Dark sector search with hadrons at BESIII

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(On behalf of the BESIII Collaboration)

The 23rd International Conference on Few-Body Problems in Physics (FB23)

September 22-27, 2024

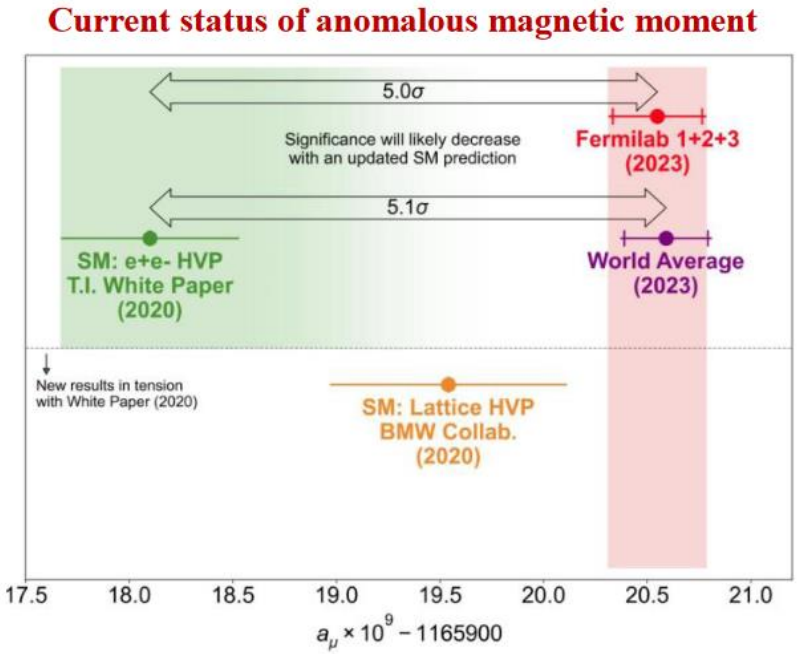
南開大學
Nankai University

Outline

- Introduction
- BEPCII and BESIII
  - BSM searches at BESIII
- Search for Axion-like particles
- Summary and outlook

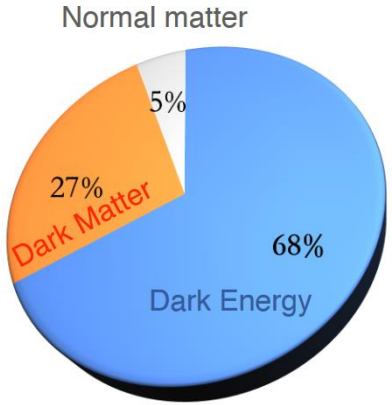
Introduction

- Standard Model (SM) has achieved great success especially in explanation of the collider experiments
  - Discovery of the Higgs boson
  - Precision study of flavour physics
  - Quantum chromo dynamics...
- Tensions have been found
  - g-2, W mass, R_D,R_{D^*}, R_K...
- Physics beyond the SM
  - **Existence & mechanism of dark matter and dark energy**
  - Baryon asymmetry of the universe
  - Neutrino masses and oscillations, hierarchy...

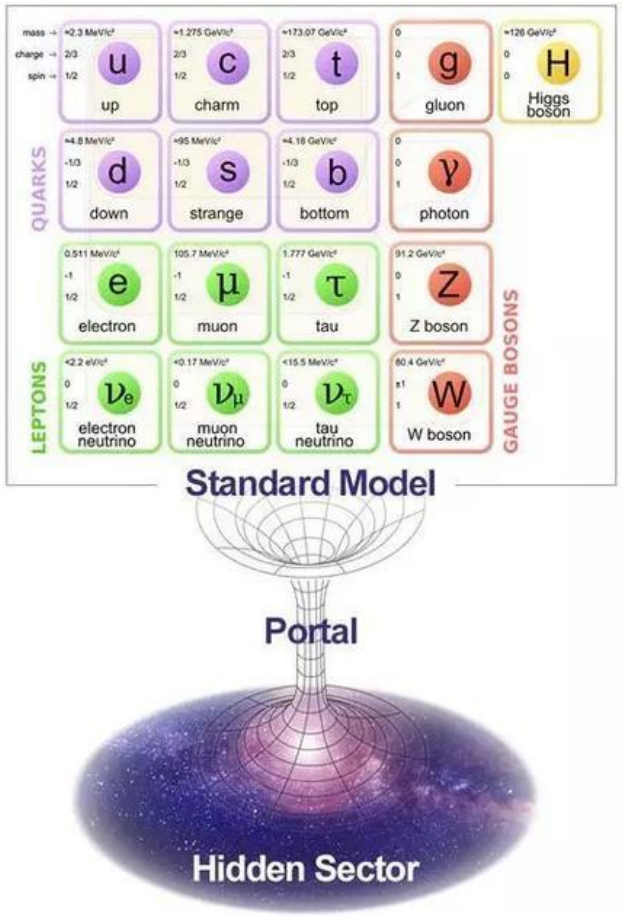


D. P. Aguillard, et. al. (Muon g-2 Collaboration)
arXiv:2308.06230

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



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

A' kinetic mixing with γ, Z

Dark Higgs (mixes with SM Higgs)

Sterile neutrino

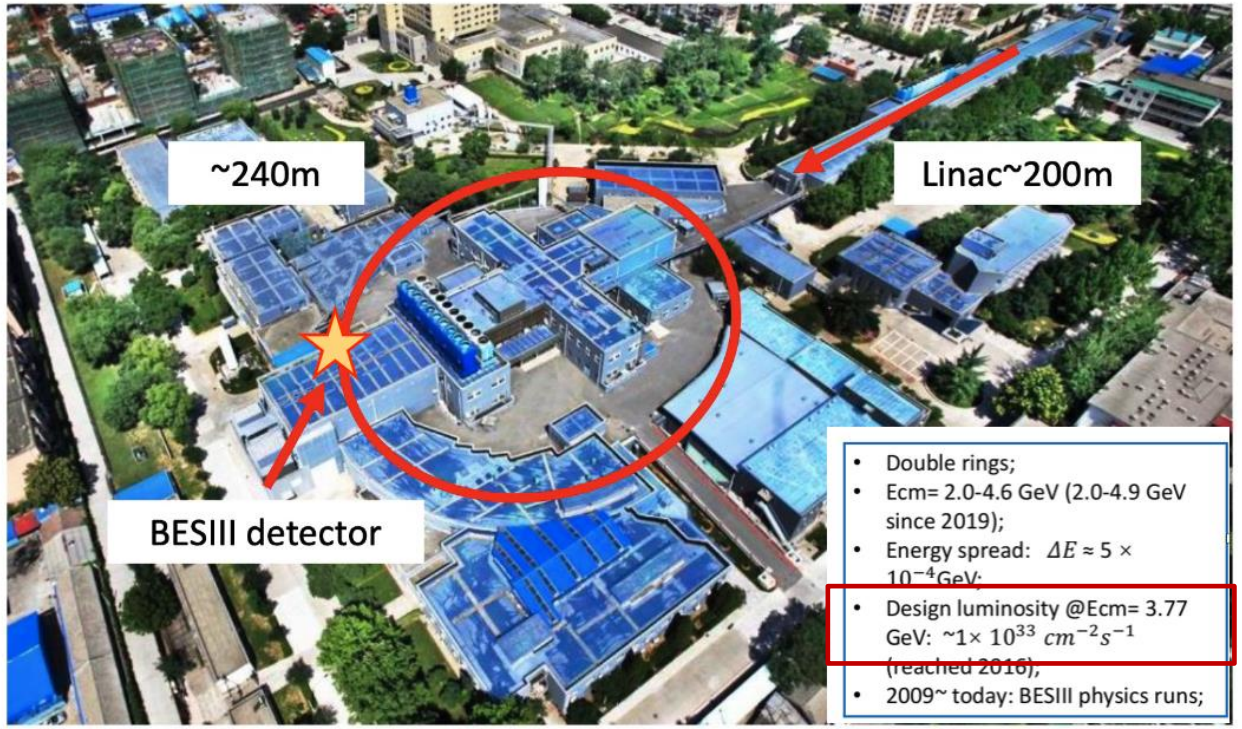
Axion, coupling to DM arxiv:1311.0029

- 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

BEPCII and BESIII

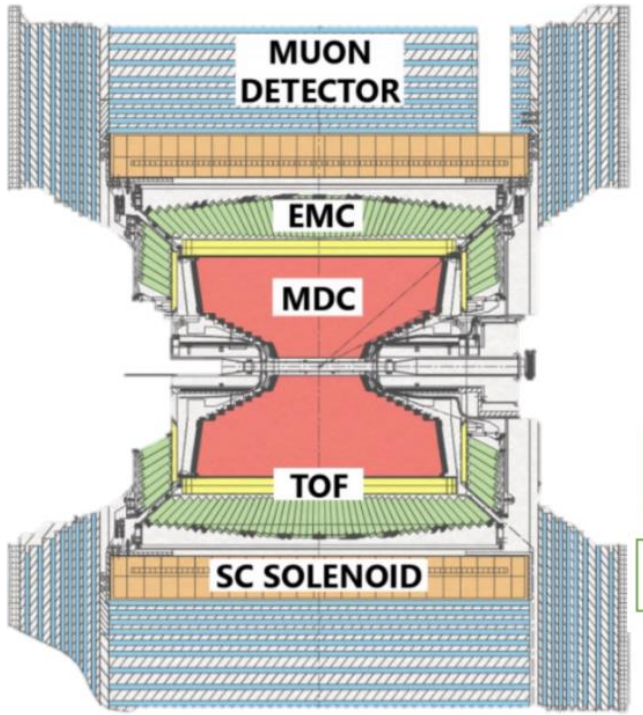
A symmetric electron-positron collider running at tau-charm (2-5 GeV) region

Beijing Electron–Positron Collider II



- Double rings;
- Ecm= 2.0-4.6 GeV (2.0-4.9 GeV since 2019);
- Energy spread: $\Delta E \approx 5 \times 10^{-4}$GeV;
- Design luminosity @Ecm= 3.77 GeV: ~1× $10^{33}\ cm^{-2}s^{-1}$ (reached 2016);
- 2009~ today: BESIII physics runs;

Beijing Spectrometer III



Main Drift Chamber
σ_p/p <0.5% (@1GeV) (1T)
σ_{xy} ~120 μm
dE/dx~6%

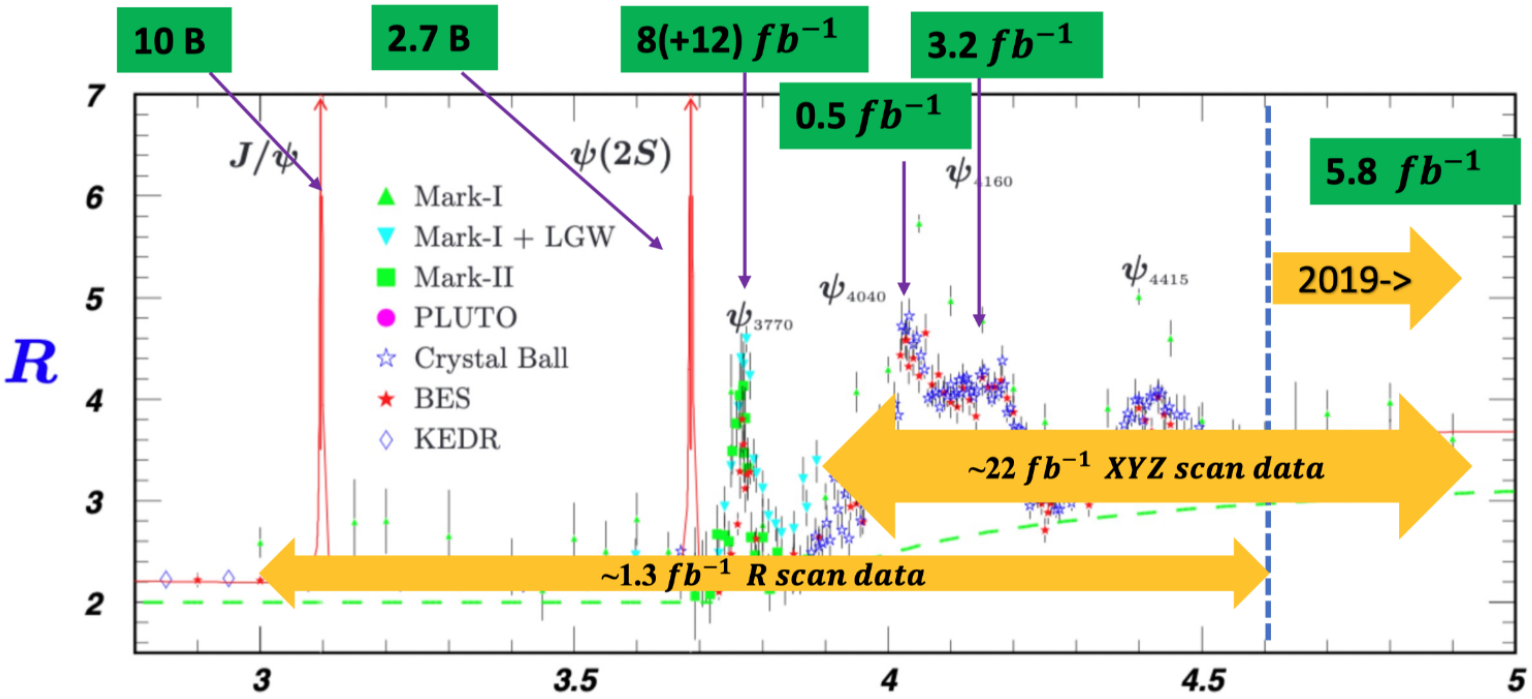
Time Of Flight
$\sigma_t < 68ps$(barrel)
$\sigma_t <$ 60ps (endcap)

Electromagnetic Calorimeter
σ_E/E<2.5%(5%) @1GeV
σ_{xy}~6mm (@1GeV)

Muon Counter
$\sigma_{\text{spatial}} < 2cm$

BESIII data sets

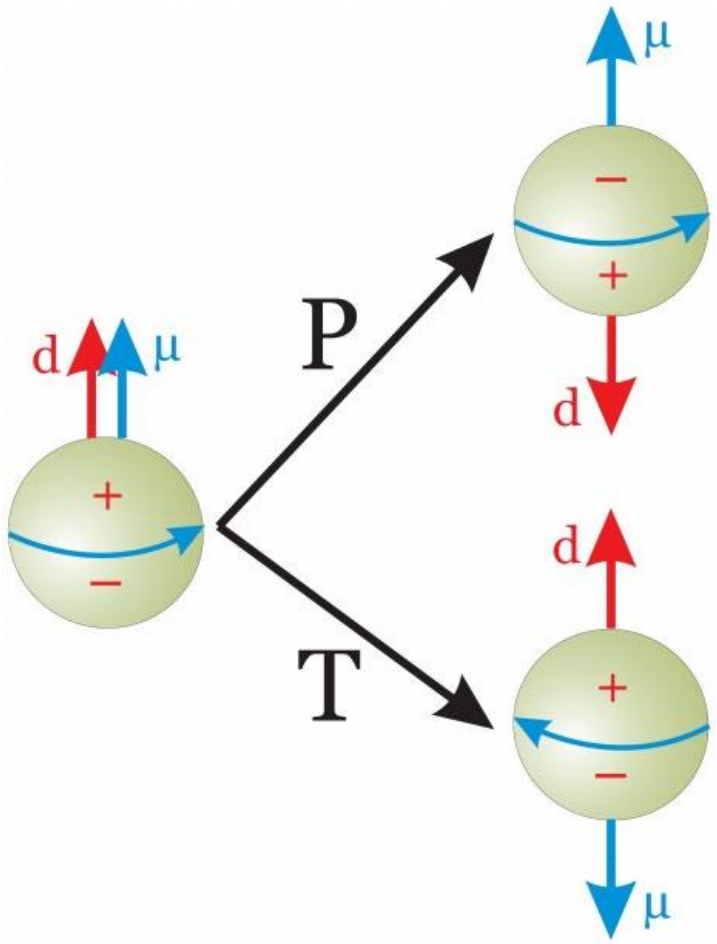
- World's largest data samples in tau-charm region
- 10 billion J/ψ, 2.7 billion $\psi(3686)$ and 20 fb^{-1} $\psi(3770)$ on threshold



- Charmonium and exotics
- Charm physics
- Light hadrons
- Tau physics, QCD
- New physics

Search for new physics at BESIII

- Symmetry violation
  - BNV/LNV processes
  - cLFV processes
  - Hyperon EDM...
- Very rare decays
  - Charmonium weak decays
  - Charm FCNC
  - ...
- Exotic particles
  - Invisible processes
  - Muon philic vector/scalars
  - **Dark matter portals**



Exotic particles search at BESIII

Dark matter portals

Axion-like particles(ALP) (this talk)

With ψ(2S) data set
- PLB 838 (2023) 137698

With J/ψ data set
- PRD 110 (2024) L031101

Invisible decays

$\Sigma^+ \rightarrow$proton+invisible (this talk)
- PLB 852 (2024) 138614

Λ baryon
- PRD 105 (2022) L071102

ω/ϕ mesons
- PRD 98 (2018) 032001

η/η' mesons
- PRD 87 (2013) 012009

Invisible muon philic scalar/vector meson
- PRD 109 (2024) L031102

Light CP-odd higgs boson

Visible decay
- PRD 105 (2022) 012008
- PRD 93 (2016) 052005
- PRD 85 (2012) 092012

Invisible decay
- PRD 101 (2020) 112005

Dark photon

With J/ψ data set
- PRD 99 (2019) 012013
- PRD 99 (2019) 012006
- PRD 102 (2020) 052005

ISR process
- PLB 774 (2017) 252 (visible)
- PLB 839 (2023) 137785 (invisible)

Massless dark photon
- PRD 106 (2022) 072008

Heavy Majorana neutrino

- PRD 99 (2019) 112002

Search for an Axion-like particle

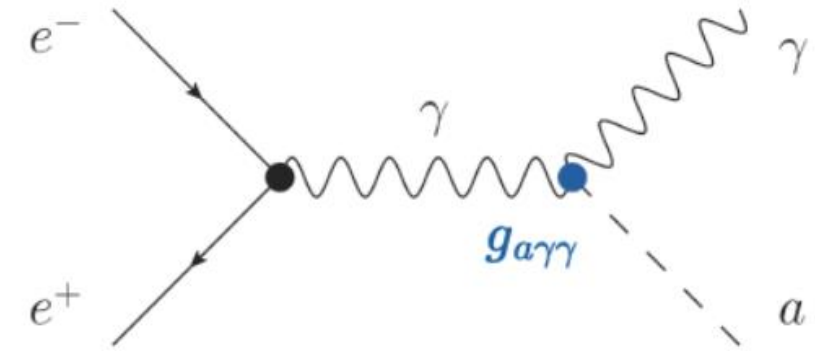
- An Axion-like particle (ALP)
  - is a pseudo-scalar particle
  - introduced by the spontaneous breaking of Peccei-Quinn symmetry to solve the strong CP problem of the QCD

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

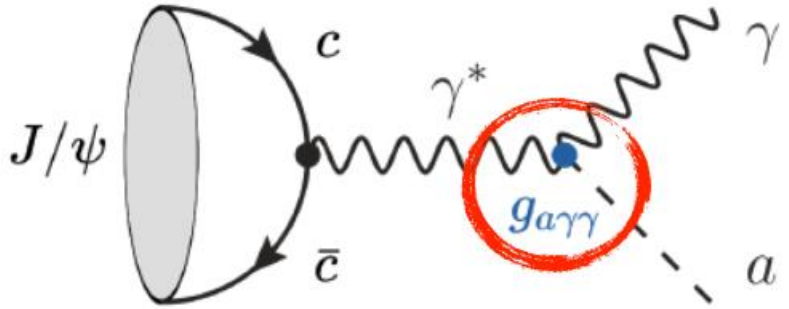
    Phys. Rev. Lett. 38, 1440 (1977); Phys. Rev. D 16, 1791 (1977)
  - predicted by many models beyond the SM and proposed to be a **cold DM candidate**
  - couples to a pair of photons with ALP-photon coupling $g_{a\gamma\gamma}$
  - experimental bounds on $g_{a\gamma\gamma}$ with m_a range of $\mathrm{MeV}/c^2 - \mathrm{GeV}/c^2$, **mainly constrained by e^+e^- colliders**

    Phys. Lett. B 753, 482 (2016)

ALP-Strahlung process



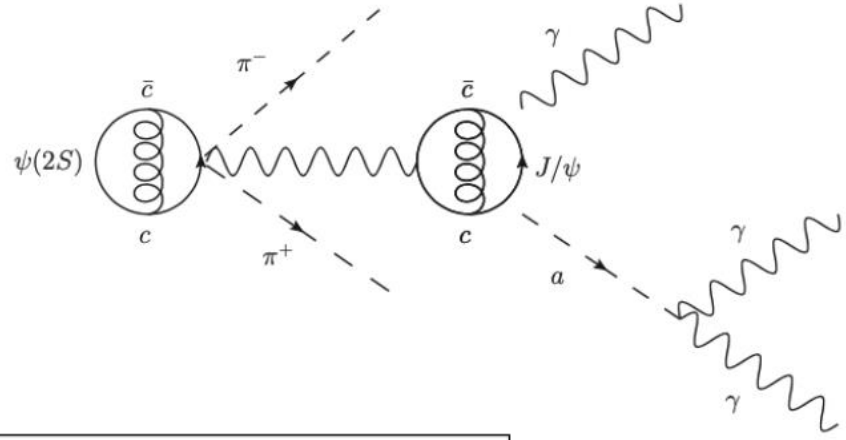
Radiative decay

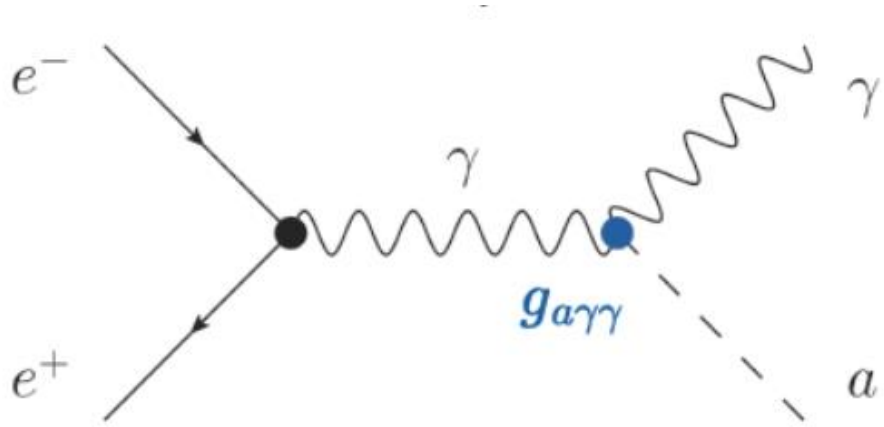


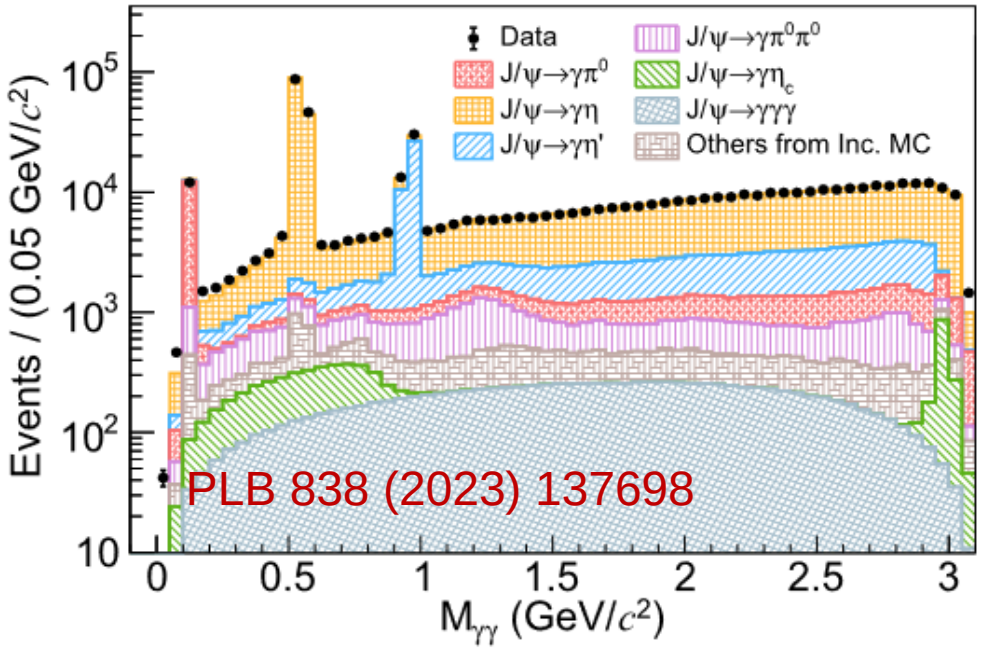
JHEP 06 (2019) 091

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

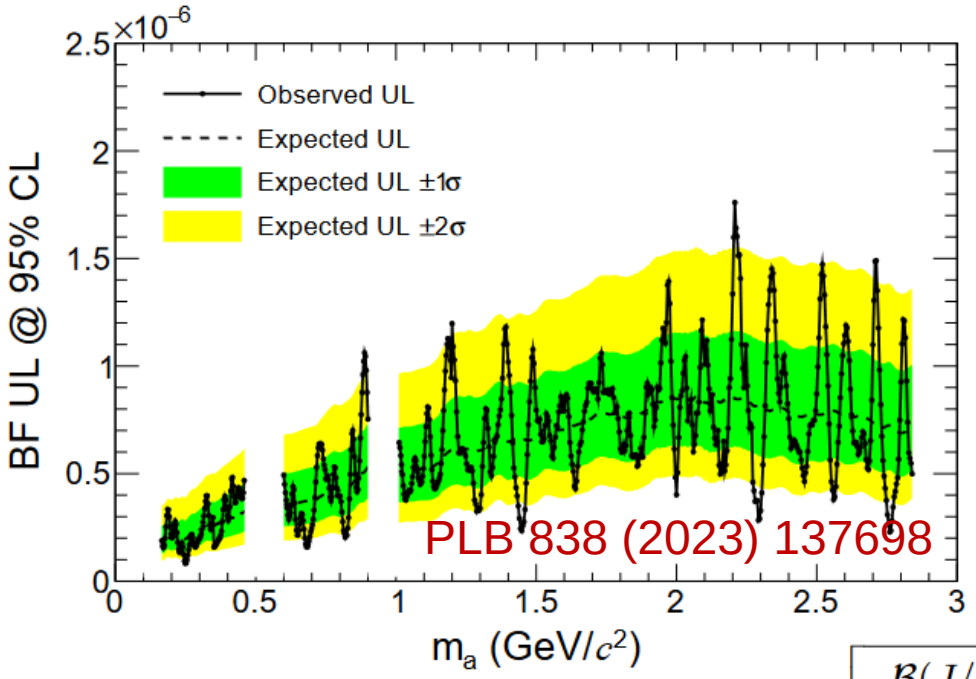
- Using 2.7 billion $\psi(2S)$ data, BESIII has set one of the best limits on $g_{a\gamma\gamma}$ via J/$\psi \to \gamma a(\to \gamma\gamma)$
- Can avoid the pollution of non-resonant production and QED background

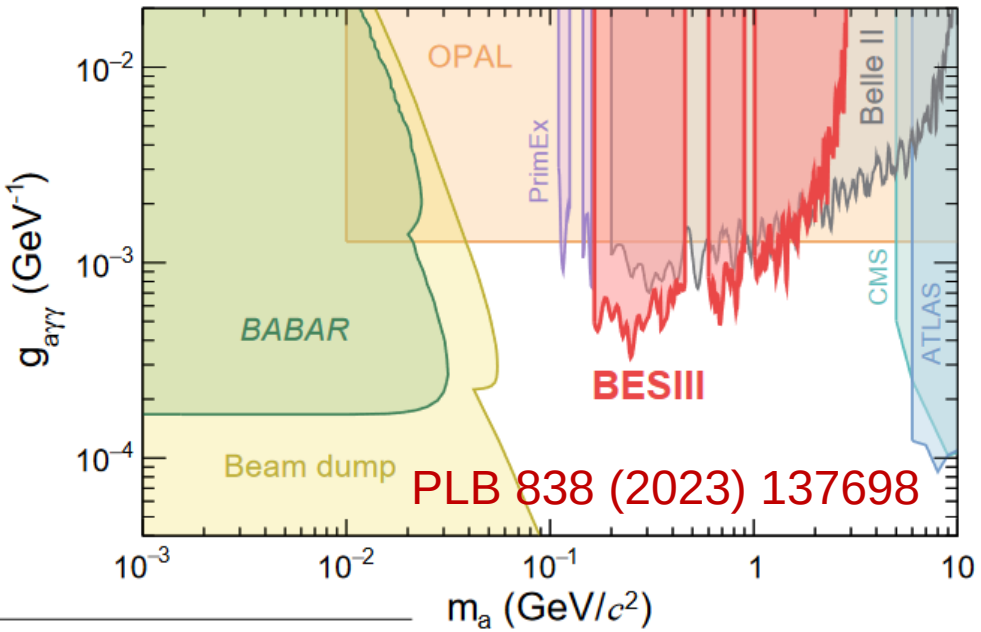






1.Search for ALP with $\psi(2S)$ data

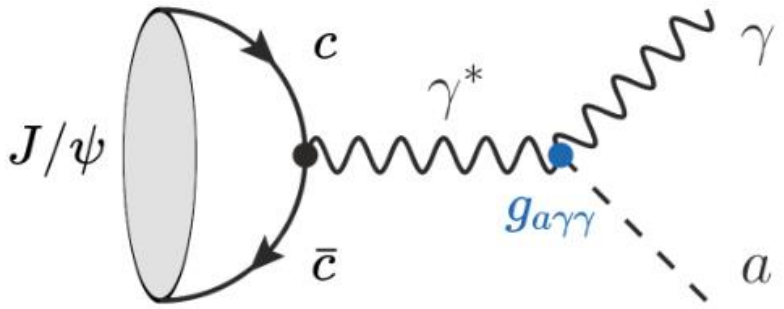




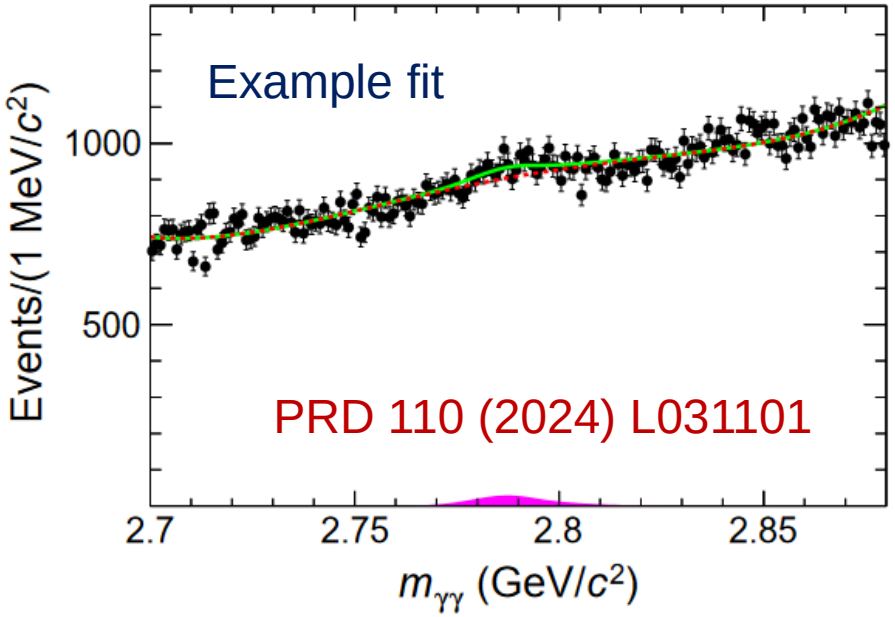
$$g_{a\gamma\gamma} = \sqrt{\frac{\mathcal{B}(J/\psi \to \gamma a)}{\mathcal{B}(J/\psi \to e^+e^-)}(1-\frac{m_a^2}{m_{J/\psi}^2})^{-3}\frac{32\pi\alpha_{\rm em}}{m_{J/\psi}^2}}$$

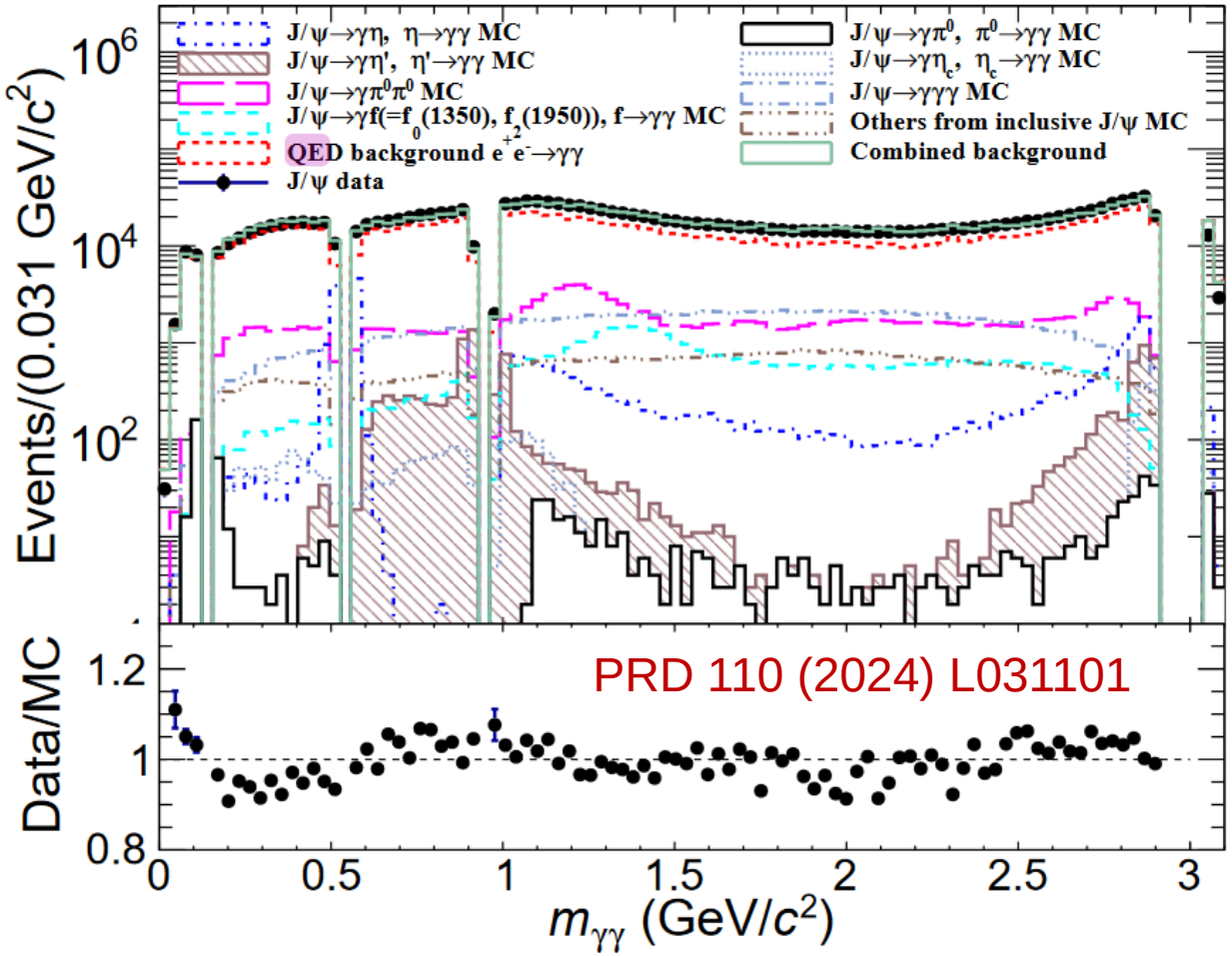
- Limits at $10^{-6} - 10^{-8}/\mathrm{GeV}$ level in the m_a range [0.165, 1.468] GeV/c^2
- To-date most stringent constraints on $g_{a\gamma\gamma}$ in the exploited range
- Can be further improved with 10 billion of BESIII J/ψ data, which can include both radiative $J/\psi \to \gamma a$ and ALP-Strahlung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

2.Search for ALP with J/ψ data



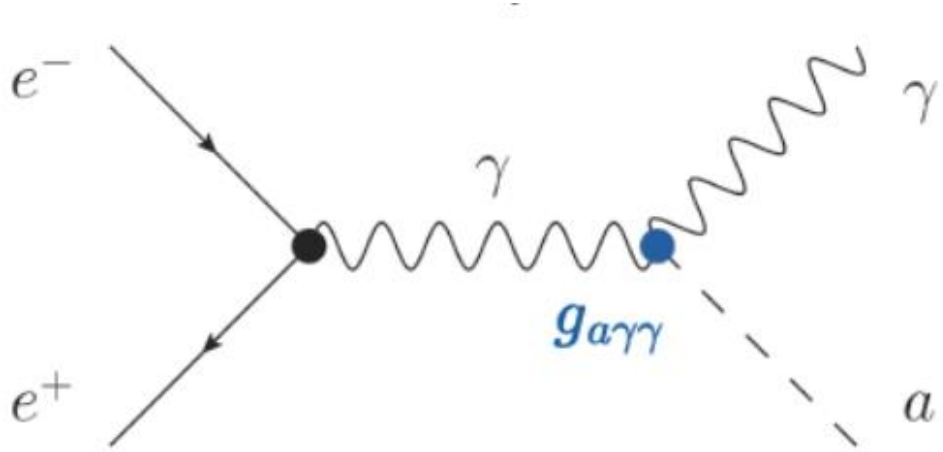
- Using 10 billion J/ψ data, BESIII has the best limits on $g_{a\gamma\gamma}$ via $J/\psi \to \gamma a(\to \gamma\gamma)$
- Huge but flat QED background (estimated with continuum data), found to have minimal effect on signal

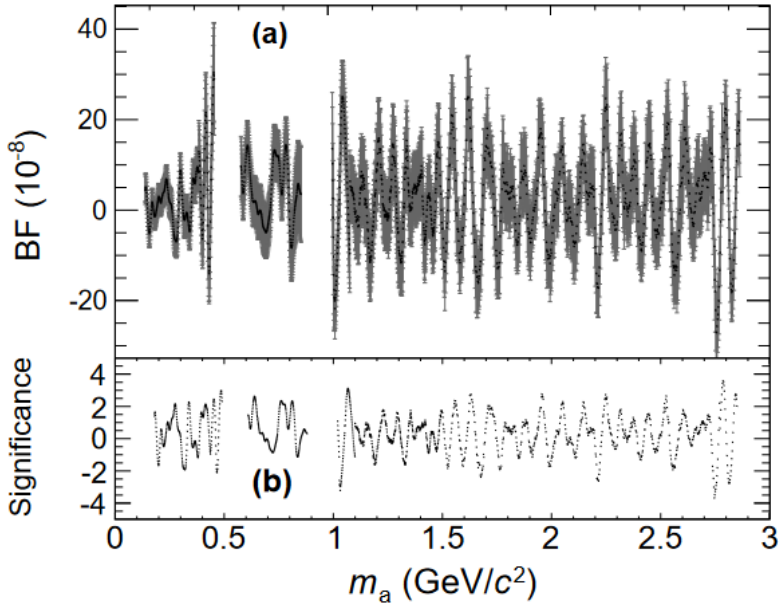




2.Search for ALP with J/ψ data

PRD 110 (2024) L031101





- Background of ALP-Strahlung process is estimated with and taken as a systematic uncertainty of 4.4%

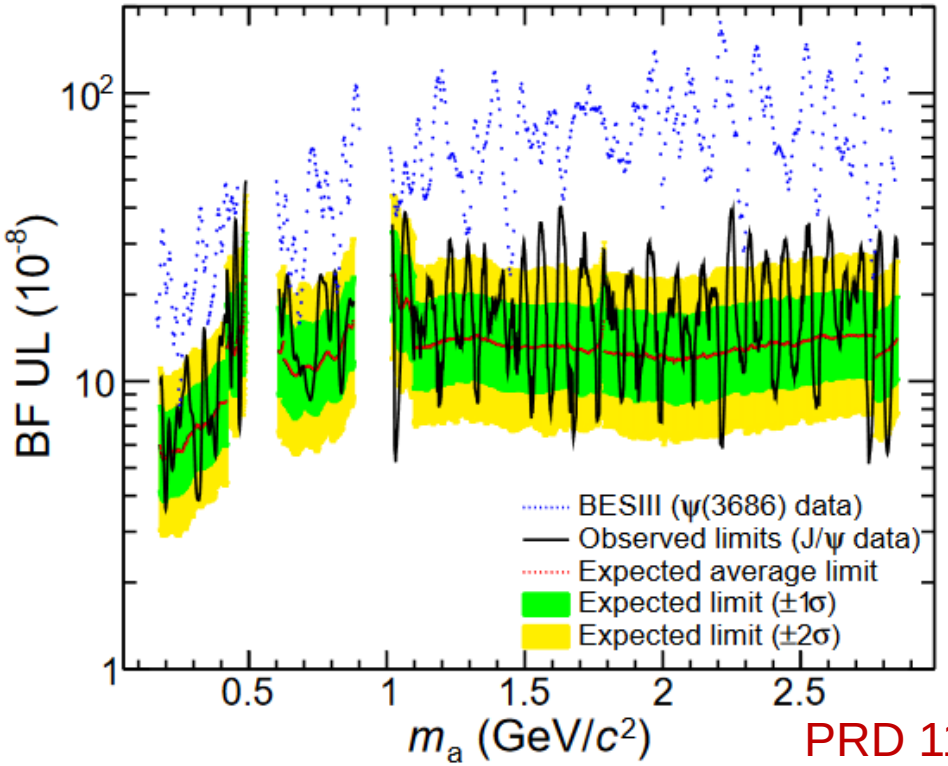
$$\sigma_a^{rad} = \frac{N_{J/\psi}}{L_{J/\psi}} . \mathcal{B}(J/\psi \to \gamma a)$$

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

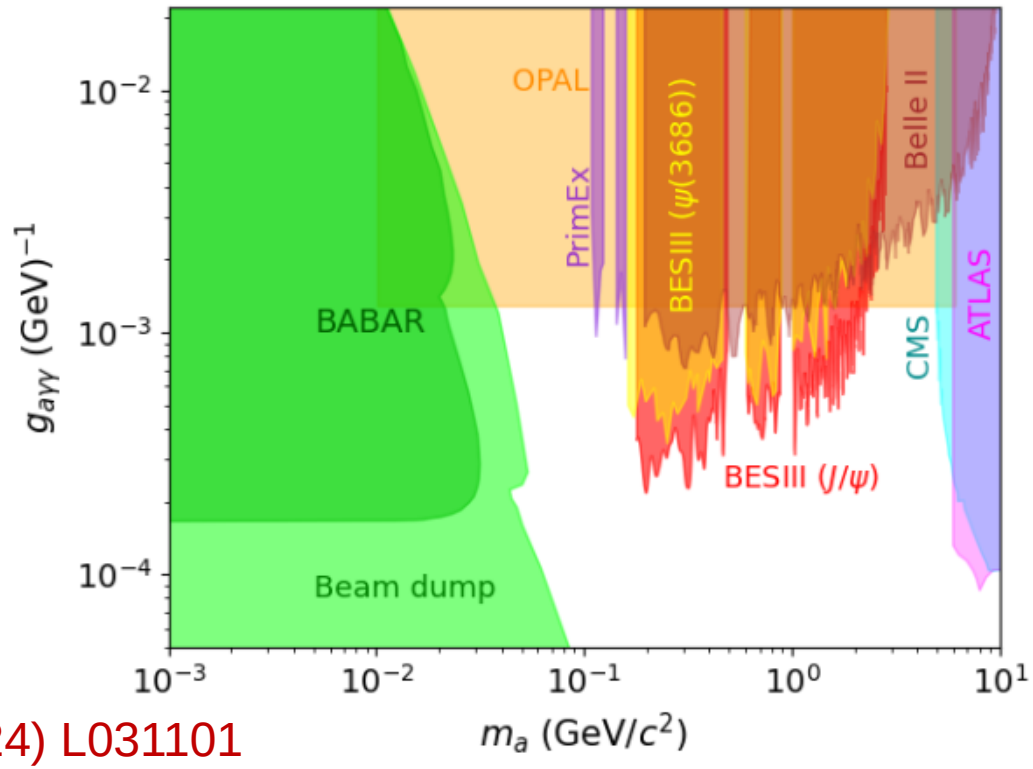
- At a given mass point $m_a = 2.786\ \mathrm{GeV}/c^2$, the global significance is 1.6sigma→no significant signal has been found

2.Search for ALP with J/ψ data

95% Confidence level ULs on product branching fraction



95% Confidence level ULs on ALP-photon coupling



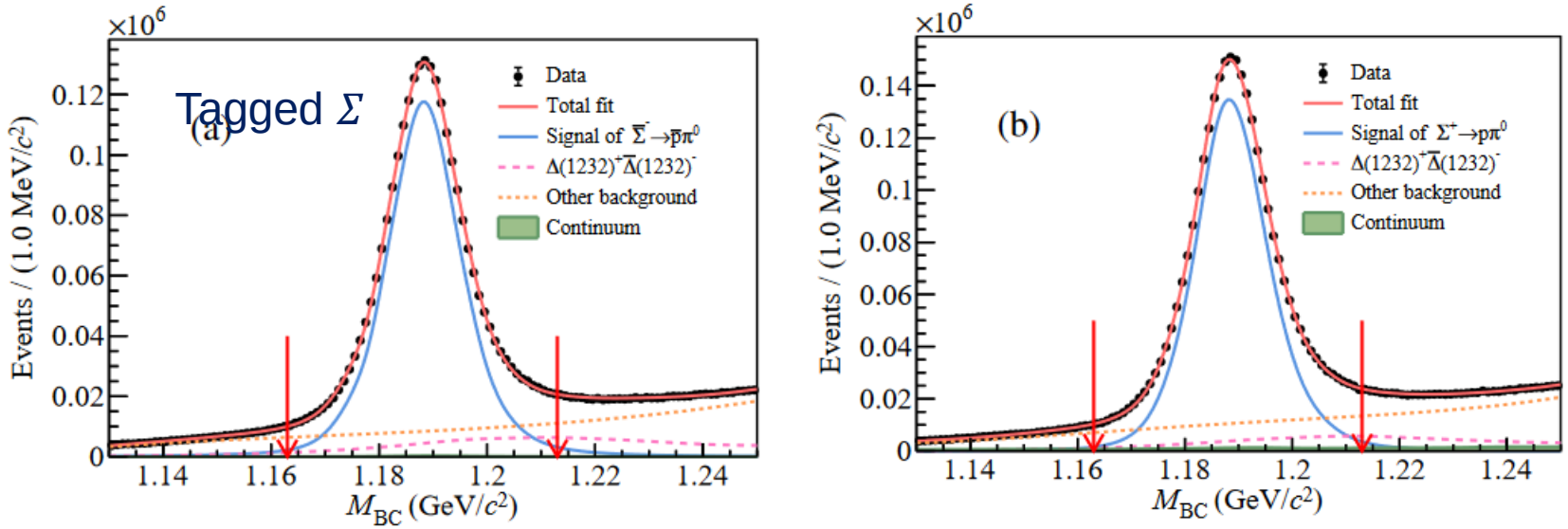
PRD 110 (2024) L031101

These results supersedes the previous BESIII (Belle-II) search by 3 (5) times

Phys. Lett. B 838, 137678 (2023); Phys. Rev. Lett. 125, 161806 (2020)

3.Search for $\Sigma^+ \rightarrow$proton+invisible

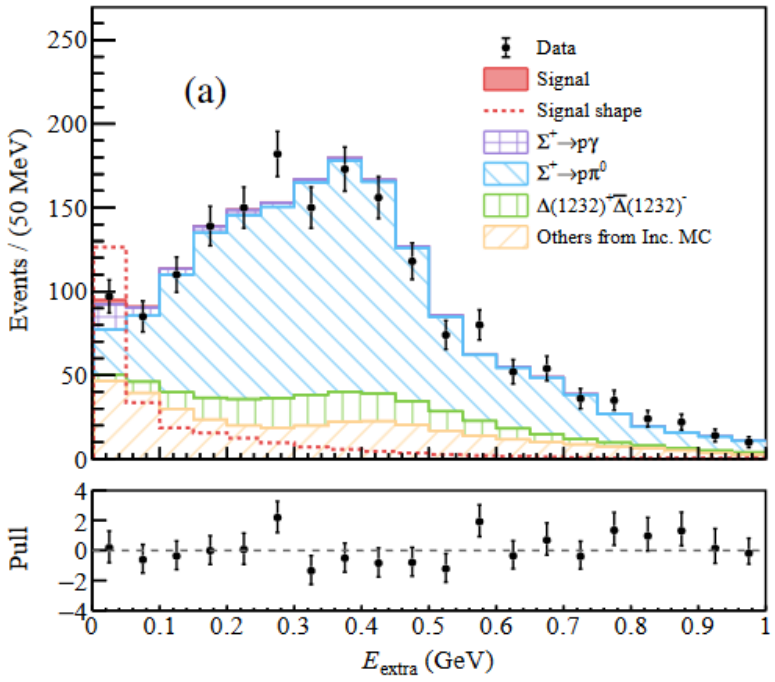
- Multiple new physics effects can enter the signal decay
  - FCNC process $s \rightarrow d\nu\nu$
  - massless dark photon
  - QCD axion...
- 10 billion J/ψ decays where 10 million pairs of $\Sigma^+\overline{\Sigma}^-$ are produced
- Enables studies of decays with “missing” particles by tagging one $\Sigma \rightarrow p\pi$

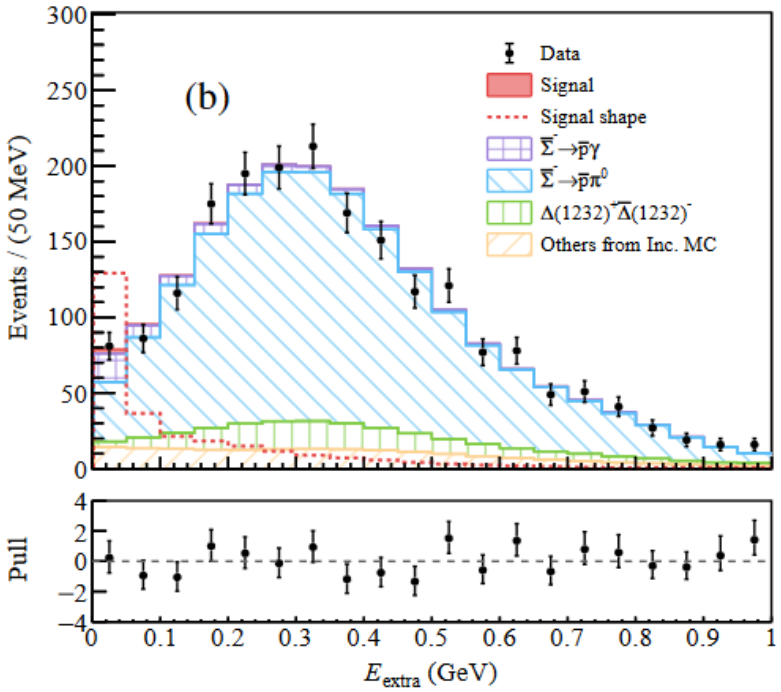


PLB 852 (2024) 138614

3.Search for $\Sigma^+ \rightarrow$proton+invisible

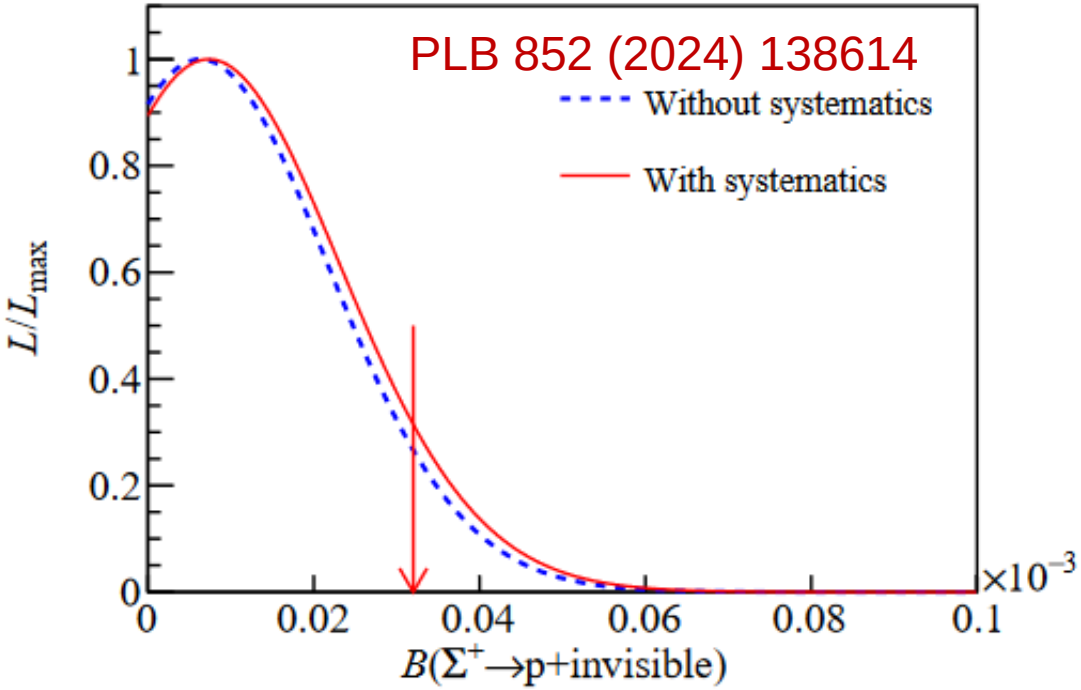
- Count the energy deposit in electro-magnetic calorimeter
- A unique method at electron-positron colliders

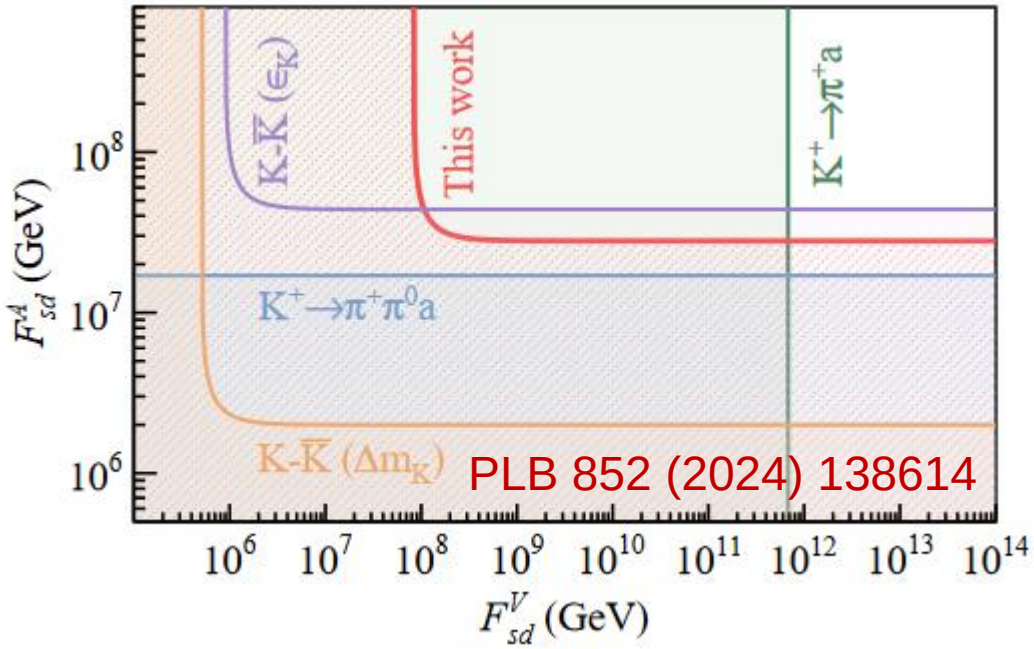




- Anti-protons are more likely to interact with detector materials, causing the energy deposit larger than proton
- Requires data-driven method to model the background

3.Search for $\Sigma^+ \rightarrow$proton+invisible





- First upper limit of the decay branching fraction is reported
- Complements other searches for the QCD axion with tiny mass (<1 eV) and long lifetime

  PLB 169 (1986) 73

Summary and outlook

- BESIII has a good potential to search for BSM physics with a “simple” collision environment, is especially ideal for decays with neutral and “missing” particles
- World’s largest data sets in charm-tau region provide opportunities to make significant contributions to such studies
- Great efforts have been made in the past years and the searches are still progressing

Thanks and stay tuned!