Search for Dark Photon and Axion-Like Particles at BESIII

11th International Workshop on Charm Physics (CHARM 2023) in Siegen

Saskia Plura

for the BESIII Collaboration

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Introduction

The Standard Model: incredibly successful but not complete!

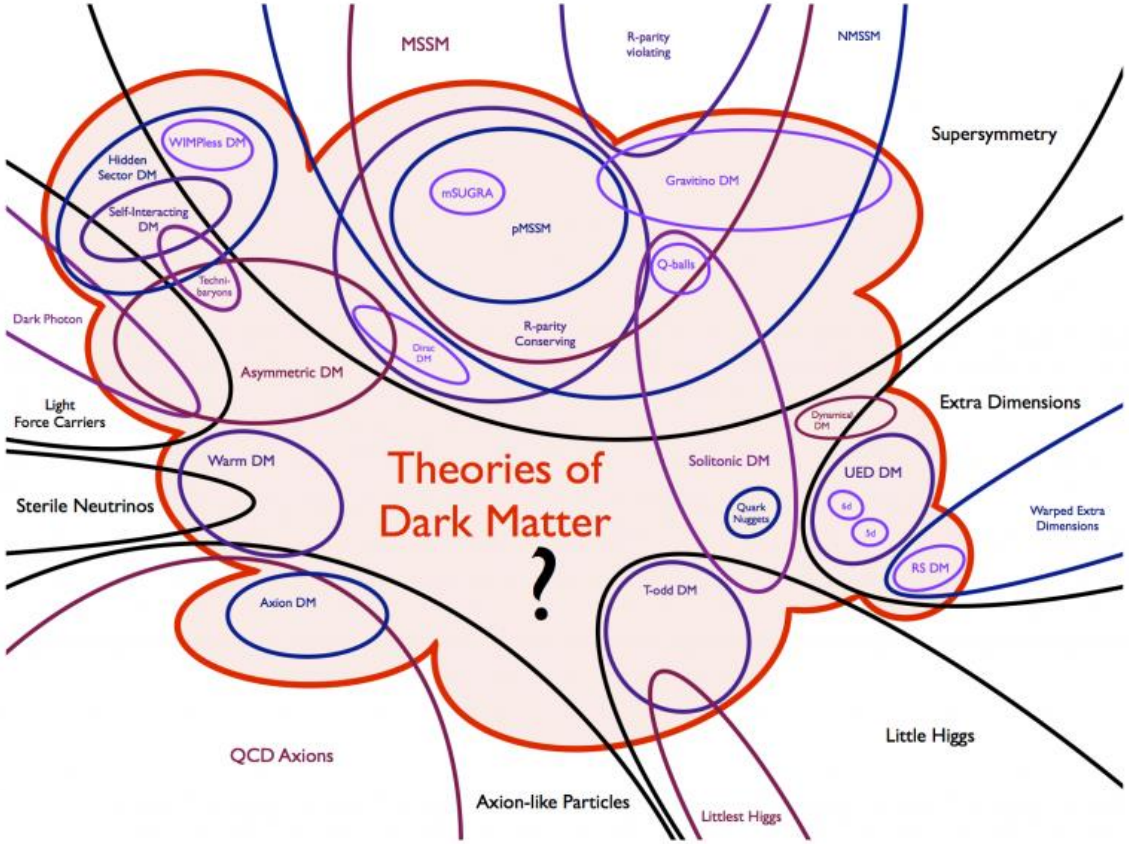
- Extensions needed to solve current problems such as missing description of Dark Matter

Portal interactions could connect SM with DM

- Vector portal: Dark Photon
- Axion portal: Axions and ALPs

Dark Sector searches need to be well-constrained

- e^+e^- colliders provide a clean environment

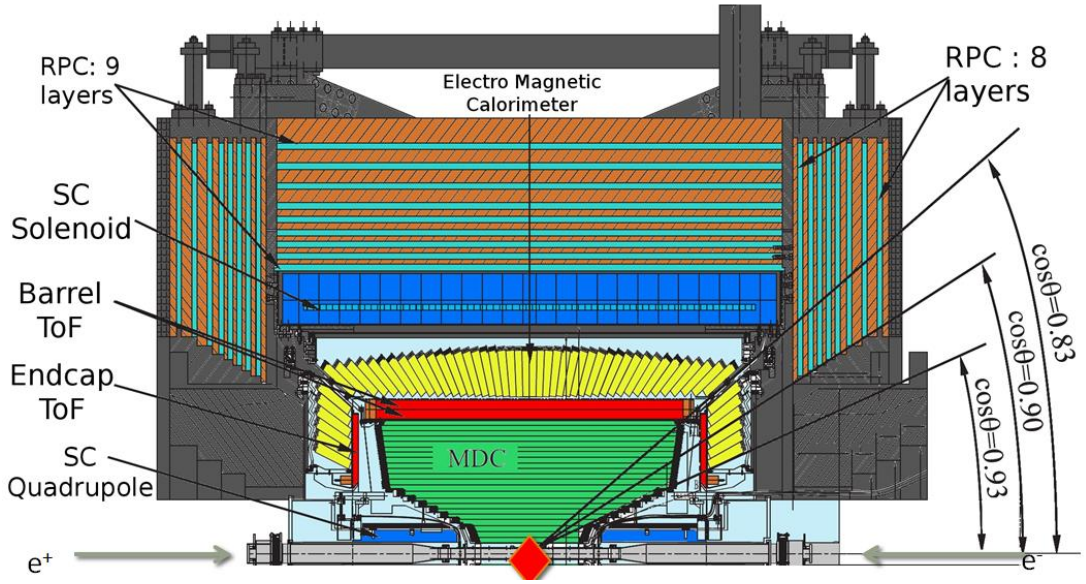


Tim Tait

The BESIII Experiment

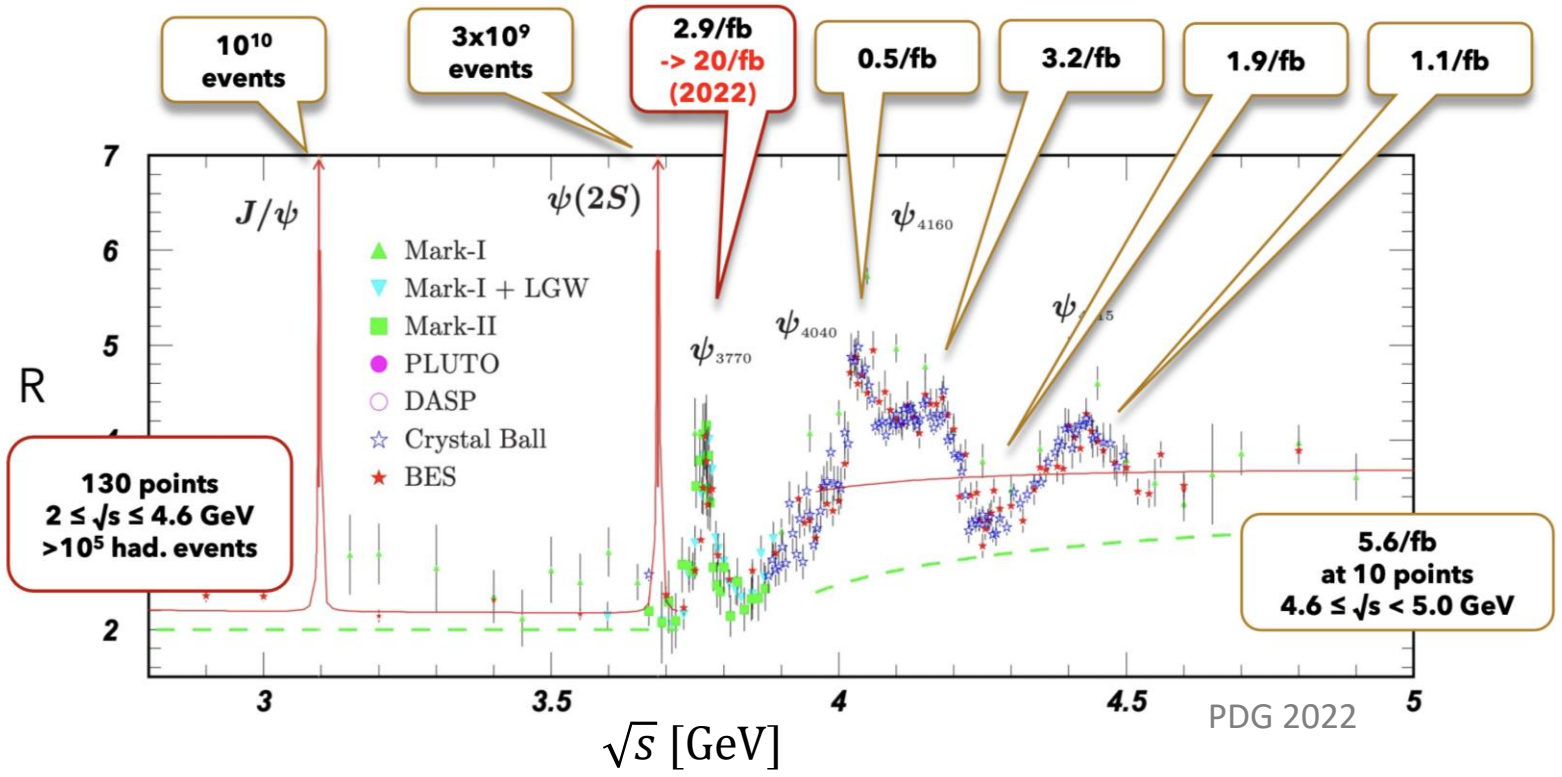
- Located at the BEPCII accelerator in Beijing, China
  - e^+e^- accelerator
  - CMS energy: $2 - 5\ \mathrm{GeV}$
  - τ-charm factory
  - Luminosity: $1 \times 10^{-33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $\psi(3770)$

- Consists of several subdetectors
  - Multilayer Drift Chamber (MDC)
  - Time-Of-Flight System (TOF)
  - Electro-Magnetic Calorimeter (EMC)
  - Solenoid magnet
  - Muon Chambers (MUC)



M. Ablikim et al., Nucl. Instrum. Meth. A 614, 345 (2010)

BESIII Data Sets



- Worlds largest τ-charm data set in e^+e^- collisions
- Detailed studies:
  - Charmonium spectroscopy
  - Charm decays
  - Light hadron dynamics
  - τ physics
  - R scan
  - New Physics

Recent Results

- Search for invisible Dark Photon decays in $e^+e^- \to \gamma\gamma'$ — PLB 839 (2023) 137785
- Search for massless Dark Photon decays in $e^+e^- \to \Lambda_c^+\overline{\Lambda_c^-}$ — PRD 106 (2022) 072008
- Search for $\Lambda \to$ invisible — PRD 105 (2022) L071101
- Search for ALPs in $J/\psi \to \gamma a$ — PLB 839 (2023) 137698
- Search for CP-odd light Higgs in $J/\psi \to \gamma A^0$ — PRD 105 (2022) 012008

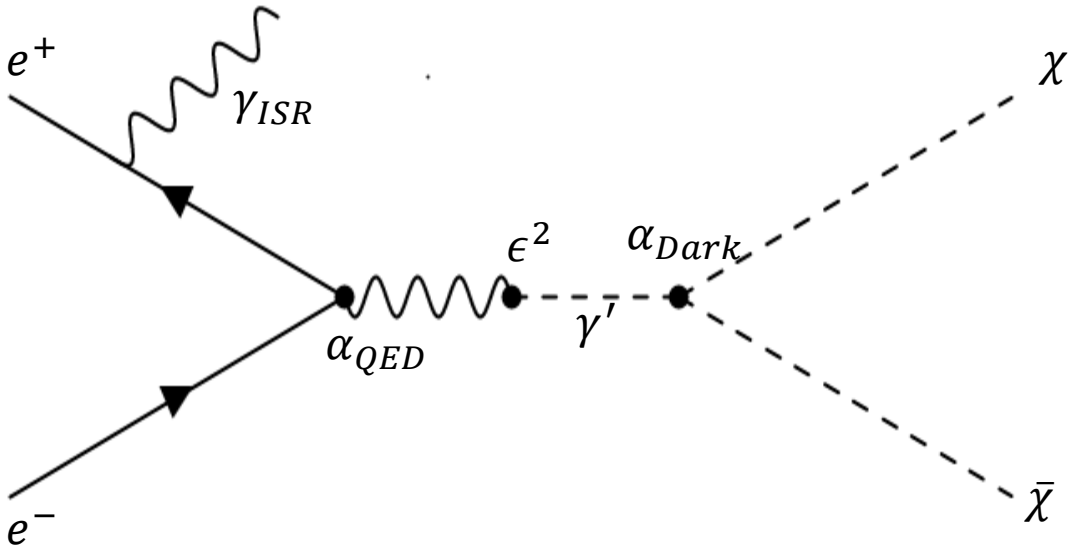
This talk

Search for Invisible Dark Photon Decays

PLB 839 (2023) 137785

Motivation: New $U(1)_D$ gauge boson γ' coupling weakly to SM photon through kinetic mixing
(PLB 166 (1986) 913778)

- Coupling scaled by mixing parameter ε



Search for the radiative annihilation process
$e^+e^- \to \gamma_{ISR}\gamma', \gamma' \to \chi\bar{\chi}$ invisible

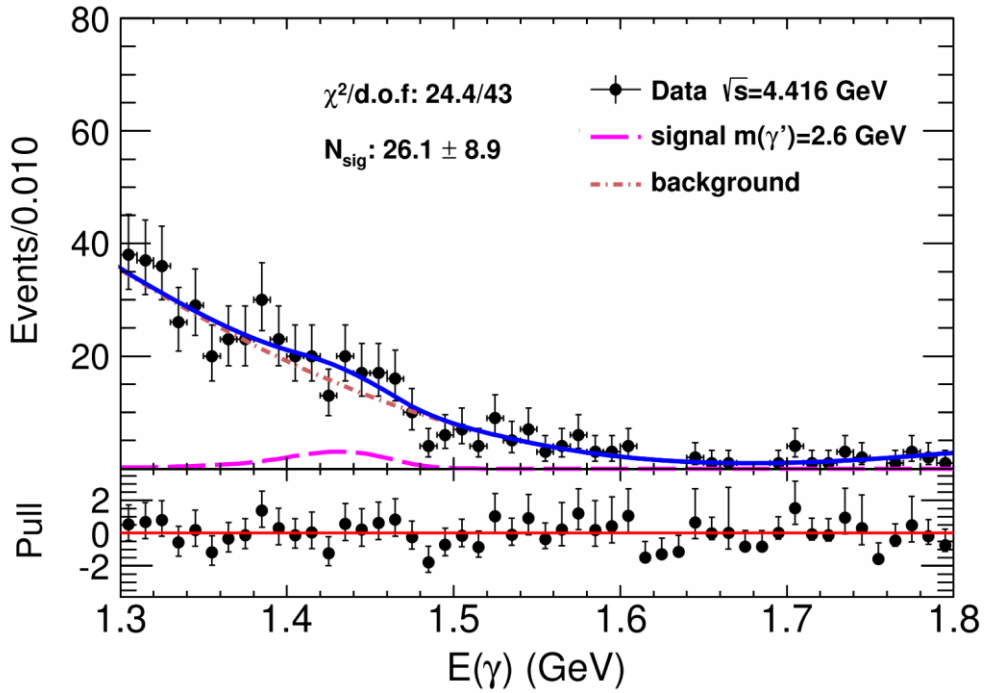
- Data set: 14.9 fb^{-1} e^+e^- annihilation events at c.m. energies from 4.13 – 4.60 GeV
- Search for single photon signals
- Most prominent background: Di-gamma processes

Search for Invisible Dark Photon Decays

PLB 839 (2023) 137785

Dark Photon search for $1.3 < E(\gamma) < 1.8$ GeV, corresponds to $1.5 < m_{\gamma'} < 2.9$ GeV

- Lower limit: reduced EMC trigger efficiency below $E(\gamma) < 1.3$ GeV & large background by di-gamma events
- Upper limit: saturation of EMC electronics
- $m_{\gamma'}$ region is scanned in 50 MeV steps
- Simultaneous maximum likelihood fit to the photon energy spectra performed for all data sets



Search for Invisible Dark Photon Decays

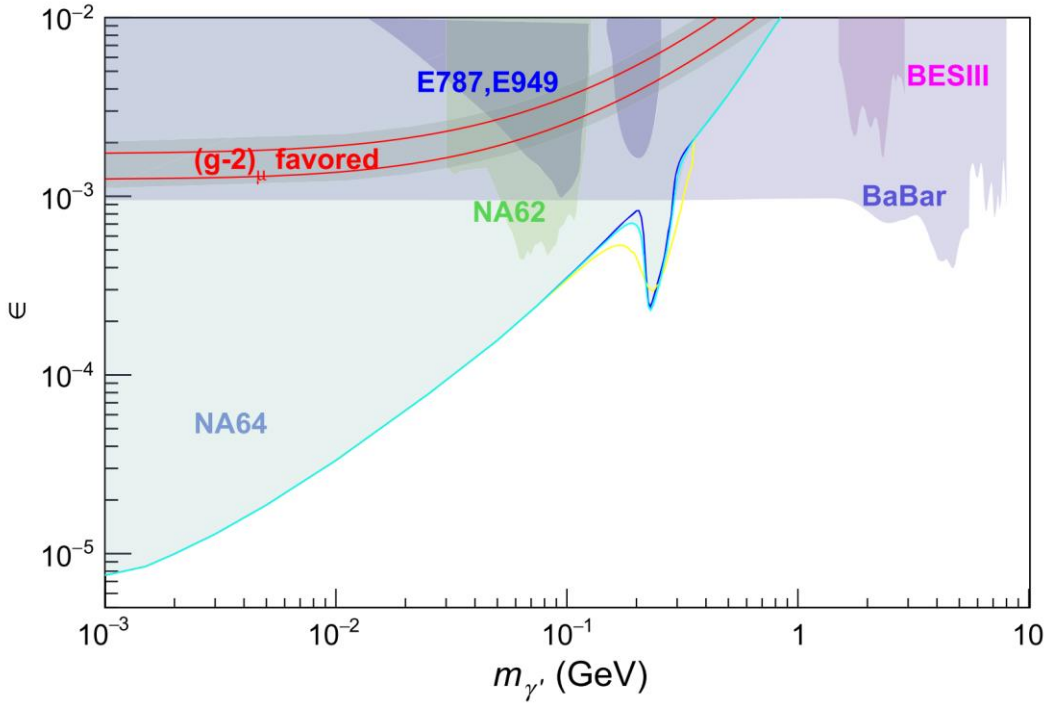
PLB 839 (2023) 137785

No signal found, maximum global significance is 2.2σ

Upper limit at $\epsilon_{90\%\ C.L.} = (1.6\ -5.7) \times 10^{-3}$ for $1.5 < m_{\gamma'} < 2.9$ GeV

- Consistent with BaBar (PRL 119 (2017) 131804)

More competitive result with upcoming 20 fb^{-1} of $\psi(3770)$ data!

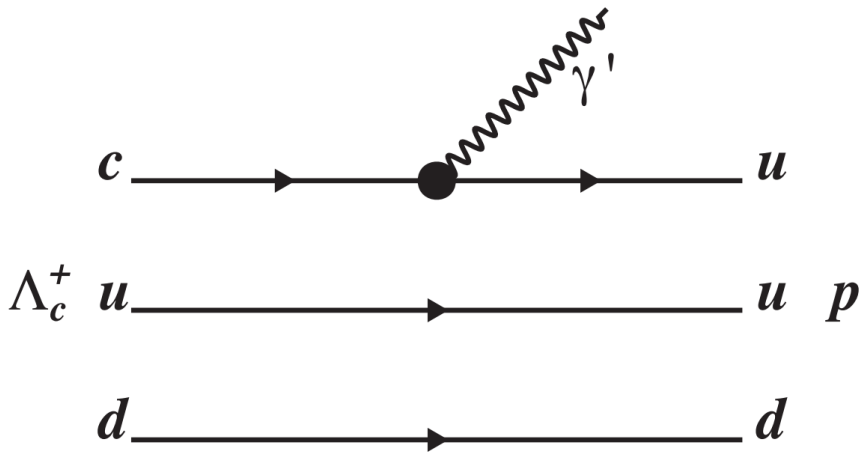


Search for Massless Dark Photon Decays

PRD 106 (2022) 072008

Motivation: FCNC are suppressed by SM, significant observation would point at New Physics

- FCNC in charm sector in SM: BR $< O(10^{-9})$
- MSSM and two-Higgs-doublet model predict 2-3 orders of magnitude larger branching ratios (PRD 15 (1977) 1958)
- Study FCNC effects with c and u quarks with $\Lambda_c^+ \to p\gamma'$

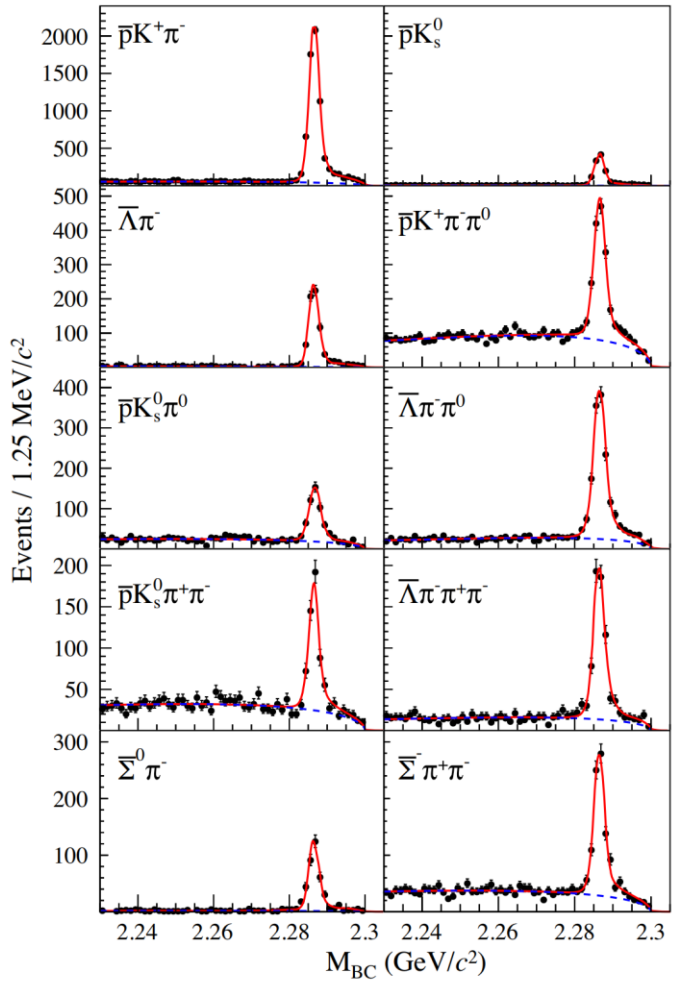


Search for Massless Dark Photon Decays

PRD 106 (2022) 072008

Search for massless Dark Photon in $e^+e^- \to \Lambda_c^+\overline{\Lambda_c^-}, \Lambda_c^+ \to p\gamma'$

- Study FCNC effects with c and u quarks
- Data set: 4.5 fb^{-1} e^+e^- annihilation events at c.m. energies from 4.6 – 4.7 GeV
- Double Tag Method: Single tag $\overline{\Lambda_c^-}$ reconstructed with 10 hadronic decay modes, yield: 105000 $\overline{\Lambda_c^-}$ events



Search for Massless Dark Photon Decays

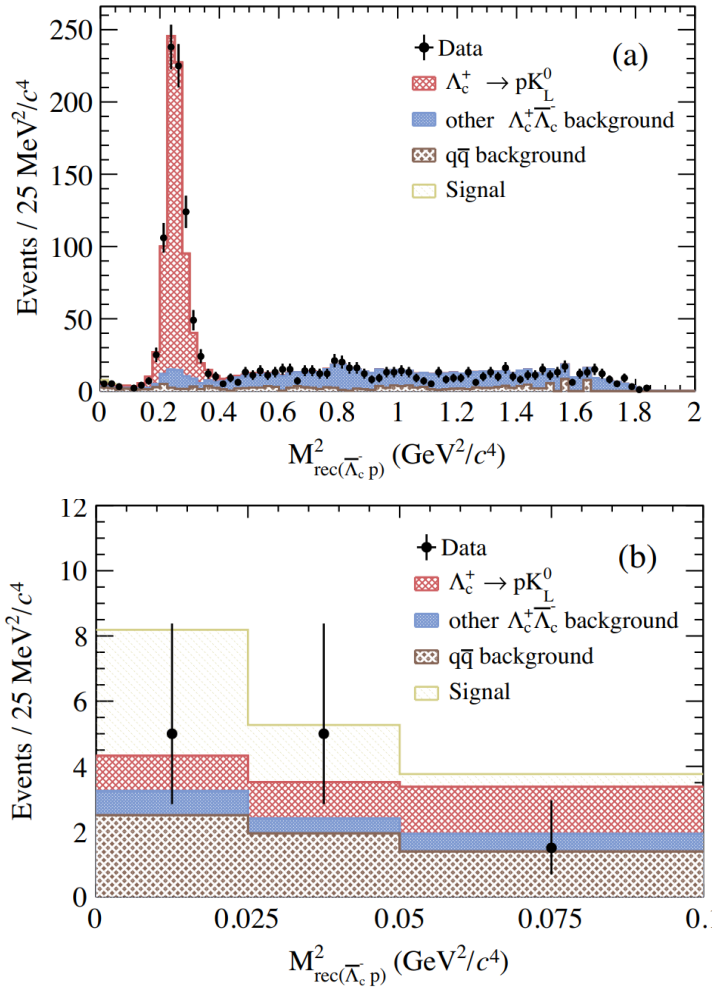
PRD 106 (2022) 072008

Search for signal on the square of the recoil mass spectrum $M^2_{rec(\overline{\Lambda_c^-}p)}$

- Backgrounds: continuum hadron production $e^+e^- \to q\bar{q}$ and from $e^+e^- \to \Lambda_c^+\overline{\Lambda_c^-}$ events
- No obvious signal observed

Upper limit on $B(\Lambda_c^+ \to p\gamma') < 8.0 \times 10^{-5}$ at 90% C.L.

- Theory prediction: $B(\Lambda_c^+ \to p\gamma') = 1.6 \times 10^{-5} \ -9.1 \times 10^{-6}$
  (PRD 102 (2020) 115029)



Search for Invisible Λ Decays

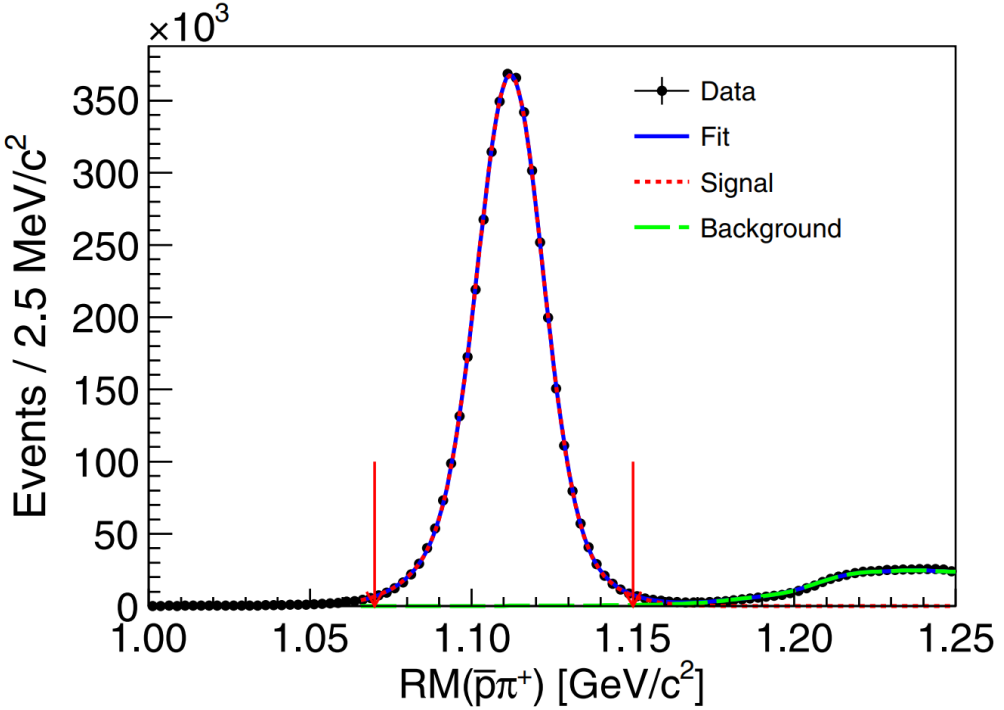
PRD 105 (2022) L071101

Motivation: Discrepancy in neutron lifetime measurements could be explained through baryon matter with invisible final state (PRD 99 (2019) 035031)

- Implications for baryon number violation

Search for $J/\psi \to \Lambda\bar{\Lambda}, \bar{\Lambda} \to \bar{p}\pi^+, \Lambda \to$ invisible

- Data set: 10 B J/ψ events
- Branching fraction $B(\Lambda \to \text{invisible}) = \frac{N_{sig}}{N_{tag} \cdot (\epsilon_{sig}/\epsilon_{tag})}$
- $\bar{\Lambda}$ tagged by $\bar{\Lambda} \to \bar{p}\pi^+$, yield: 4.1 M $\bar{\Lambda}$ events
- Dominant background: $\Lambda = n\pi^0$



Search for Invisible Λ Decays

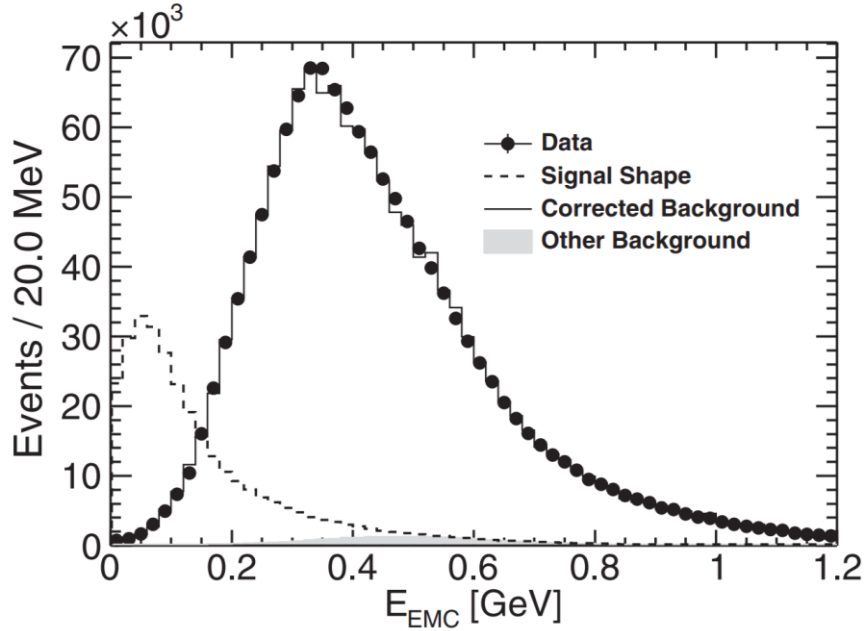
PRD 105 (2022) L071101

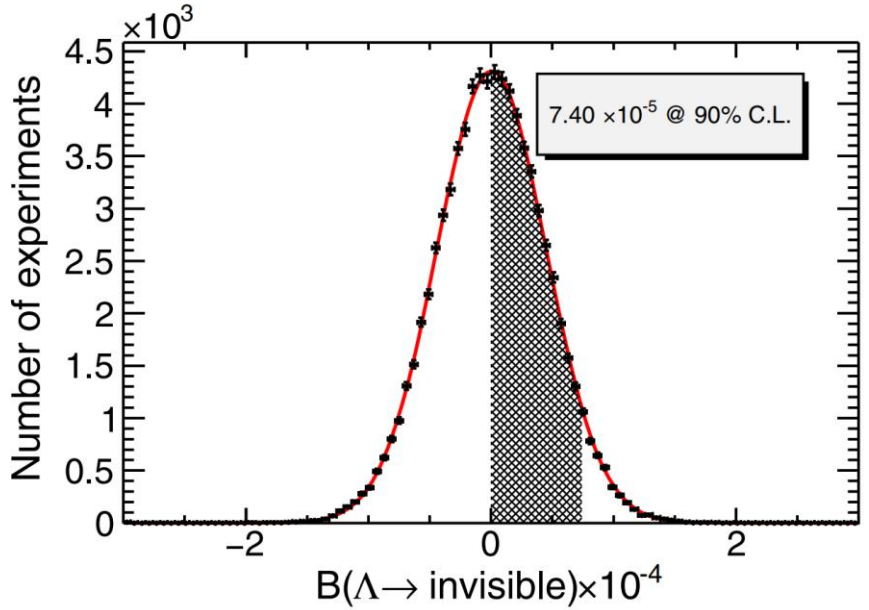
Fit on deposited energy in the EMC

- Invisible decay signal expected to peak close to 0
- No obvious signal observed

Upper limit on $B(\Lambda \to invisible) < 7.4 \times 10^{-5}$ at 90% C.L.

First search for $\Lambda \to$ invisible!





Search for Axion-Like Particles

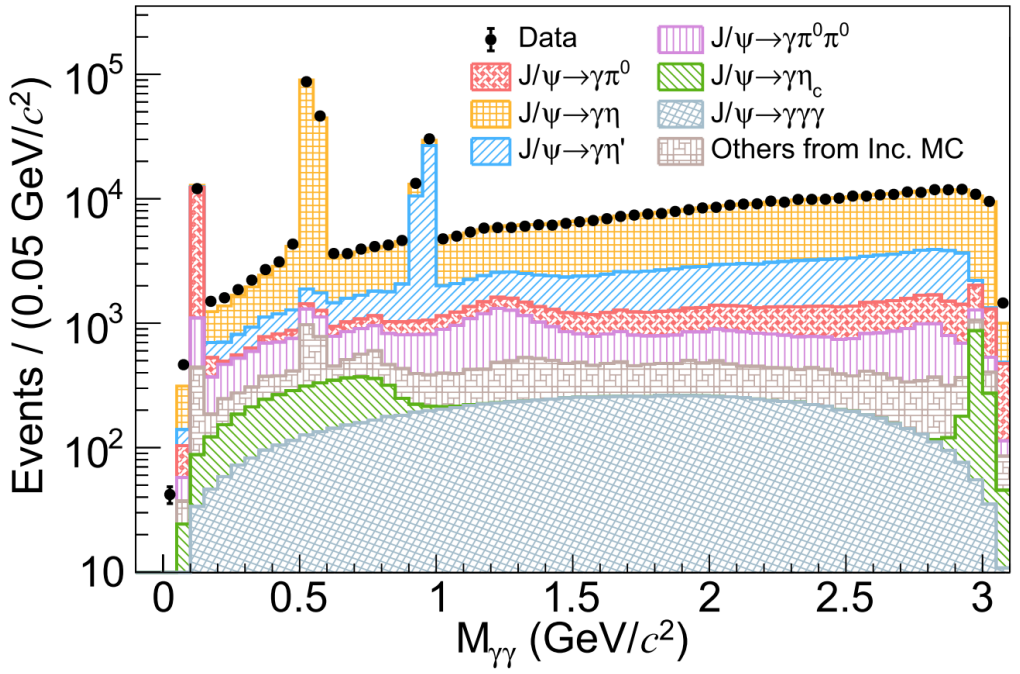
PLB 839 (2023) 137698

Motivation: Pseudo-Goldstone bosons arising from spontaneously broken global symmetry, could solve the strong CP problem (PRL 115 (2015) 221801)

- ALPs predominantly decay to two photons
- Here: assume 100% decay to two photons

Search for $\psi(3686) \to \pi^+\pi^- J/\psi, J/\psi \to \gamma a, a \to \gamma\gamma$

- Data set: 2.7 B $\psi(3686)$ decays
- Utilise $\psi(3686)$ decays to avoid pollution from non-resonant production and QED background
- Exclude intervals around π^0, η, η' peaks
- Three $\gamma\gamma$ combinations per event



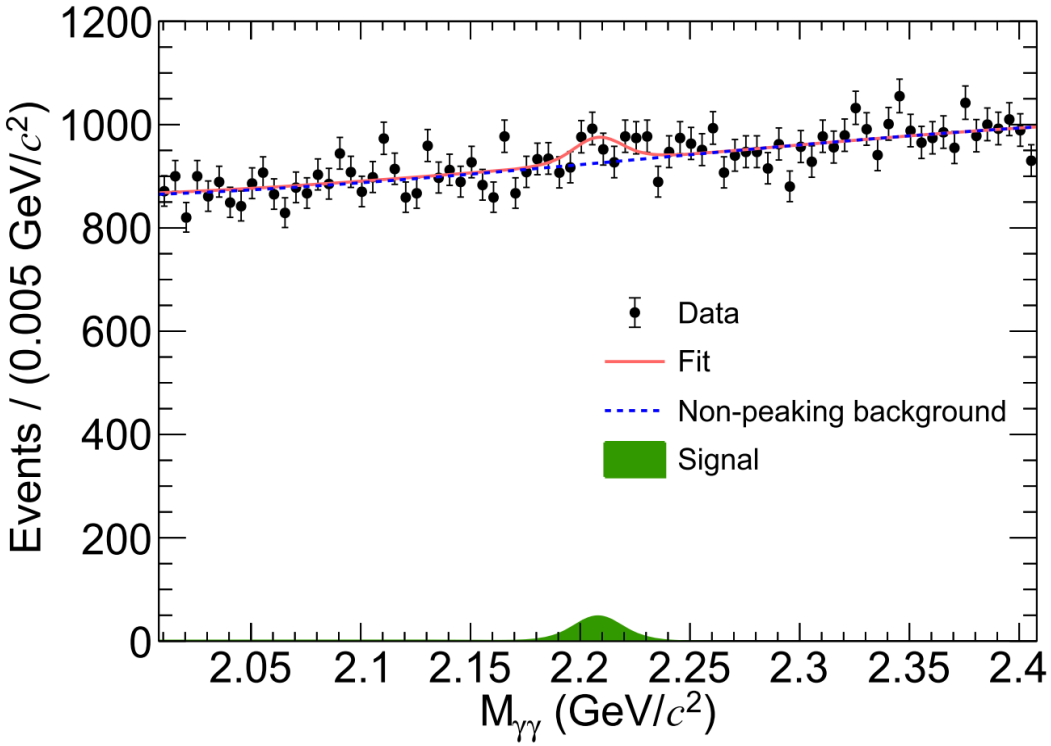
Search for Axion-Like Particles

Series of unbinned maximum-likelihood fits perfomed on $M_{\gamma\gamma}$ with 674 mass hypotheses

- Mass range: $0.165 \leq m_a \leq 2.84$ GeV
- Fit intervals are mass-dependent
- Local significance less than 2.6 σ for all mass points

No significant signal observed!

PLB 839 (2023) 137698



Search for Axion-Like Particles

Upper limit on $B(J/\psi \to \gamma a) = 8.3 \times 10^{-8} - 1.8 \times 10^{-6}$ at 95% C.L. for $0.165 \leq m_a \leq 2.84$ GeV

Constraints on $g_{a\gamma\gamma}$ are the most stringent to date for $0.165 \leq m_a \leq 1.468$ GeV

- Exclude the parameter region of coupling $g_{a\gamma\gamma} > 3 \times 10^{-4}\ \mathrm{GeV}^{-1}$ for $m_a \approx 0.25$ GeV, 3x better than Belle II result

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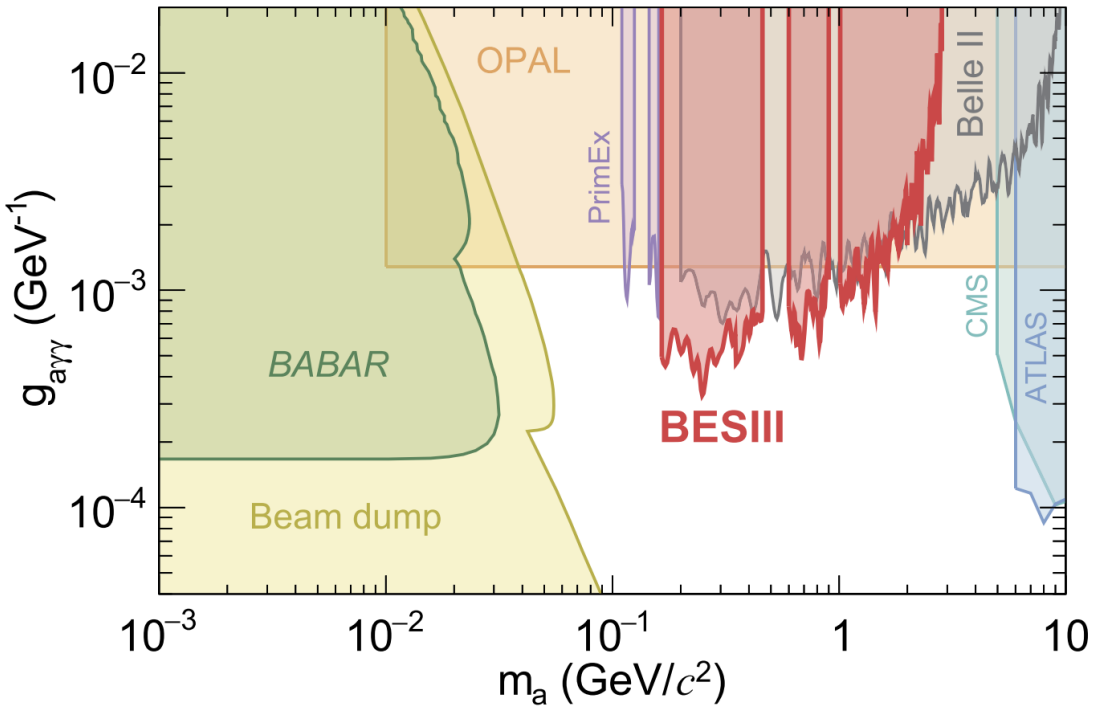

Summary and Outlook

Thank you for your attention!

BESIII is performing many Dark Sector and ALP searches

- e^+e^- colliders provide clean environments
- Dark Sector searches faciliated by world's largest data sets of J/ψ and $\psi(2S)$ on resonances
- Searches for both visible & invisible decays ongoing:
  - $\boldsymbol{e^+e^- \to \gamma\gamma'}$: first measurement at BESIII
  - $\boldsymbol{\Lambda \to invisible}$: first search with baryons
  - $\boldsymbol{\Lambda_c^+ \to p\gamma'}$: first search for FCNC in the charmed sector
  - $\boldsymbol{J/\psi \to \gamma a, a \to \gamma\gamma}$: new most stringent limit on $g_{a\gamma\gamma}$
  - $\boldsymbol{J/\psi \to \gamma A^0}$: 6-7 times improvement over previous BESIII result

New large data sets will become available soon – stay tuned for new results!

Backup

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JG|U

Search for CP-Odd Light Higgs

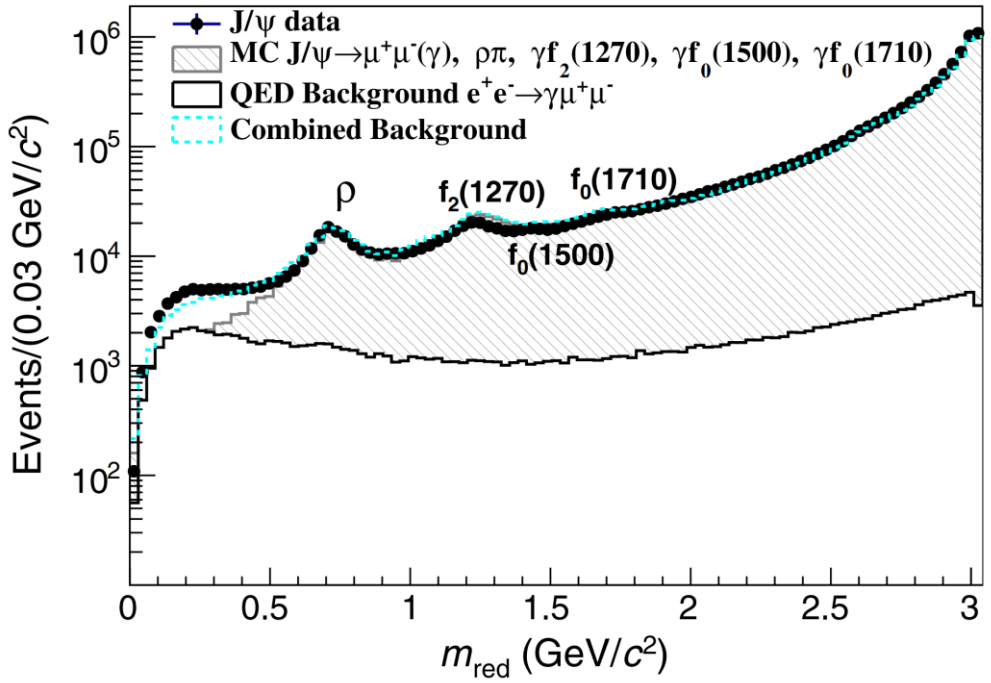
PRD 105 (2022) 012008

Motivation: Next-to-minimal supersymmetric Standard Model – extension of Higgs sector (PRL 39 (1977) 1304)

- 3 CP-even, 2 CP-odd and 2 charged Higgs bosons
- Lightest Higgs A^0 lighter than $2m_{charm}$

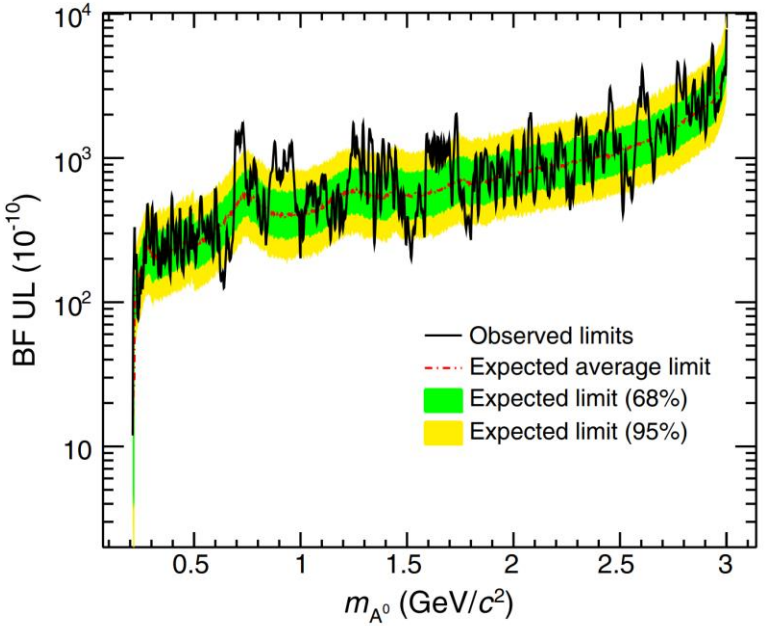
Search for CP-odd light Higgs via $J/\psi \to \gamma A^0,\ A^0 \to \mu^+\mu^-$

- Data set: 9 B J/ψ events
- BESIII sensitive on effective Yukawa coupling $g_c = \cos(\theta_A)/\tan(\beta)$
- A^0 search for $0.212 \leq m_{A^0} \leq 3.0$ GeV through unbinned extended maximum likelihood fits to the reduced mass



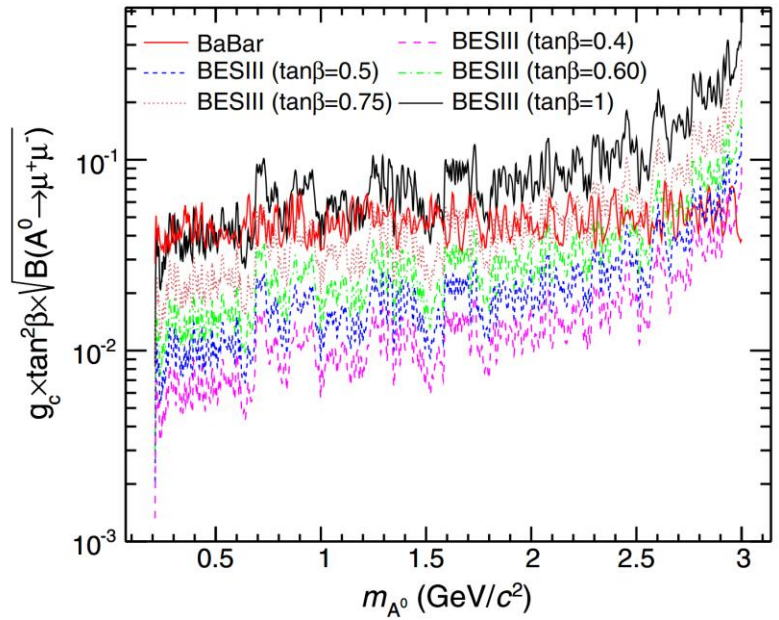
Search for CP-Odd Light Higgs

PRD 105 (2022) 012008



No signal found, maximum global significance at 1σ

Upper limit on branching fraction at $(1.2 - 778.0) \times 10^{-9}$ for $0.212 \leq m_{A^0} < 3.0$ GeV



Limits on the effective Yukawa coupling

- 6-7 times improvement to previous BESIII measurement
- Better than BaBar in the low-mass region for $\tan(\beta) = 1$