Dark matter searches at BESIII

Vindhyawasini Prasad

(On behalf of the BESIII Collaboration)

Email: vindymishra@gmail.com

Instituto de Alta Investigacion
Universidad de Tarapaca
Casilla 7D, Arica, Chile

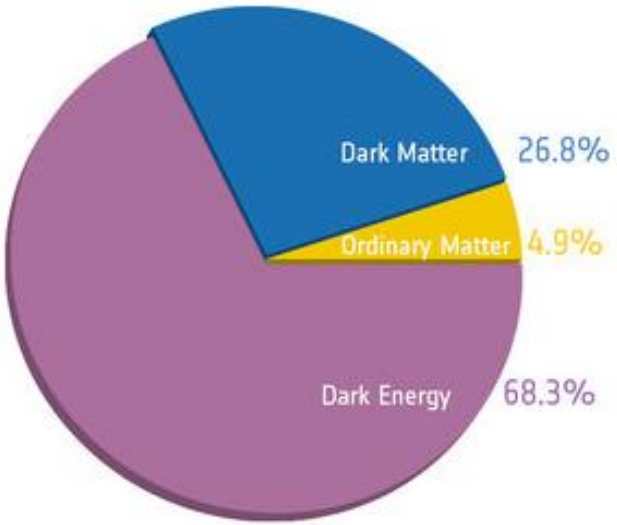
Outline

- ✓ Motivation
- ✓ BESIII experiment and its data-sets
- ✓ Status of Dark matter searches at BESIII
  - Search for an Axion-like particle — BESIII Preliminary
  - Light Higgs boson A^0 search in radiative J/ψ decay — PRD **105**, 012008 (2022)
  - Invisible decays of dark photon — PLB **839**, 137785 (2023)
  - Visible decays of dark photon — PLB **774**, 252 (2017)
  - Invisible decays of Λ baryon — Phys. Rev. D **105**, L071101 (2022)
  - Search for a massless dark photon in $\Lambda_c^+ \to p\gamma'$ — PRD **106**, 072008 (2022)
- ✓ Summary

Motivation

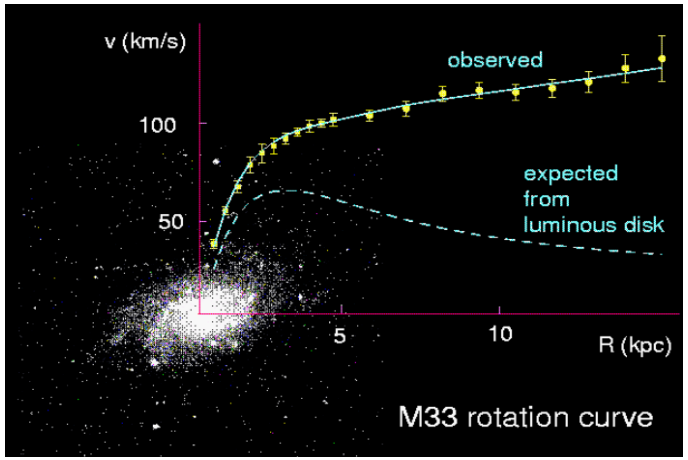
❖ **Standard Model (SM) is incredibly successful but not complete!**

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

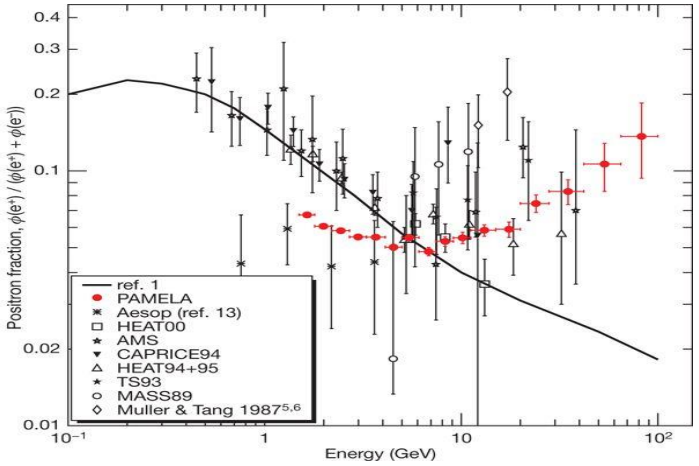


❑ Why DM?

- 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



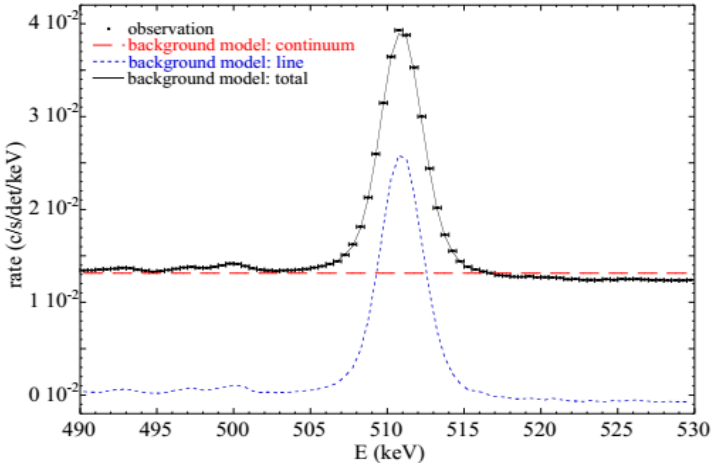
arXiv:astro-ph/0403324



PAMELA: Positron fraction

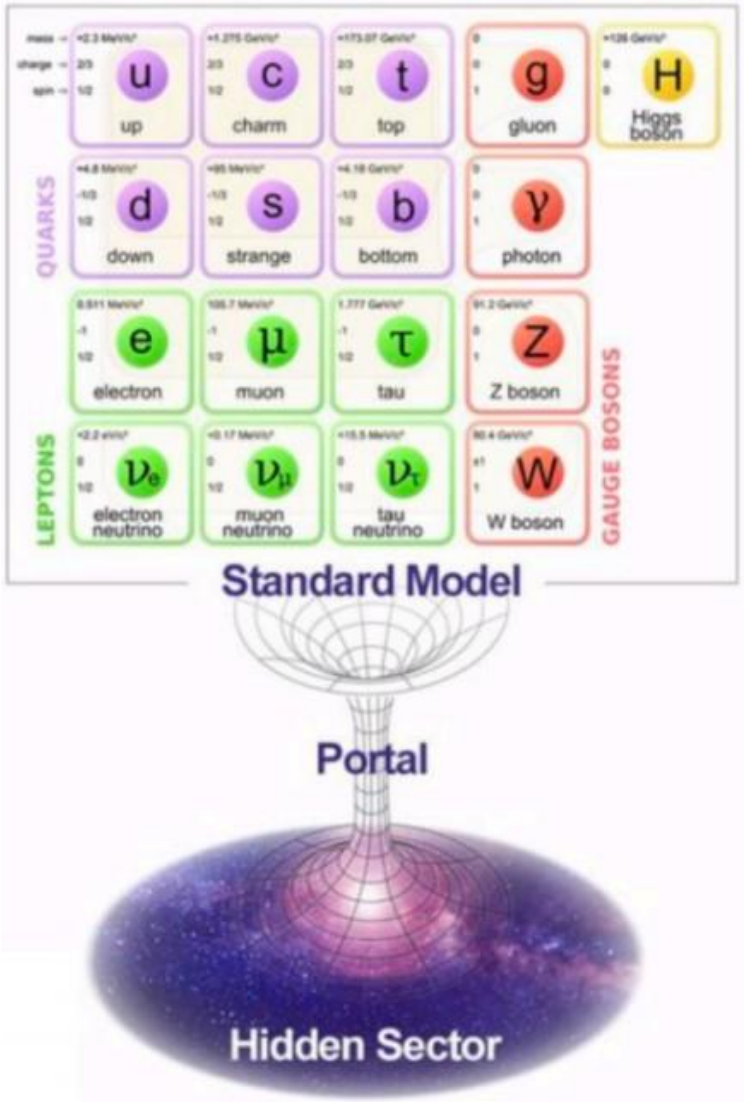
O Adriani et al., Nature **458** (2009) 607

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"

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

A' kinetic mixing with γ, Z

Dark Higgs (mixes with SM Higgs)

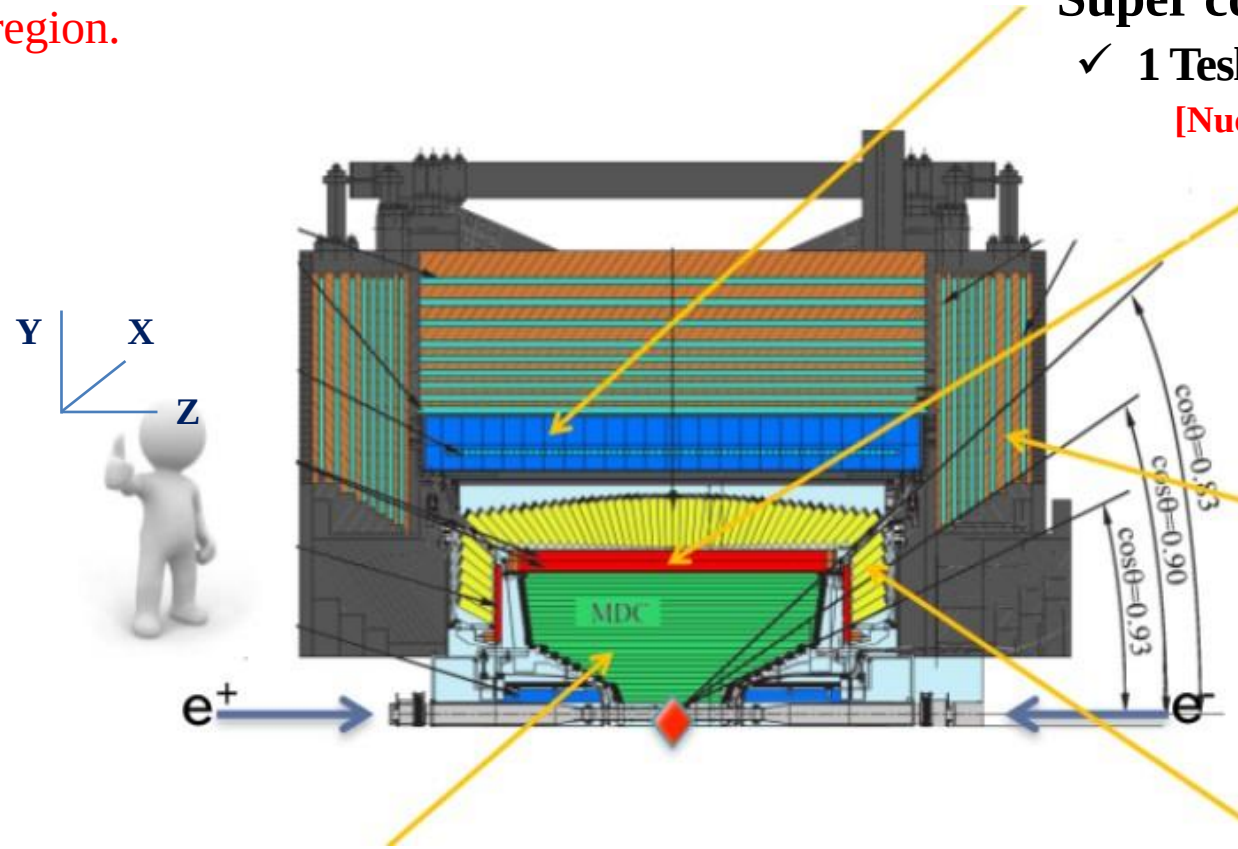
Sterile neutrino

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

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.

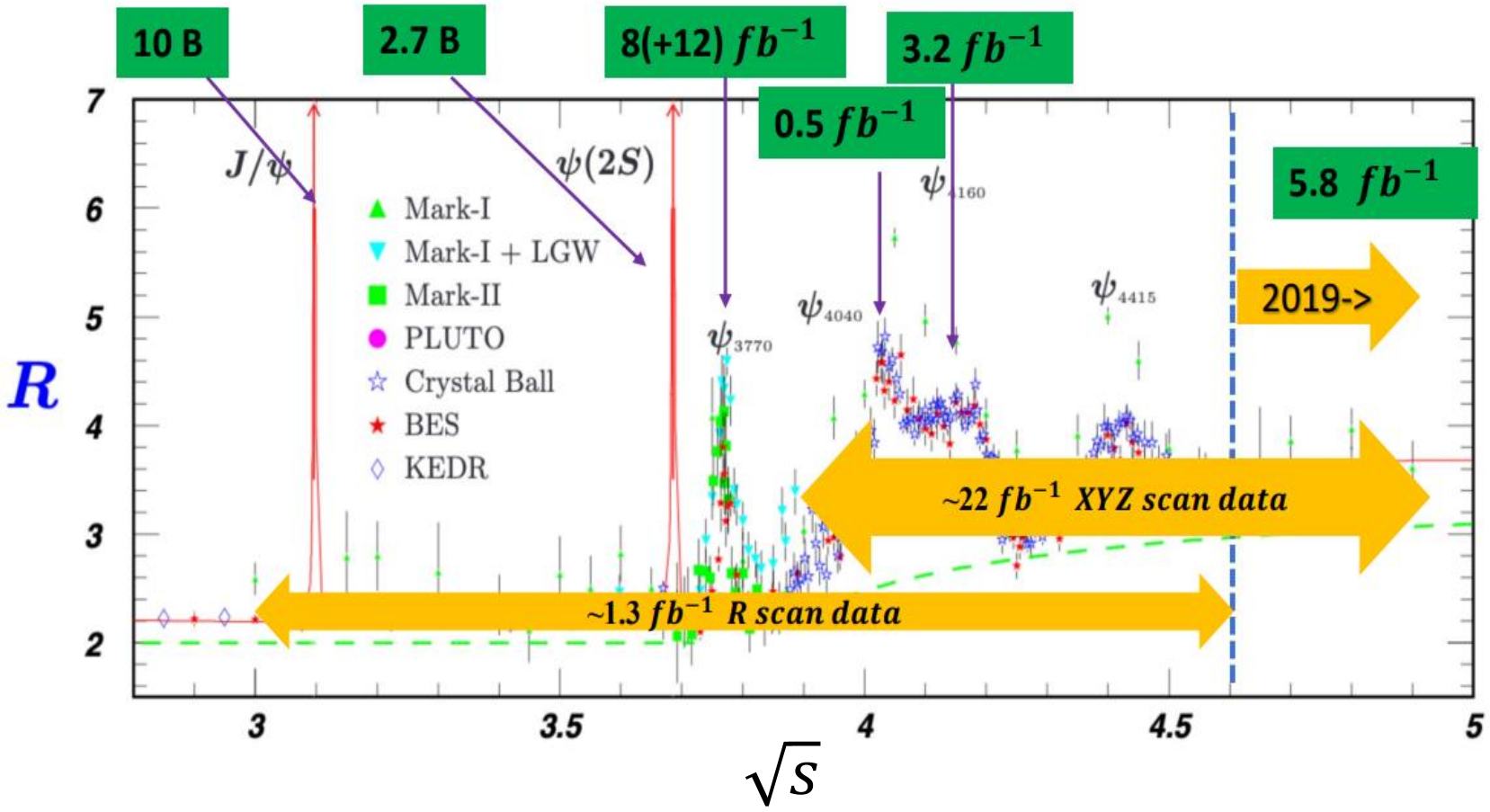
Electromagnetic calorimeter (EMC) (CsI(Tl))

→ 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!

Status of Dark matter 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)
(**This talk**)
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)
(**This talk**)

Invisible decays of ω/ϕ mesons

PRD **98**, 032001 (2018)

Invisible decays of η/η' mesons

PRD **87**, 012009 (2013)

Search for massless dark photon

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

Search for heavy Majorana neutrino

PRD **99**, 112002 (2019)

Search for an Axion-like particle

BESIII
Preliminary

An Axion-like particle (ALP), a

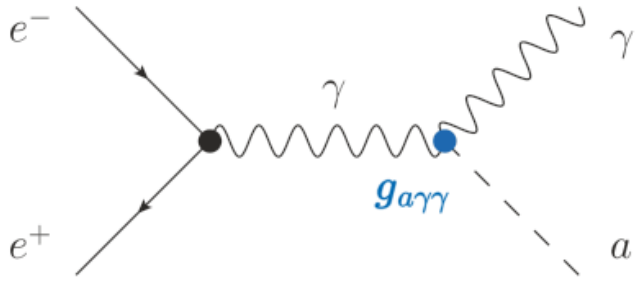
- is a pseudo-scalar particle
- introduced by the spontaneous breaking of Peccei-Quinn symmetry to solve the strong CP problem of the QCD

  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 MeV/c^2 – GeV/c^2 mainly come from e$^+$e$^-$ collider experiments

  Phys. Lett. B 753, 482 (2016)

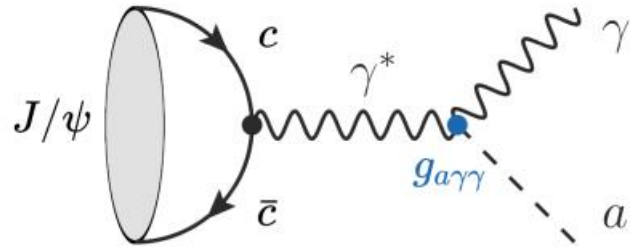
ALP-Strahlung process



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

Radiative decay process

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

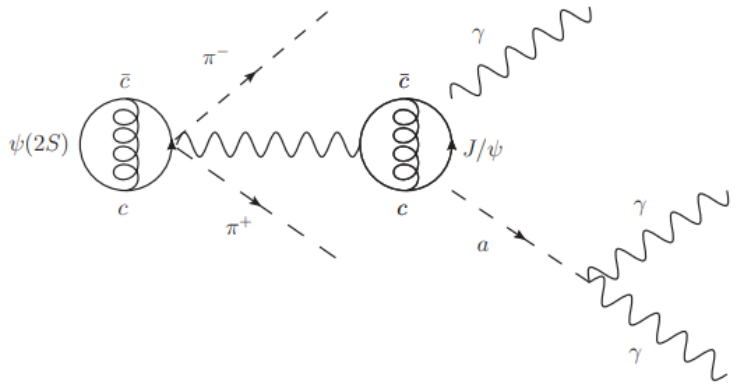


JHEP **06**, 091 385 (2019)

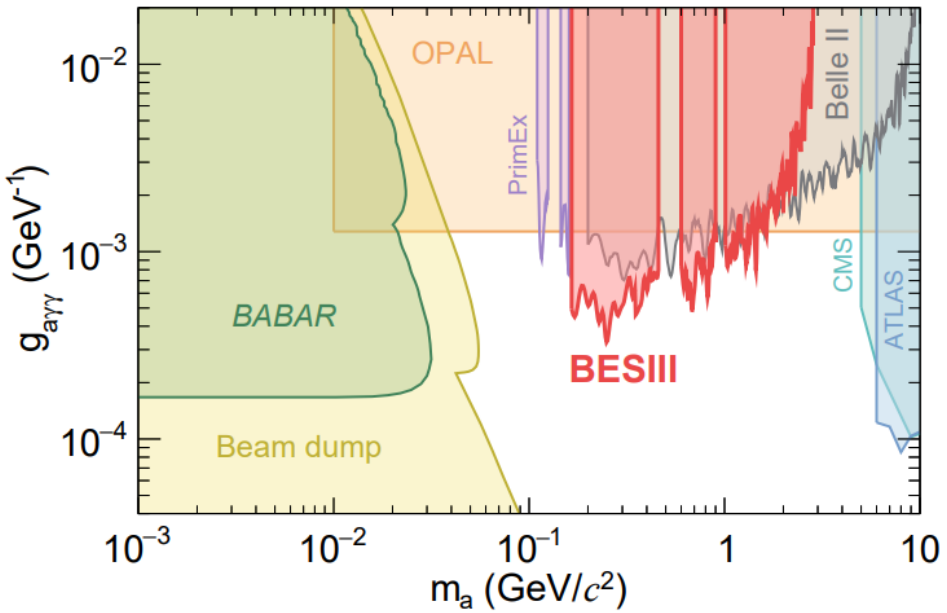
$$\mathcal{B}(J/\psi \to \gamma a) = \frac{m_{J/\psi}^2}{32\pi\alpha} g_{a\gamma\gamma}^2 \left(1-\frac{m_a^2}{m_{J/\psi}^2}\right)^3 \mathcal{B}(J/\psi \to e^+e^-)$$

Search for an Axion-like particle

- 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)

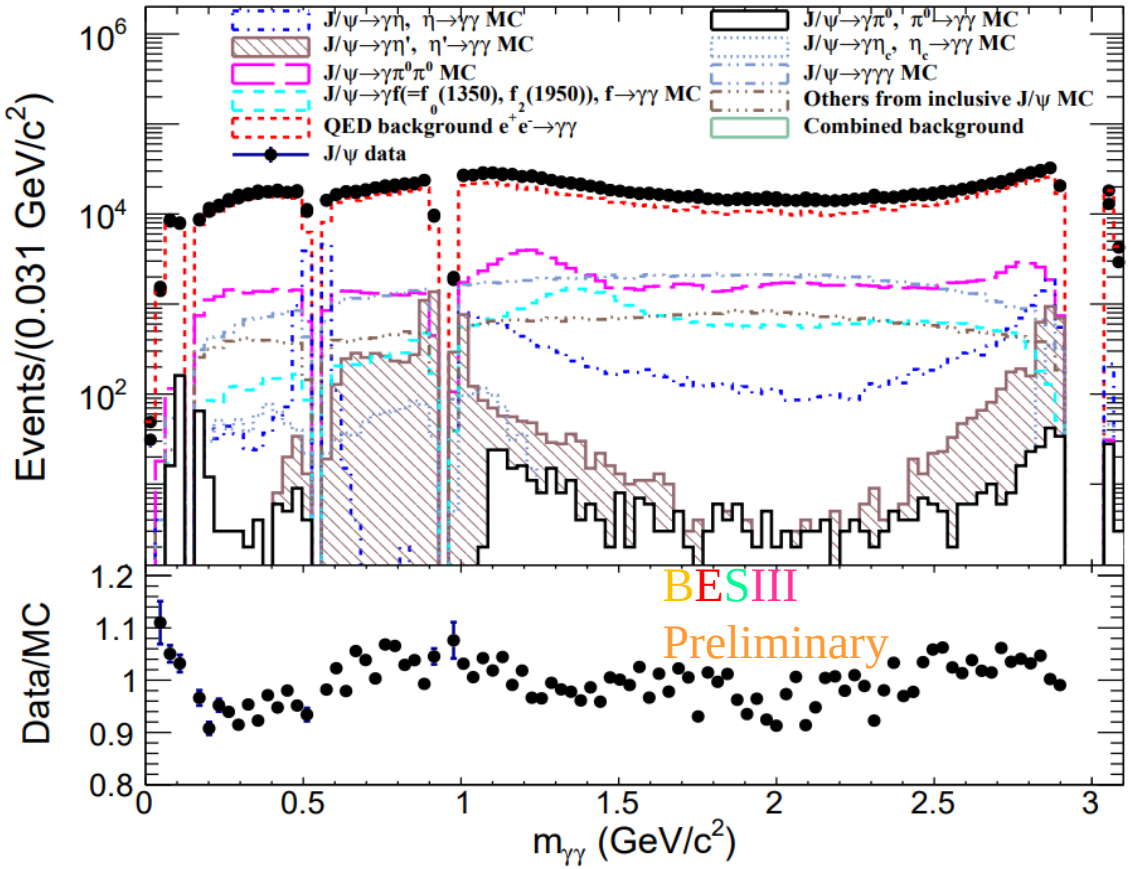
σ_a/σ_a^{rad} is calculated to be 0.044. (To be considered as systematic uncertainty)

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

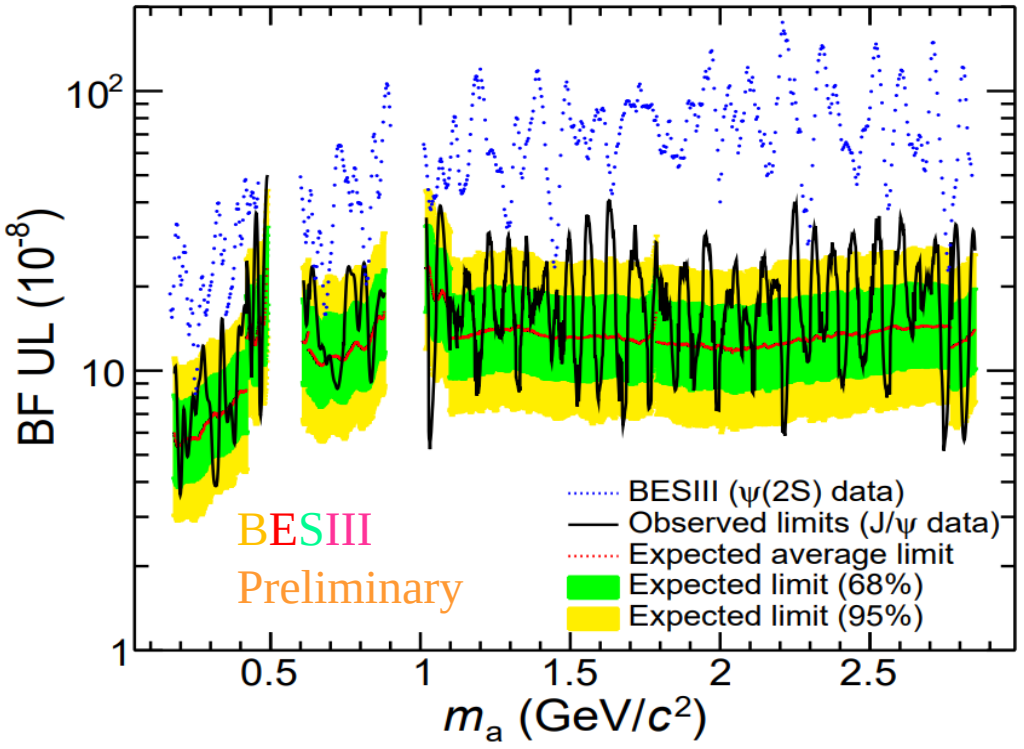


No evidence of ALP production is found.

Search for an Axion-like particle

BESIII
Preliminary

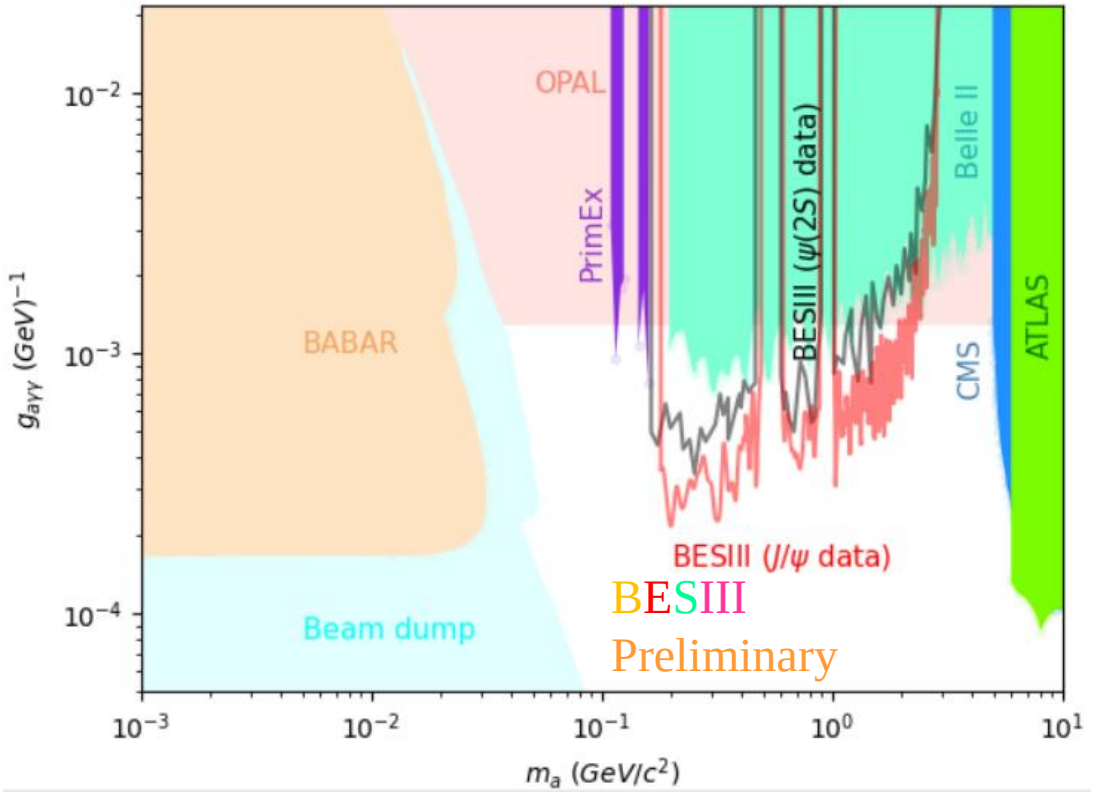
95% Confidence level upper limits on product branching fractions



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.

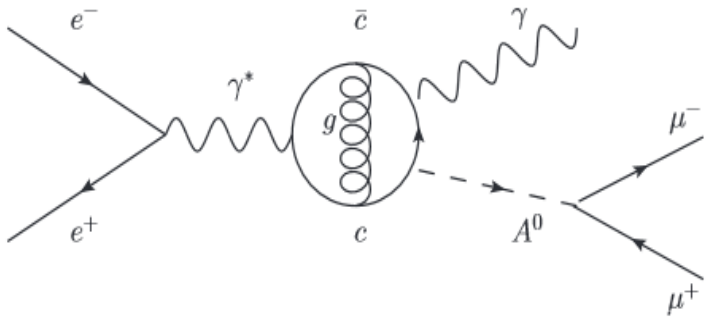
Phys. Lett. B **838**, 137678 (2023)

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

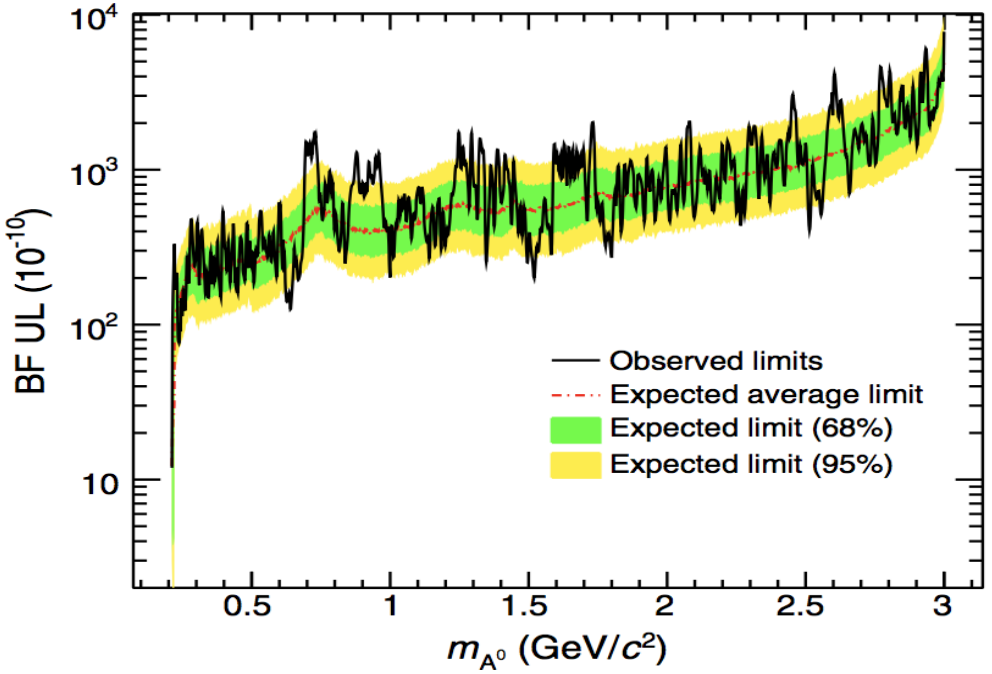
Light Higgs boson A^0 search in radiative J/ψ decay

PRD 105, 012008 (2022)

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



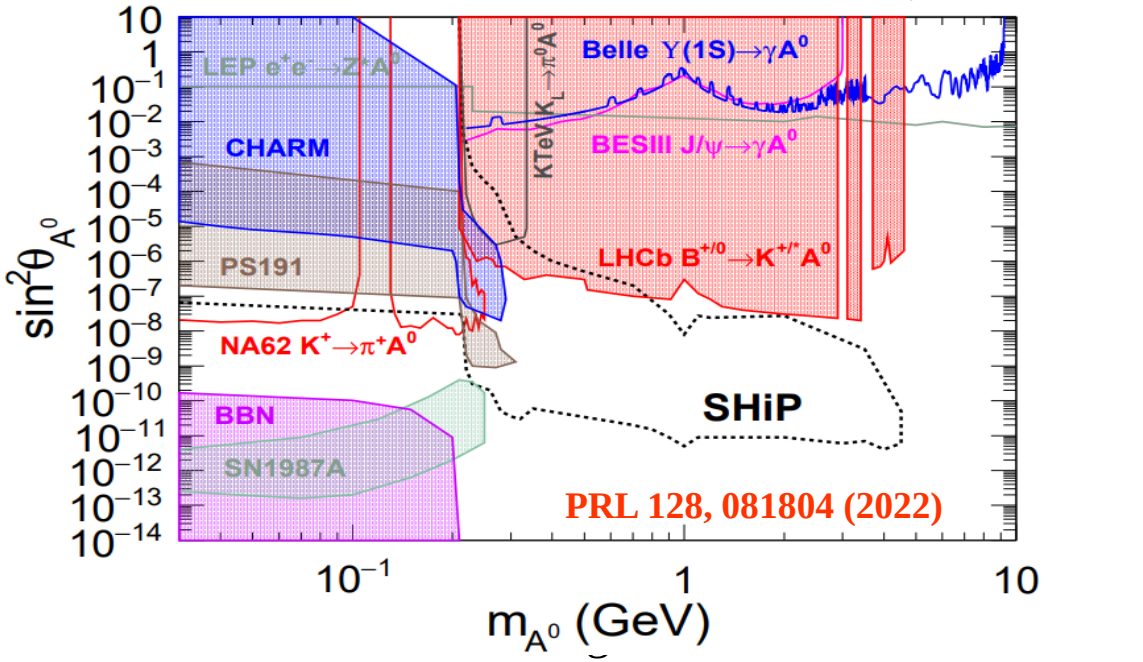
- No evidence of A^0 production is found and set 90% confidence level upper limits on product BFs .



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

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]

Invisible decays of dark photon

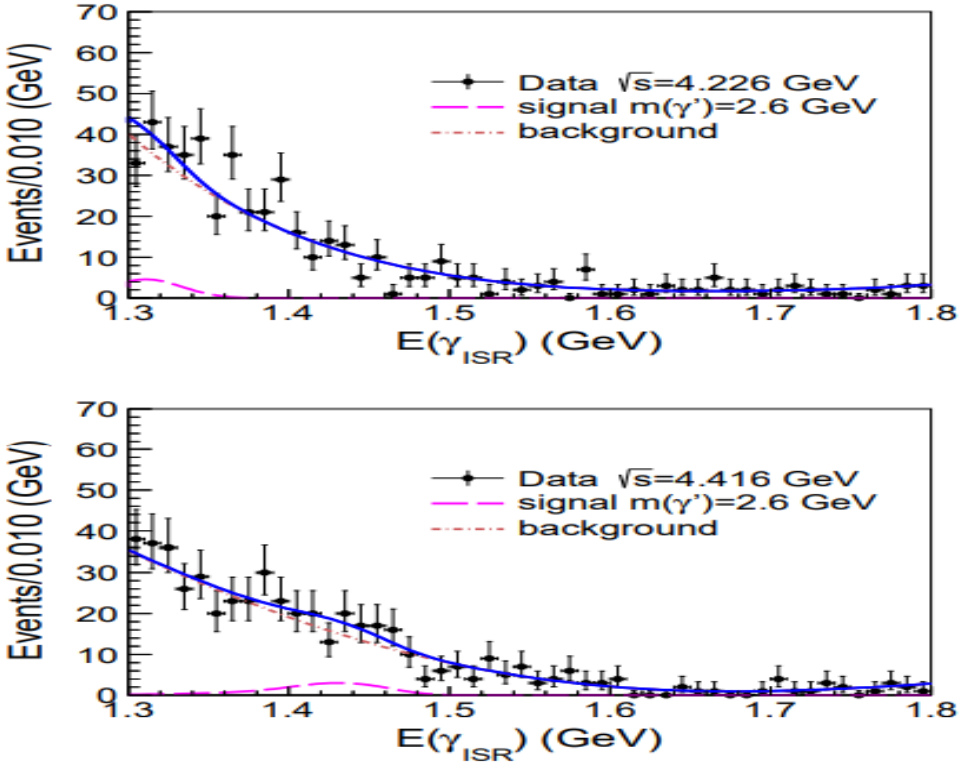
- This search is based on 14.9 fb^{-1} of e^+e^- annihilation data taken at center-of-mass (CM) energies from 4.13 to 4.60 GeV.

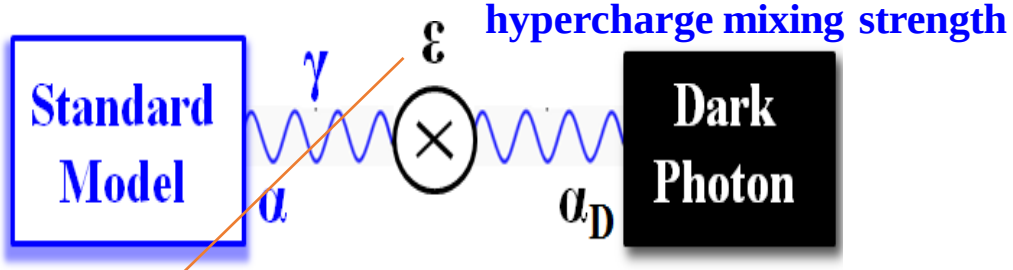
PLB 839, 137785 (2023)

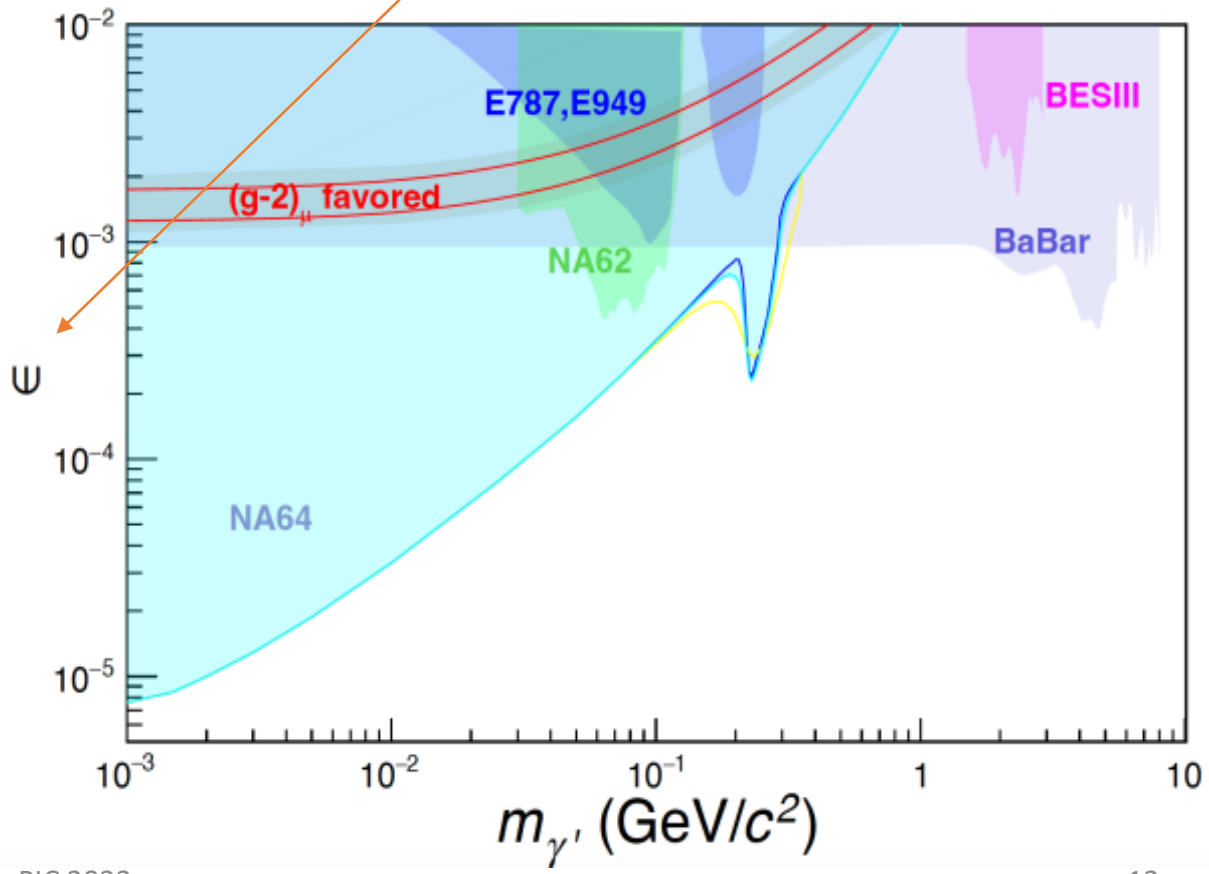
Dark photon search is explored via Initial-State-Radiation (ISR) production ($e^+e^- \to \gamma_{ISR}\gamma'$), where γ_{ISR} is an ISR photon.

Energy of monochromatic photon:

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





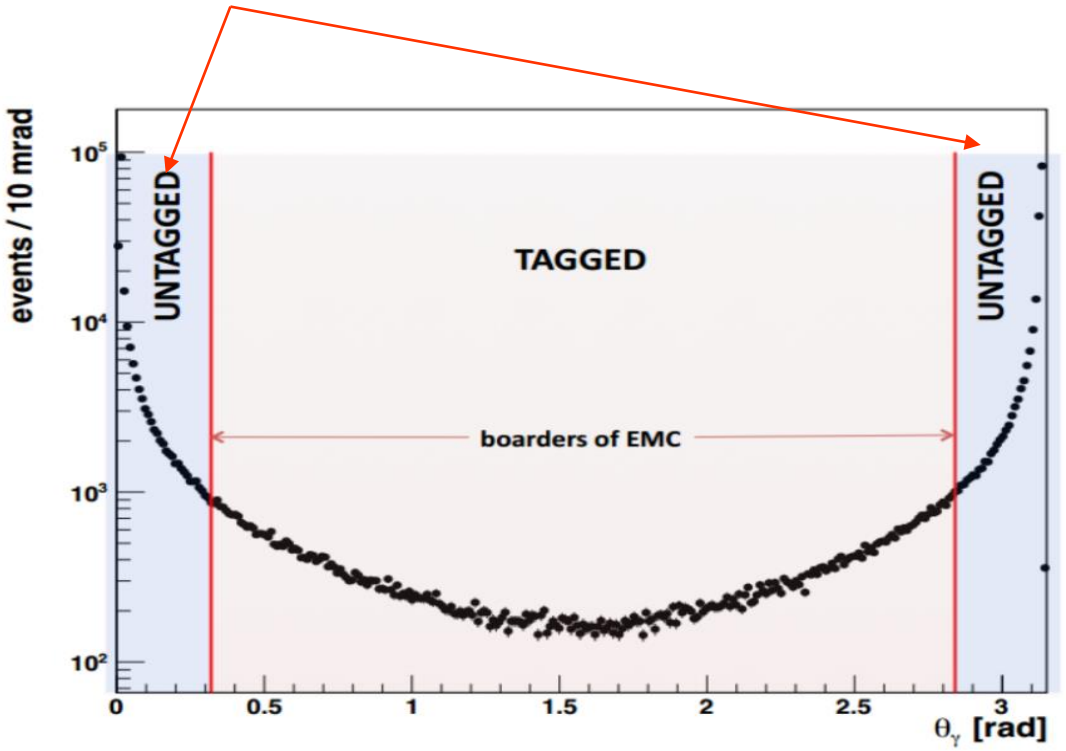


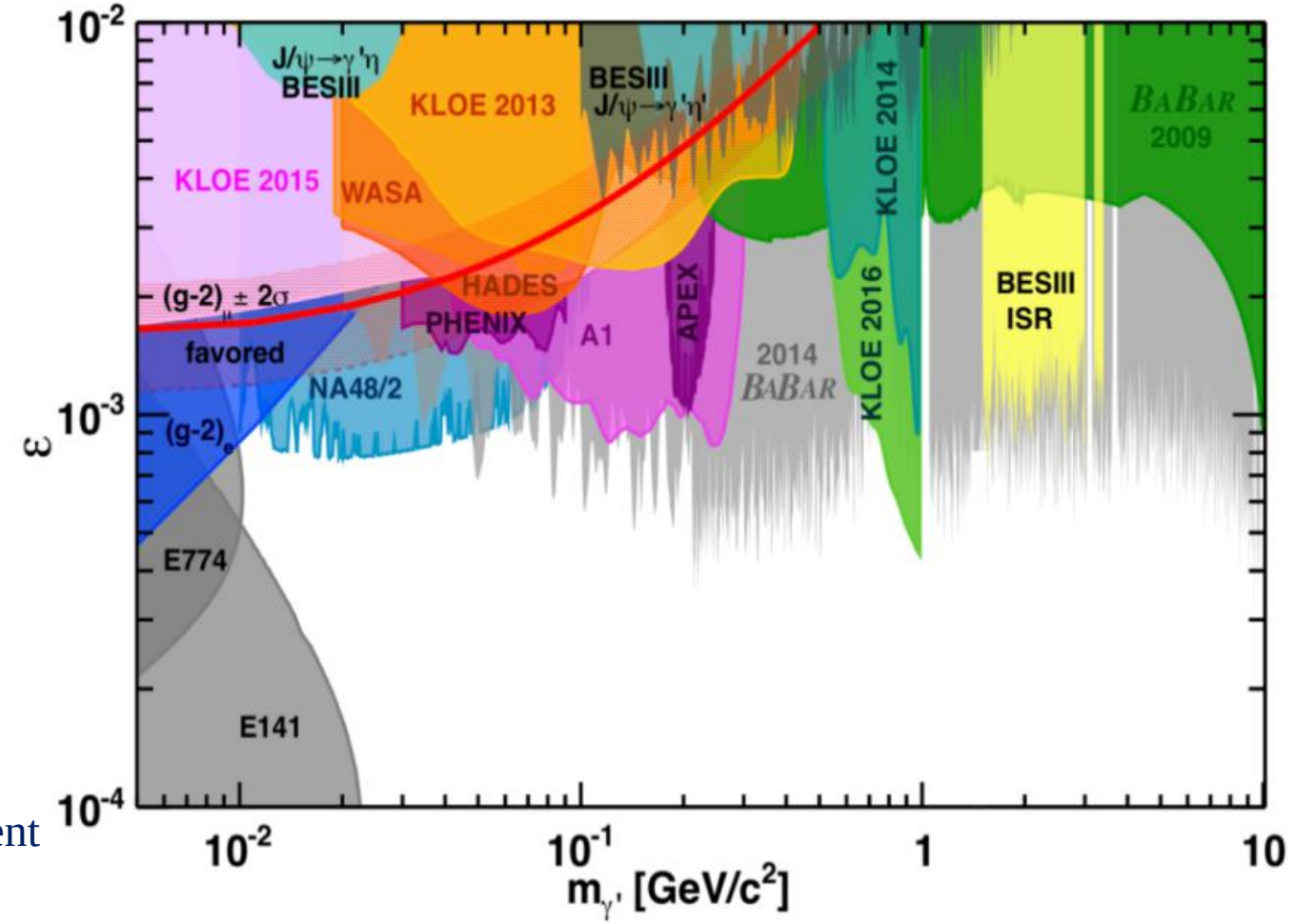
Visible decays of dark photon

PLB 774, 252 (2017)

Search is performed via Initial-State-Radiation (ISR) production ($e^+e^- \to \gamma_{ISR}\gamma'(\to e^+e^-, \mu^+\mu^-)$) with 2.93 fb^{-1} of $\psi(3770)$ data.

Untagged photon method is used for this search





Obtained limits are compatible with BaBar measurement (based on 514 fb^{-1} of Upsilon data)

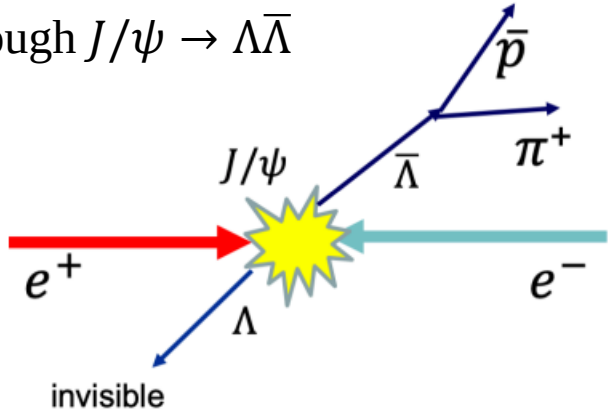
Will update the results with 20 fb^{-1} of $\psi(3770)$ data.

Invisible decays of Λ baryon

Phys. Rev. D **105**, L071101 (2022)

- ✓ Dark matter may relate with the invisible decays of baryonic matter arXiv:2111.12712
- ✓ Indivisible decays of Λ baryon search is performed with 10 billion of J/ψ data through $J/\psi \to \Lambda\bar{\Lambda}$
- ✓ 4 million single tag $\bar{\Lambda}$ events are obtained.

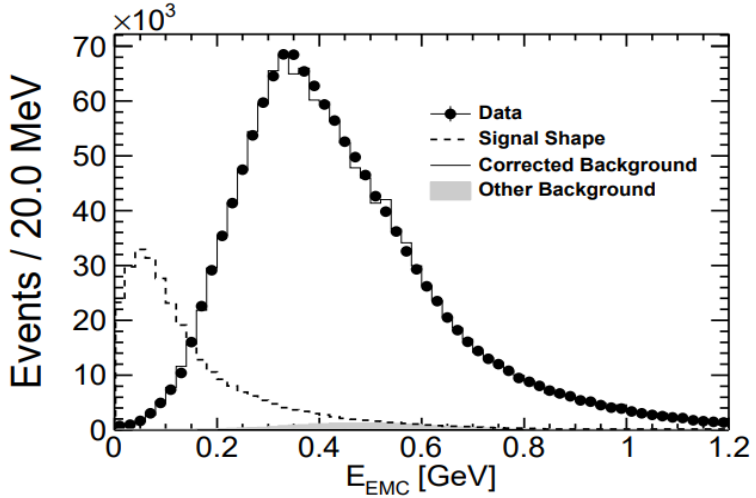
$$\mathcal{B}(\Lambda \to \text{invisible}) = \frac{N_{\text{sig}}}{N_{\text{tag}} \cdot (\varepsilon_{\text{sig}}/\varepsilon_{\text{tag}})}$$



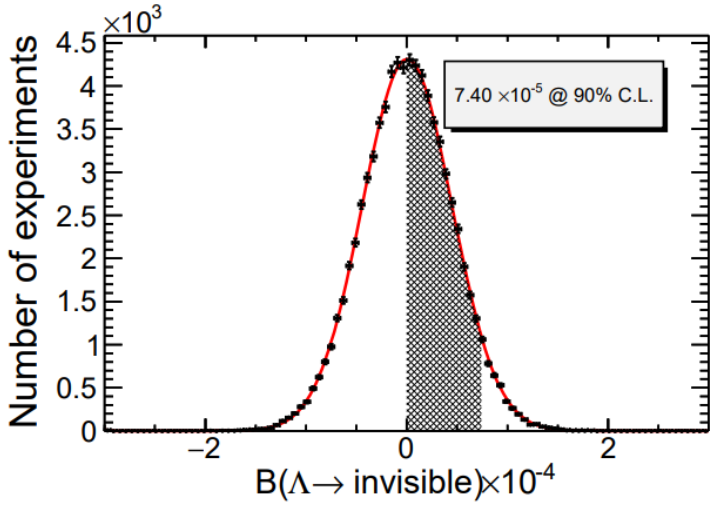
- ✓ Signal yield is extracted by fit to the energy deposited in EMC

$$E_{\text{EMC}} = E^{\pi^0}_{\text{EMC}} + E^{n}_{\text{EMC}} + E^{\text{noise}}_{\text{EMC}}$$

- ✓ Background modelling is improved with a data-driven approach.



No evidence of significant signal events, set 90% CL upper limit



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

PRD **106**, 072008 (2022)

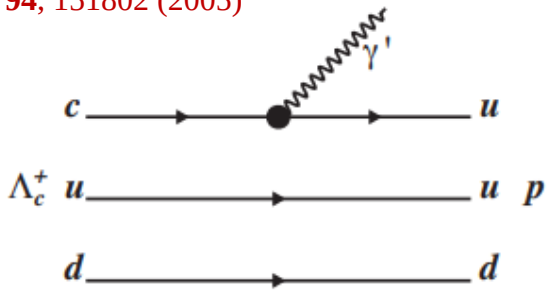
- A massless dark photon γ' is predicted by the BSM via spontaneously broken of Abelian group $U(1)_D$.

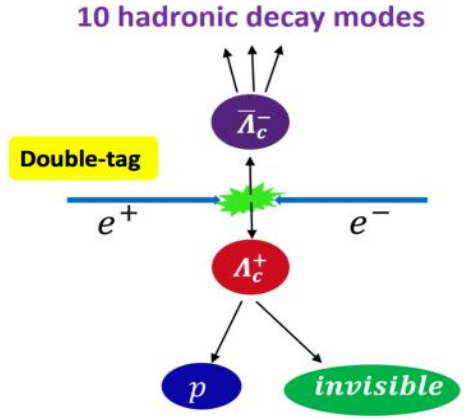
B. Holdom, Phys. Lett. B **166**, 196 (1986)
B. A. Dobrescu, Phys. Rev. Lett. **94**, 151802 (2005)

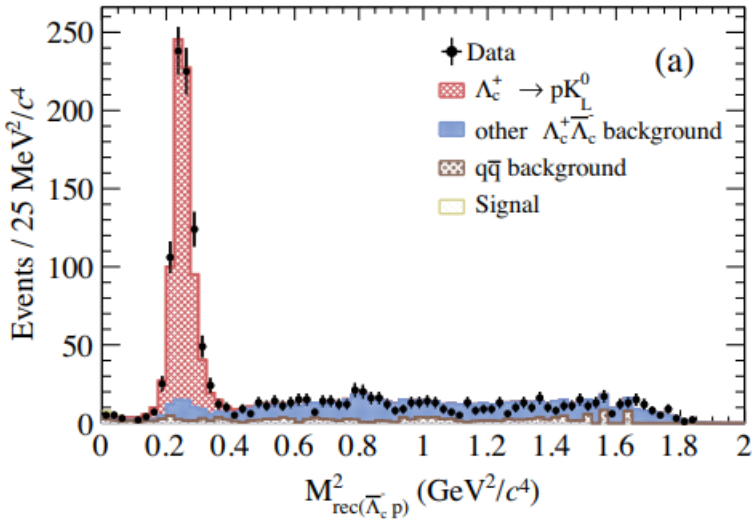
- Massless dark photon γ' may enhance the branching fractions of flavor changing neutral current (FCNC) decays, which are highly suppressed in charm-sector

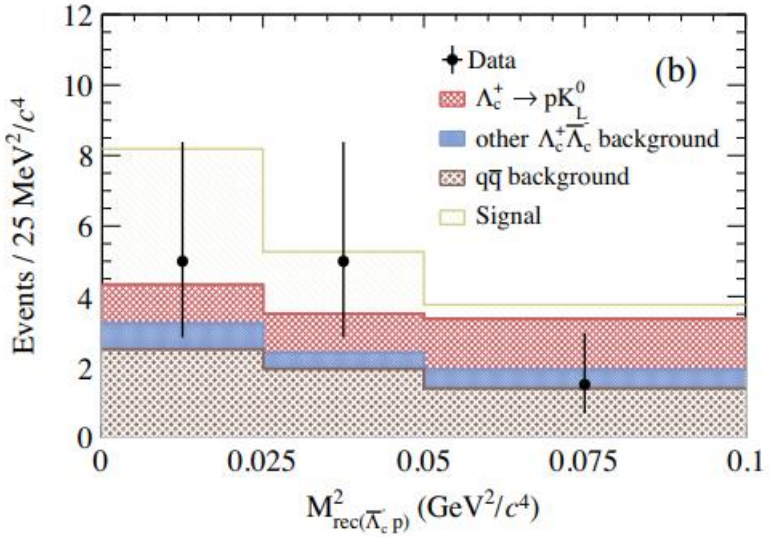
S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D **2**, 1285 (1970).

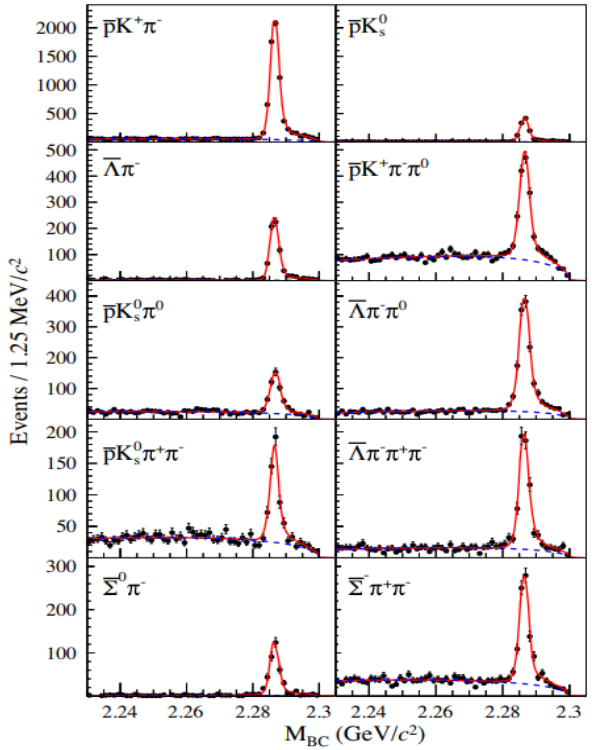
- Search for a massless dark photon is conducted using 4.5 fb^{-1} of data collected at CM energies between 4.6 and 4.699 GeV .











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

Summary

- Searching for the possible extensions of the SM is the top priority of the current experimental investigations.
- BESIII has searched for various flavors of dark matter particles.
- Both visible and invisible decays of dark matter candidates have been explored by the BESIII experiment.
- 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.

Thanks!