

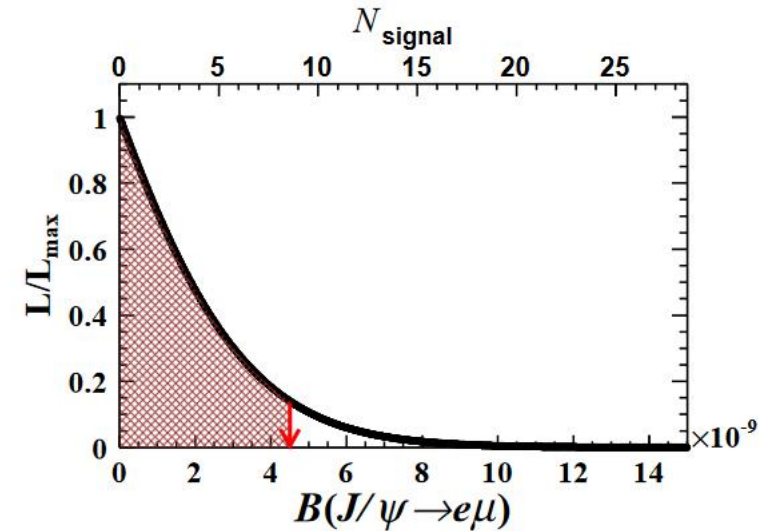
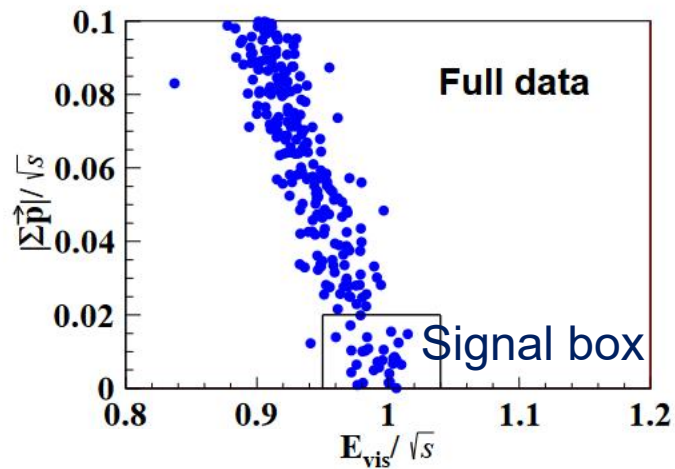
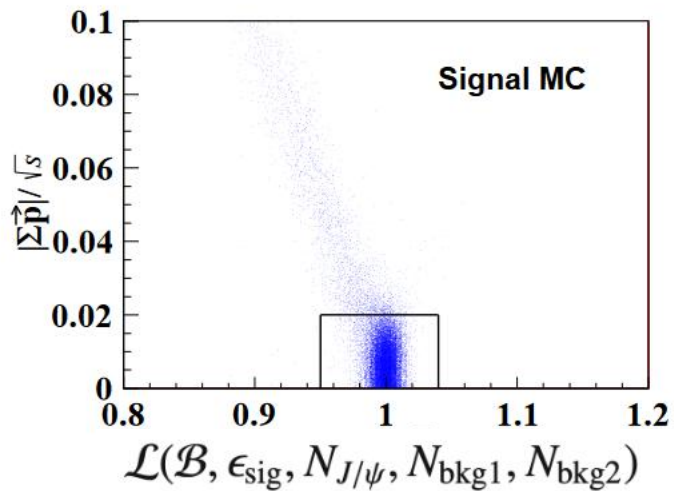
- First search in ϕ decays
- $\text{BF}(\phi \rightarrow \pi^+\pi^+e^-e^-) < 3.7 \times 10^{-6}$



Search for cLFV process $J/\psi \rightarrow e\mu$



- Forbidden in SM
- Suppressed with non-zero neutrino mass
- Good channels to probe new physics



$$\begin{aligned}
 &= \mathcal{P}(N_{\text{obs}} | N_{J/\psi} \cdot \mathcal{B} \cdot \epsilon_{\text{sig}} + N_{\text{bkg1}} + N_{\text{bkg2}}) \\
 &\cdot \mathcal{G}(\epsilon_{\text{sig}} | \epsilon_{\text{sig}}^{\text{MC}}, \epsilon_{\text{sig}}^{\text{MC}} \cdot \sigma_{\text{sig}}^{\text{EFF}}) \cdot \mathcal{P}(N_{\text{bkg1}}^{J/\psi\text{-MC}} | N_{\text{bkg1}}/f_1) \\
 &\cdot \prod_k \mathcal{P}(N_{\text{cont}}^k | N_{\text{bkg2}}/f_2^k) \cdot \mathcal{G}(N_{J/\psi} | N_{J/\psi}^{\text{data}}, \delta N_{J/\psi}^{\text{data}}).
 \end{aligned}$$

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- $\text{BF}(J/\psi \rightarrow e\mu) < 4.5 \times 10^{-9}$
- Improve the previous results by 30 times
- Most stringent ever in quarkonium decays

Summary and outlook

- BESIII has a good potential to search for BSM physics with a clean collision environment, is especially ideal for decays with **neutral and “missing” particles**
- The searches performed so far have significantly constrained the allowed phase space of theoretical models
 - **Muonphilic particles, ALPs, cLFV**
- More results will come soon by analysing the **10 billion J/ψ , 2.7 billion $\psi(3686)$ and $20 \text{ fb}^{-1} \psi(3770)$ decays**; new round of data taking is also underway

Thanks!