Dark sector and Axion-like particle search at BESIII

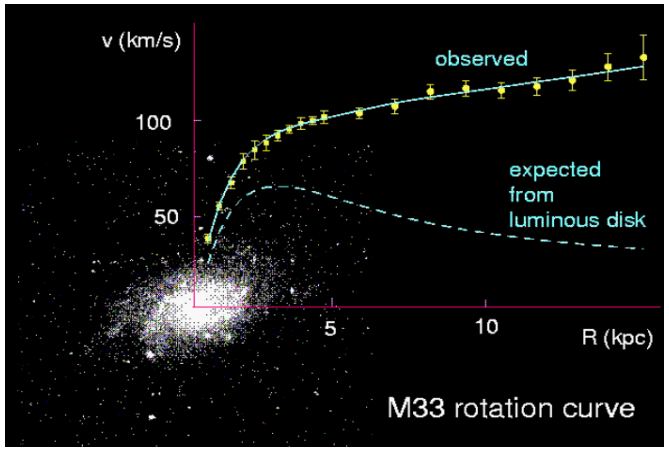
Vindhyawasini Prasad

(On behalf of the BESIII Collaboration)

Email: vindymishra@gmail.com

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

Motivation

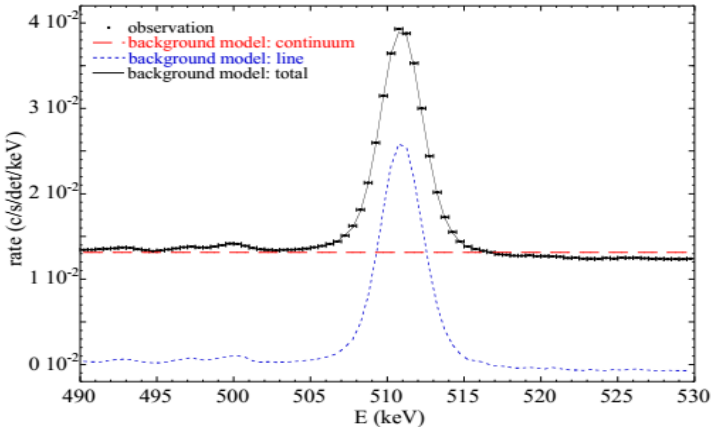


arXiv:astro-ph/0403324

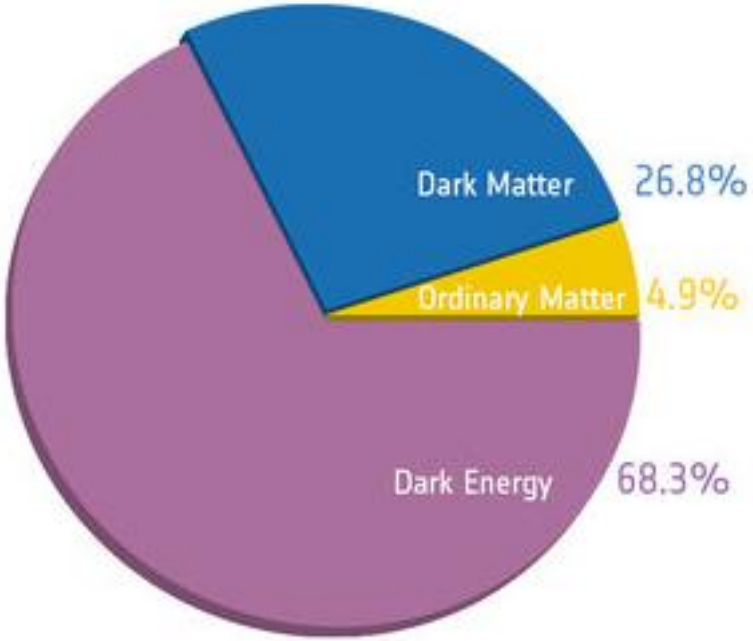
SPI/Integral

P. Jean et al.,

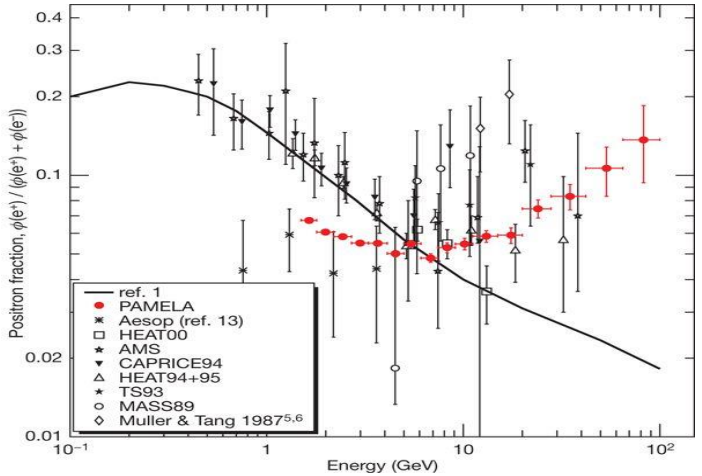
A&A **407**, L-55-L58 (2003)



Plenty of astrophysical observations evidence the existence of Dark matter (DM), but its nature is still elusive

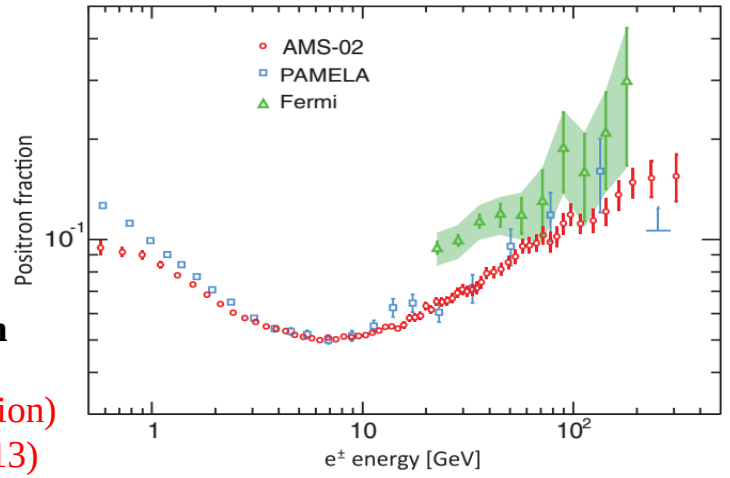


Presence of DM is inferred via gravitational effects only



PAMELA: Positron fraction

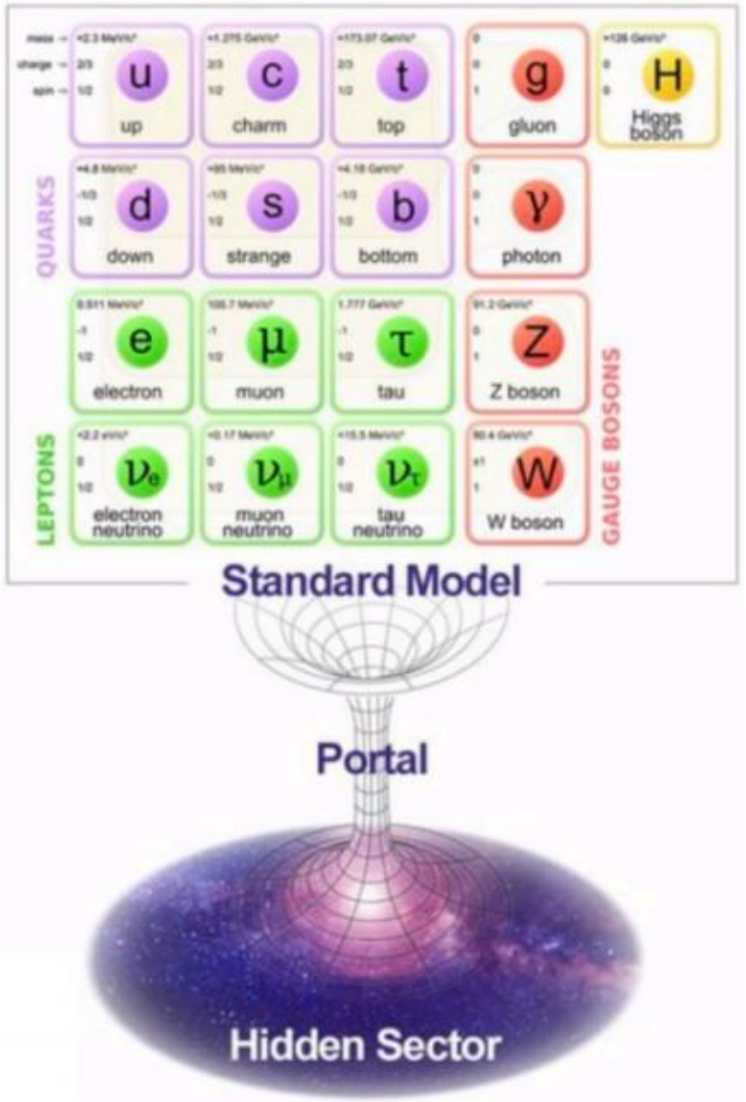
O Adriani et al., Nature **458** (2009) 607



AMS: Positron fraction

M. Aguilar et al. (AMS Collaboration)
Phys. Rev. Lett. **110**, 141102 (2013)

Motivation



- New physics models beyond the Standard Model introduce light weak interacting dark matter (DM) hidden sectors

  ✓ Motivated by recent experimental anomalies.

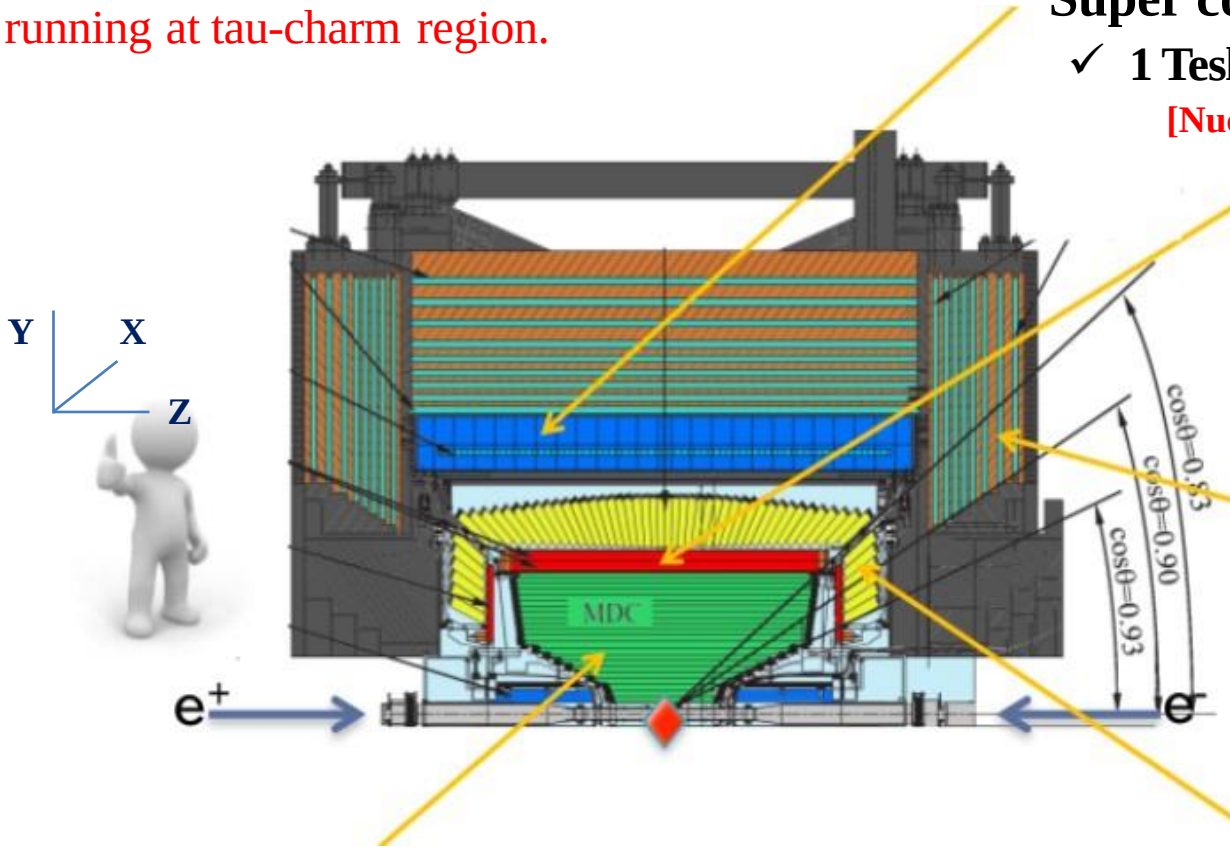
  ✓ DM hidden sectors couple to the SM particles via the so called "portals"

Portal	Particles	Operator(s)
"Vector"	Dark photons	$-\frac{\epsilon}{2\cos\theta_W}B_{\mu\nu}F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{a}{f_a}F_{\mu\nu}\widetilde{F}^{\mu\nu}, \frac{a}{f_a}G_{i\mu\nu}\widetilde{G}_i^{\mu\nu}, \frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
"Higgs"	Dark scalars	$(\mu S + \lambda S^2)H^\dagger H$
"Neutrino"	Sterile neutrinos	$y_N L H N$

- If the masses of these particles are in sub MeV – GeV range, they can be accessible by high intensity e^+e^- collider experiments, such as BESIII experiment.

BESIII Experiment

BESIII experiment is 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.**

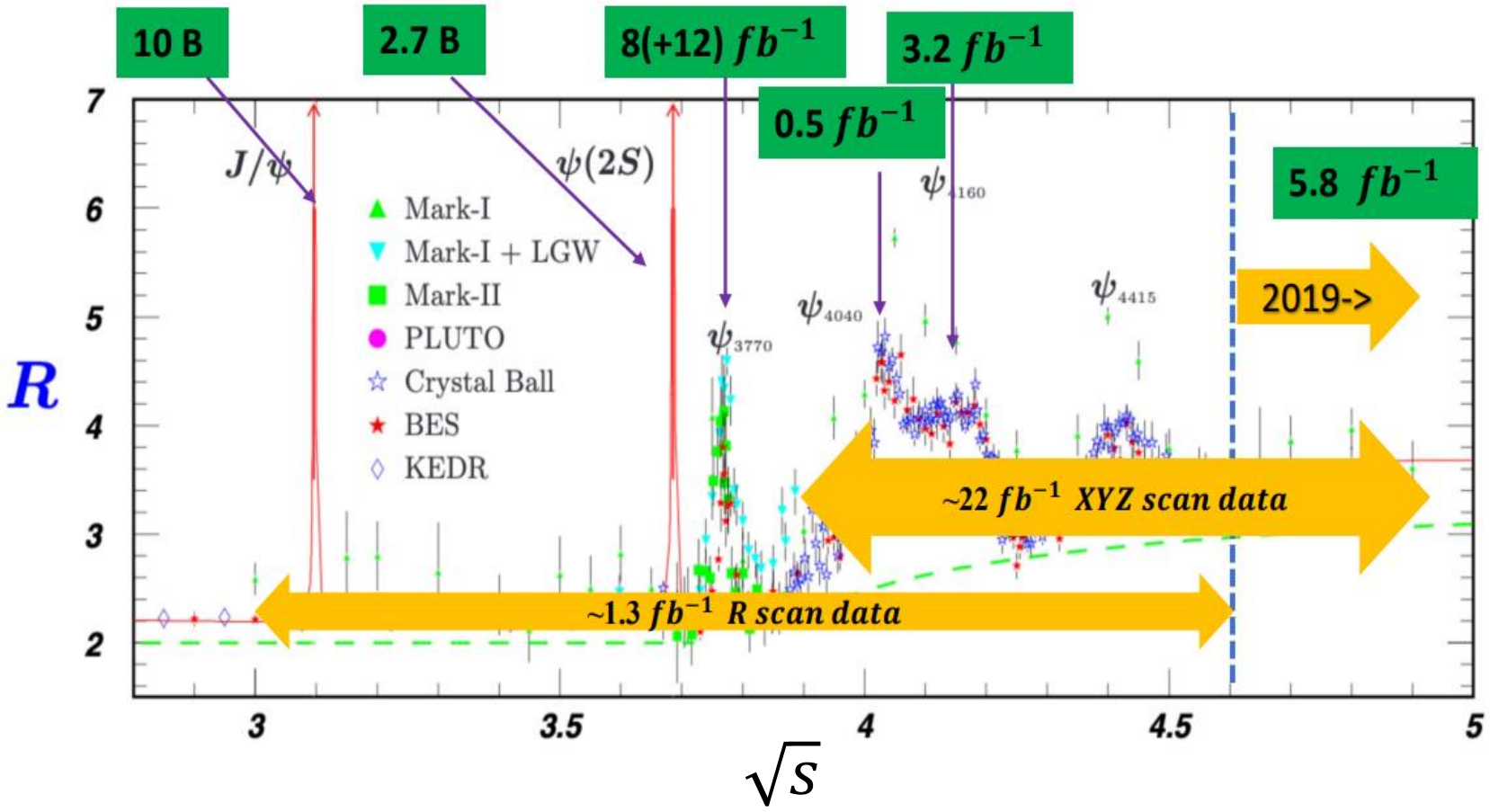
Electromagnetic calorimeter (EMC) (CsI(Tl))

→ 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



World largest data in tau-charm region

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

IDEAL ENVIRONMENT TO STUDY HADRON SPECTROSCOPY & SEARCH FOR NEW PHYSICS PHENOMENA!!

Searches for light dark matter particles at BESIII

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 an Axion-like particle

BESIII
Preliminary

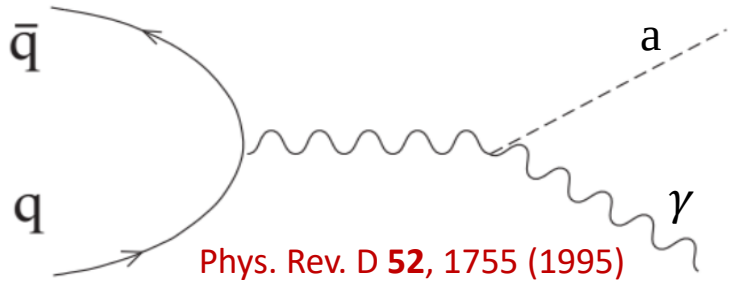
An Axion-like particle (ALP), a

- 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. **38**, 1440 (1977); Phys. Rev. D **16**, 1791 (1977)
Phys. Rev. Lett. **40**, 223 (1978); Phys. Rev. Lett. **40**, 279 (1978)

- couples to bosons. Here focus on $a \to \gamma\gamma$
- ALP production at e^+e^- collider experiments

Radiative decay process

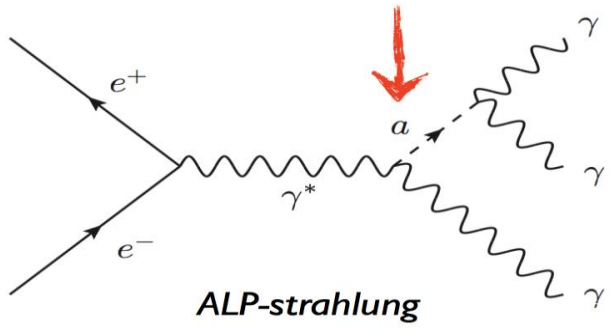


Phys. Rev. D **52**, 1755 (1995)

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

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

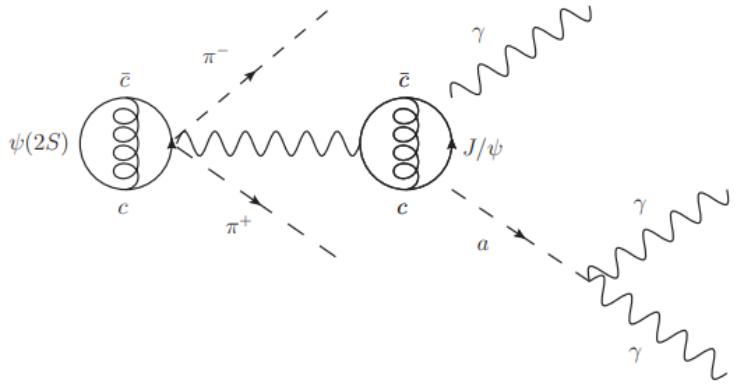
ALP-Strahlung process



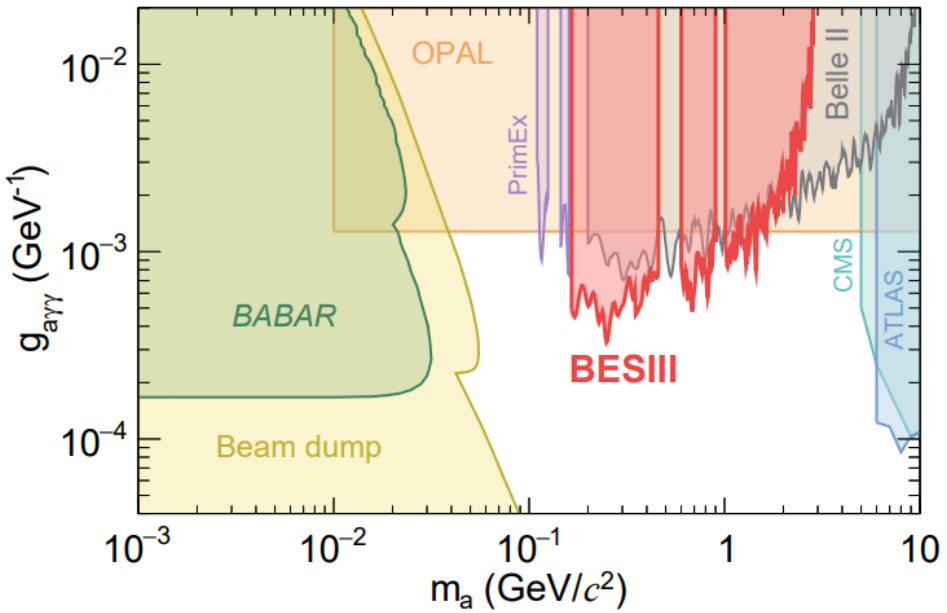
$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha.(\hbar.c)^2}{24} \left(1 - \frac{m_a^2}{m_{J/\psi}^2}\right)^3$$

Search for an Axion-like particle

- Current best limit comes from the BESIII experiment via $J/\psi \to \gamma a$ using 2.7 billion $\psi(2S)$ data



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



- Exclusion limits can be further improved using 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)

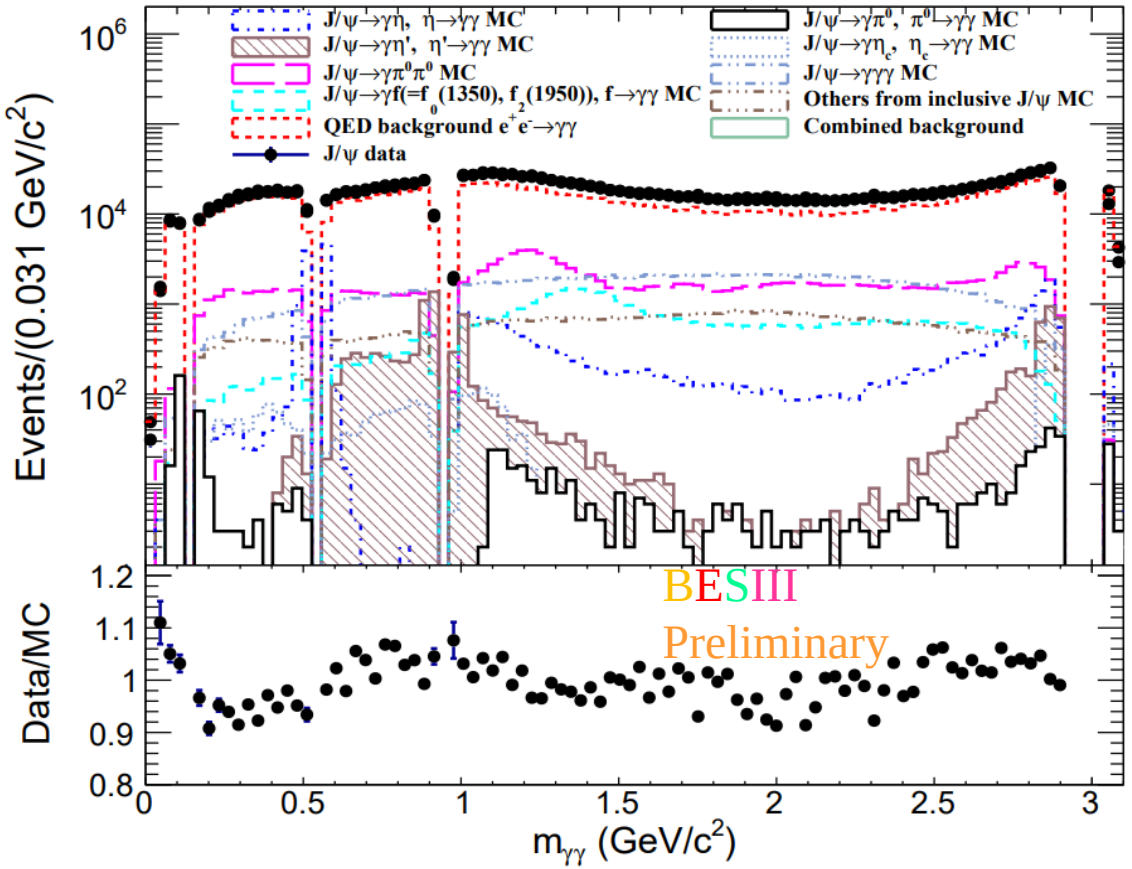
σ_a/σ_a^{rad} is calculated to be 0.044. (To be considered as systematic uncertainty)

Search for an Axion-like particle

BESIII
Preliminary

- Select at three photon candidates in the EMC barrel region
- Mass resolution is improved by performing the four-constraint kinematic fit
- 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 of all the three combinations of photons after vetoing the $J/\psi \to \gamma P$ ($P = \pi^0, \eta, \eta', \eta_c$) backgrounds

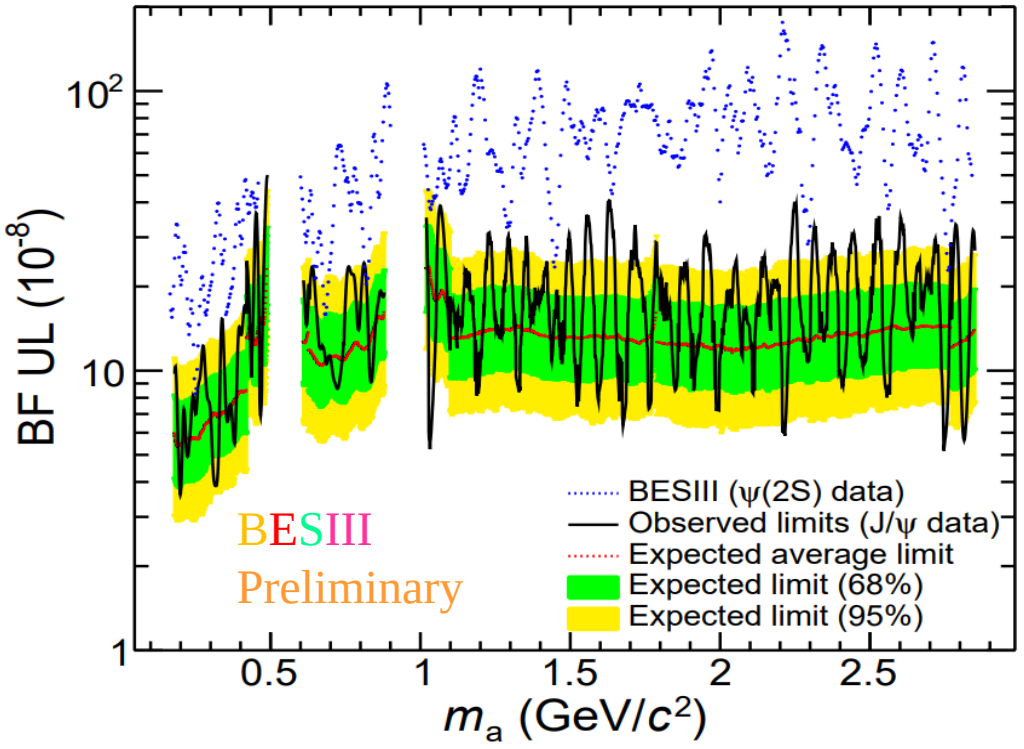


No significant signal events are found.

Search for an Axion-like particle

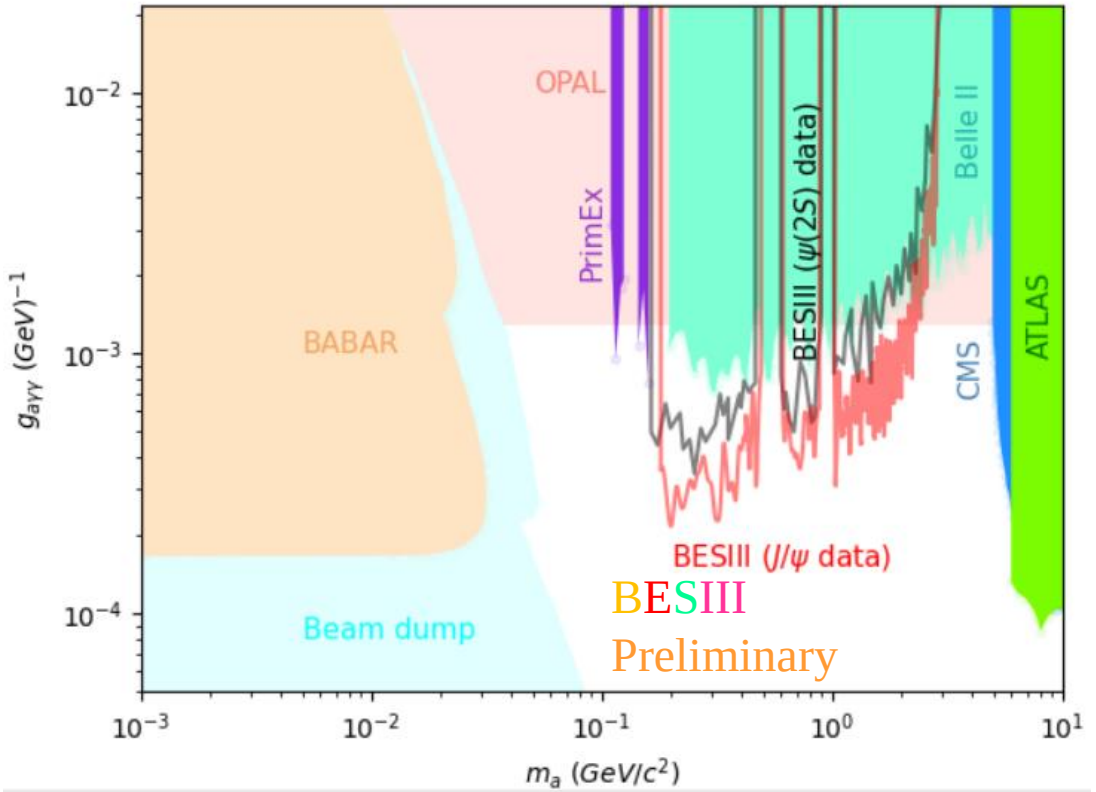
BESIII
Preliminary

95% Confidence level upper limits on product branching fractions



Our measurement has 8-9 times improvement over the previous BESIII measurement

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)

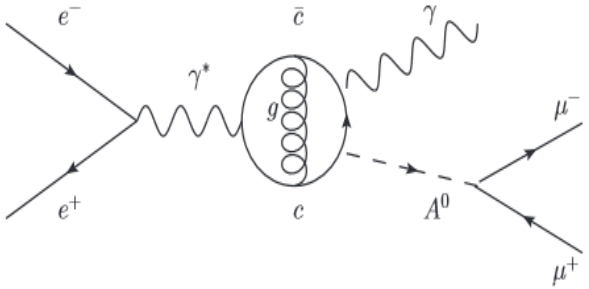
Phys. Rev. Lett. **125**, 161806 (2020)

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

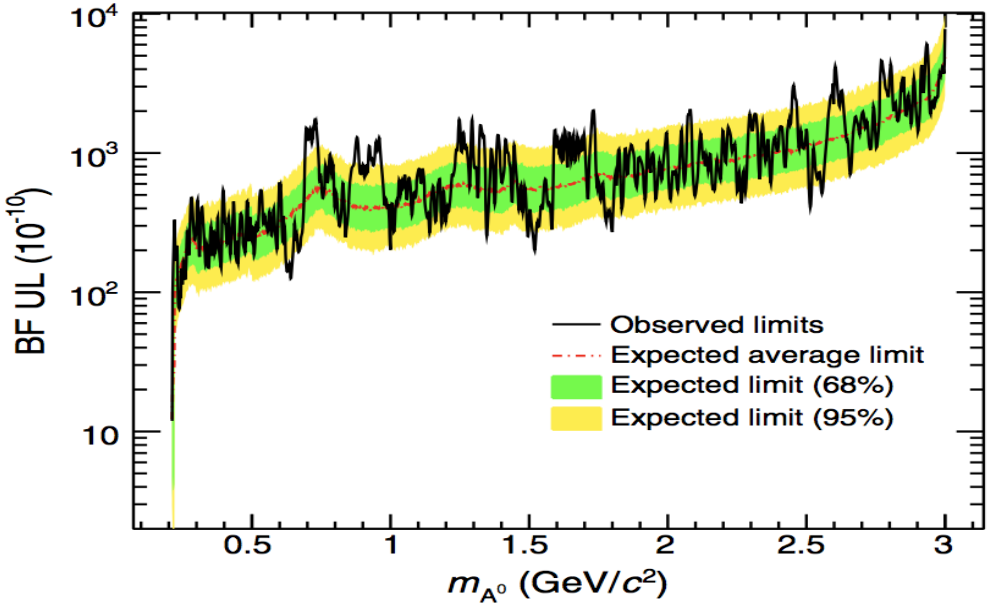
PRD 105, 012008 (2022)

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 .

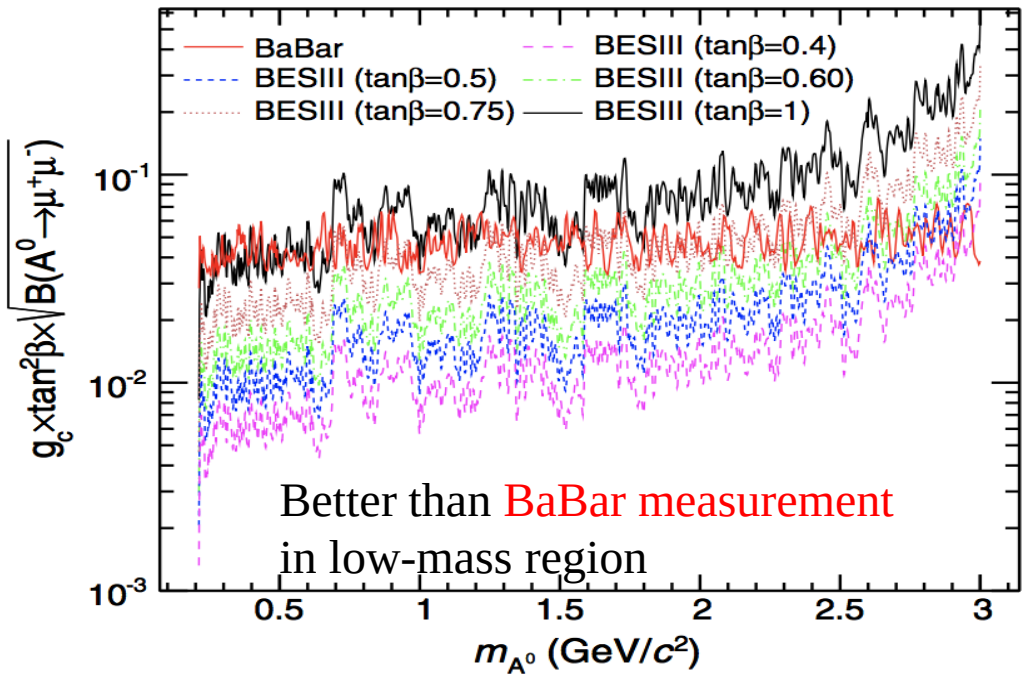


- Use 9 billion J/ψ events collected by BESIII experiment to perform this study.

$$\frac{\mathcal{B}(V \to \gamma A^0)}{\mathcal{B}(V \to l^+ l^-)} = \frac{G_F m_q^2 g_q^2 C_{\mathrm{QCD}}}{\sqrt{2}\pi\alpha}\left(1 - \frac{m_{A^0}^2}{m_V^2}\right)$$

In Next-to-Minimal Supersymmetric Model (NMSSM), $g_c = cos\theta_A / tan\beta$ for Charm quark and $g_b = cos\theta_A tan\beta$ for bottom quark.

Annu. Rev. Nucl. Part. Sci. 70, 197 (2020)



Search for invisible decays of dark photon

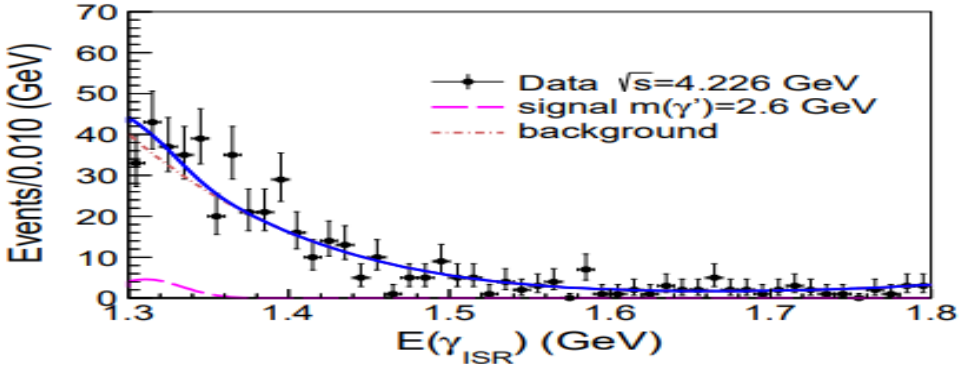
Use 14.9 fb^{-1} of e^+e^- annihilation data taken at center-of-mass (CM) energies from 4.13 to 4.60 GeV to perform this search

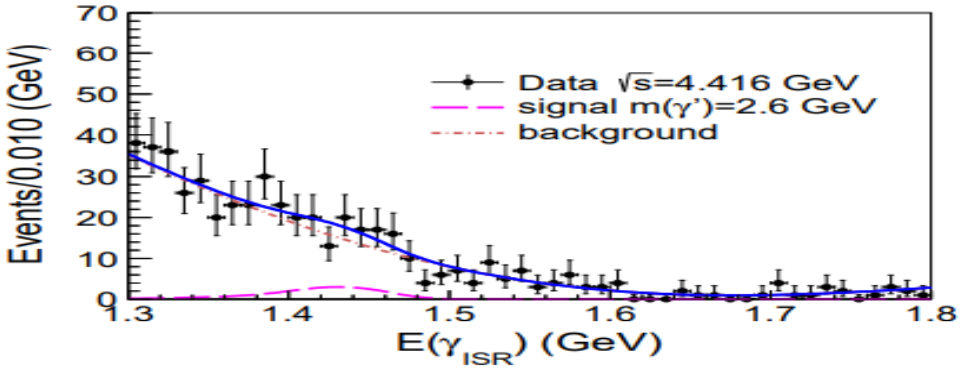
PLB 839, 137785 (2023)

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

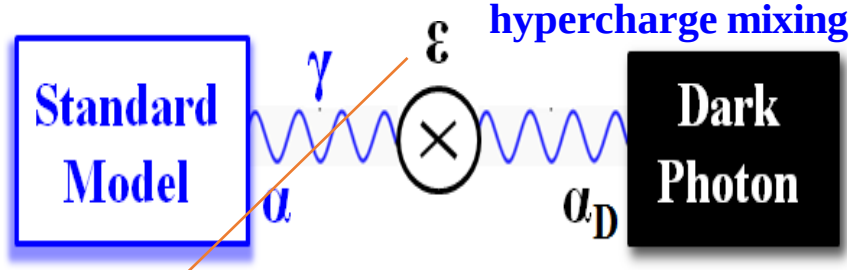
Energy of monochromatic photon:

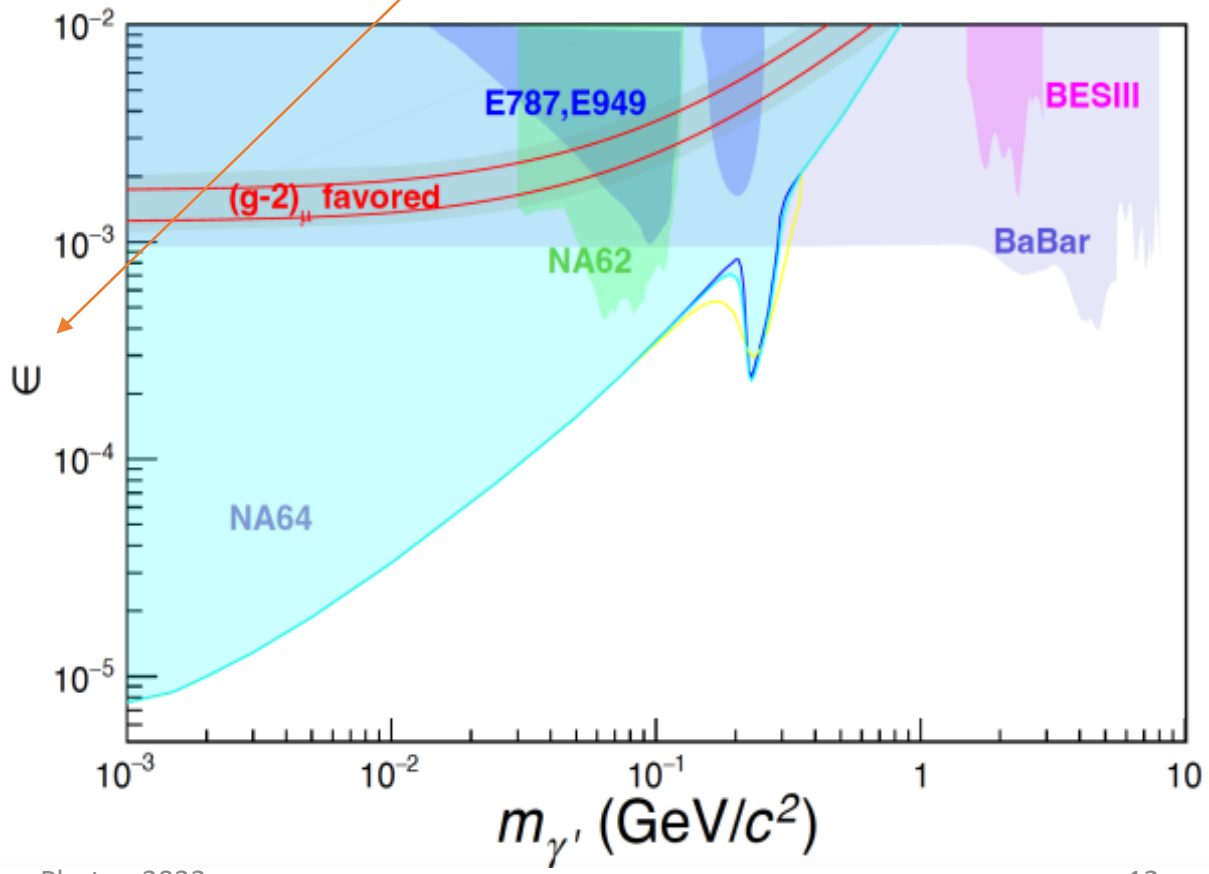
$$E_{\rm ISR} = \frac{s - m^2_{\gamma'}c^4}{2\sqrt{s}},$$





hypercharge mixing strength

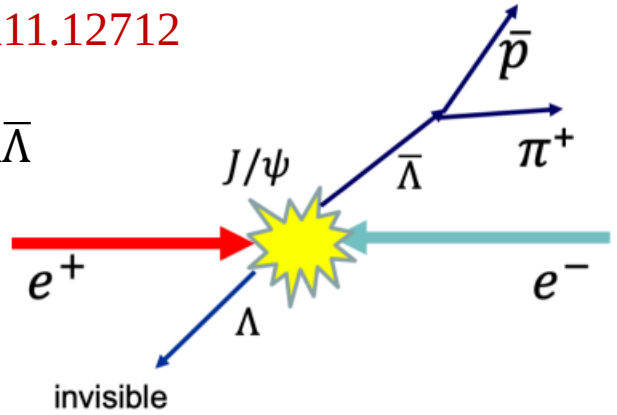




Invisible decays of Λ baryon

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

- ✓ Dark matter may be represented by baryon matter with invisible final state arXiv:2111.12712
- ✓ First search for Λ baryon 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 to probe invisible decays

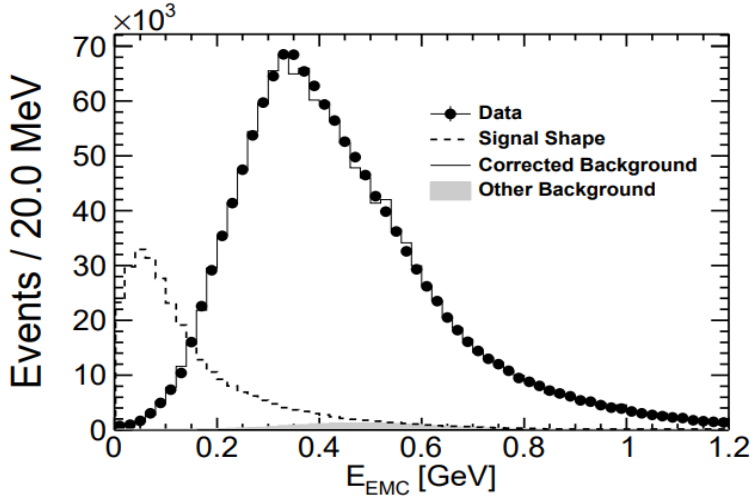


$$\mathcal{B}(\Lambda \to \text{invisible}) = \frac{N_{\text{sig}}}{N_{\text{tag}} \cdot (\varepsilon_{\text{sig}}/\varepsilon_{\text{tag}})}$$

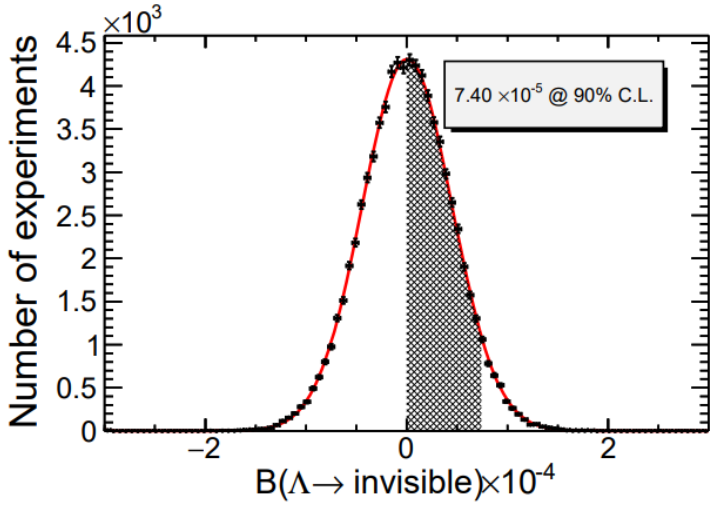
- ✓ Signal events are extracted by fit to the energy deposited in EMC

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

- ✓ Data-driven approach is adopted to improve the background modeling.



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)

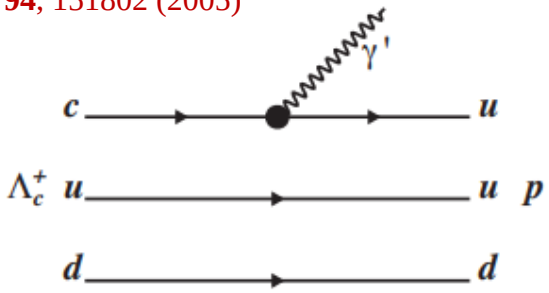
- A massless dark photon γ' is predicted by spontaneously broken of Abelian group $U(1)_D$.

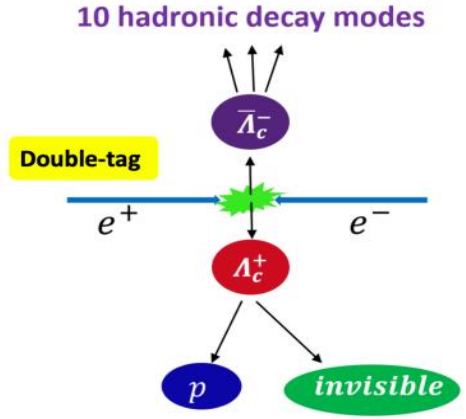
B. Holdom, Phys. Lett. B **166**, 196 (1986)
B. A. Dobrescu, Phys. Rev. Lett. **94**, 151802 (2005)

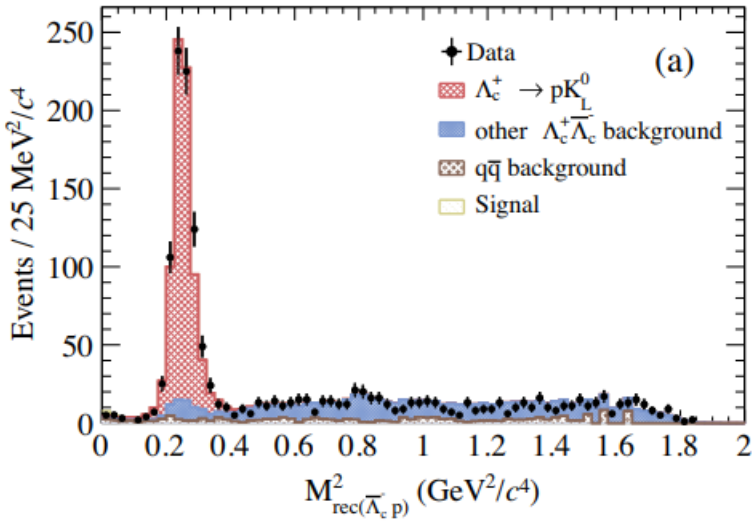
- Presence of γ' may enhance the branching fractions of flavor changing neutral current (FCNC) decays, which are highly suppressed in charm-sector

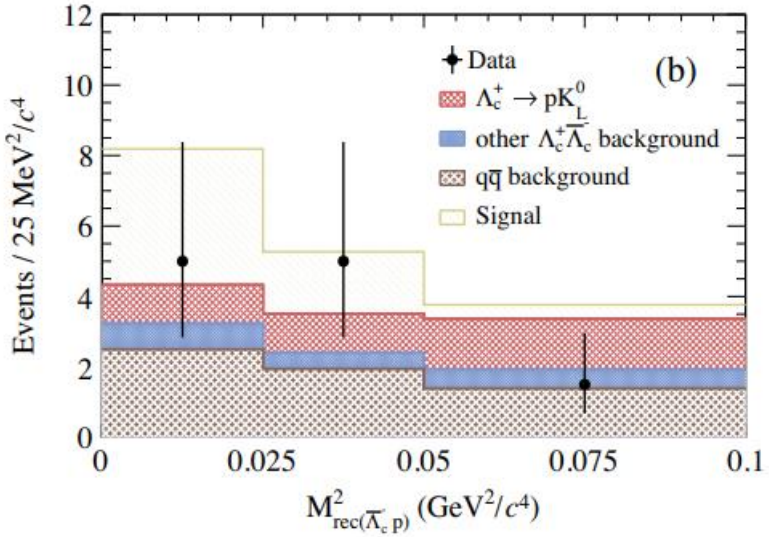
S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D **2**, 1285 (1970).

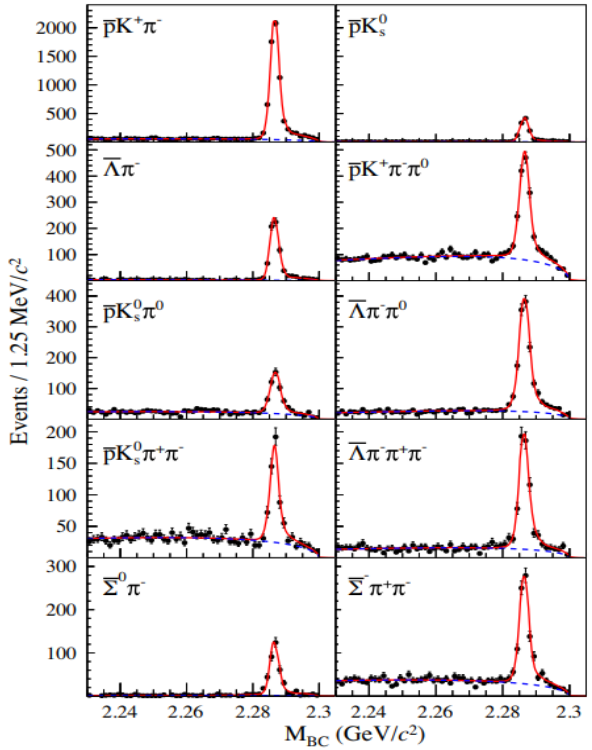
- Search for a massless dark photon is conducted using 4.5 fb^{-1} of data collected at CM energies between 4.6 and 4.699 GeV .











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

Summary

- Search for new physics beyond the SM is the top priority of the current experimental investigations.
- BESIII plays an active role on searches for a variety of dark matter particles.
- BESIII explored the possibility of both invisible and visible decays of dark matter candidates.
- BESIII excluded a large fraction of the parameter space of the new physics models beyond SM.
- Many more to come with recently collected 20 fb^{-1} of $\psi(3770)$ data.

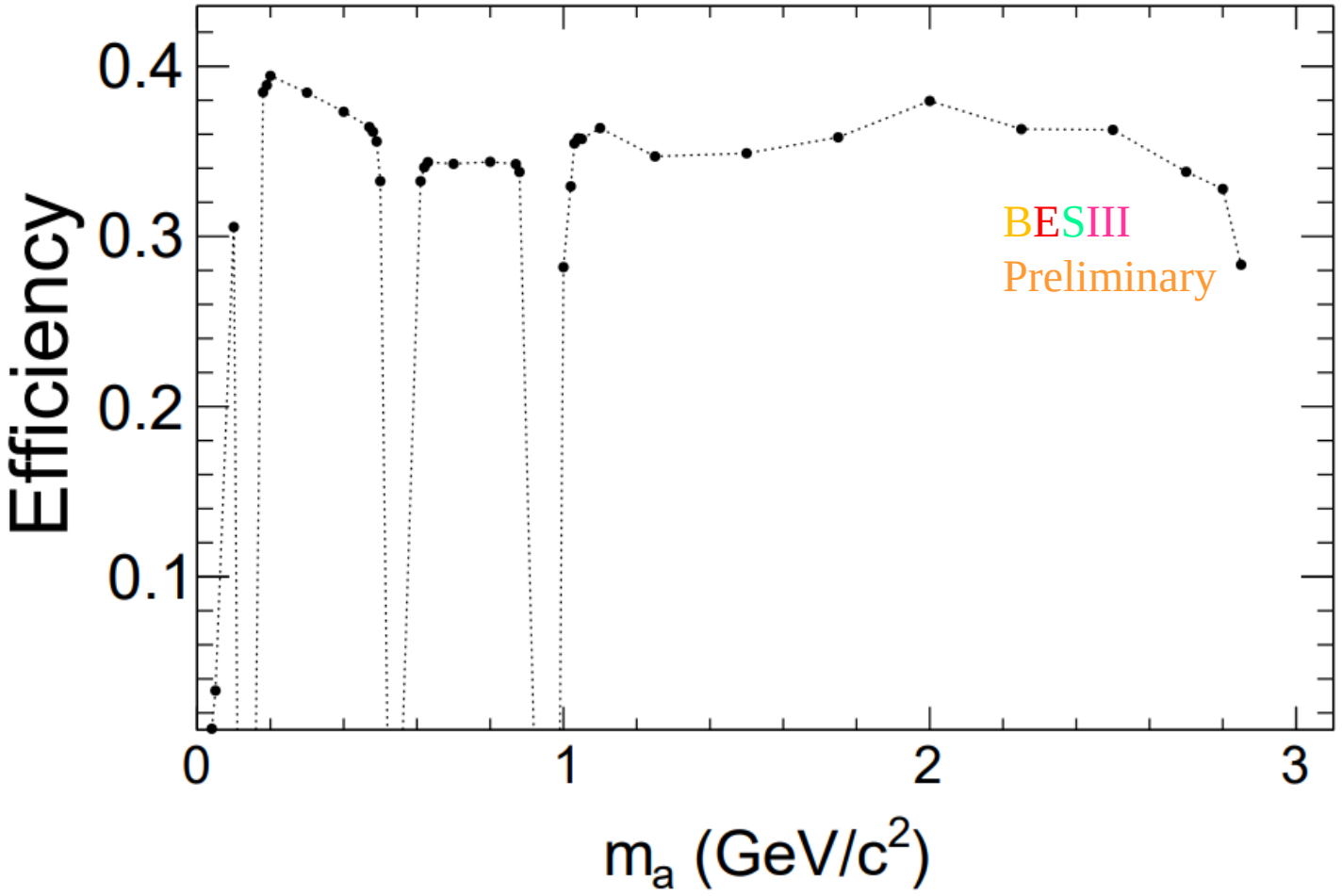
Thanks!

Back up Slide

Search for an Axion-like particle

BESIII
Preliminary

Signal selection efficiency



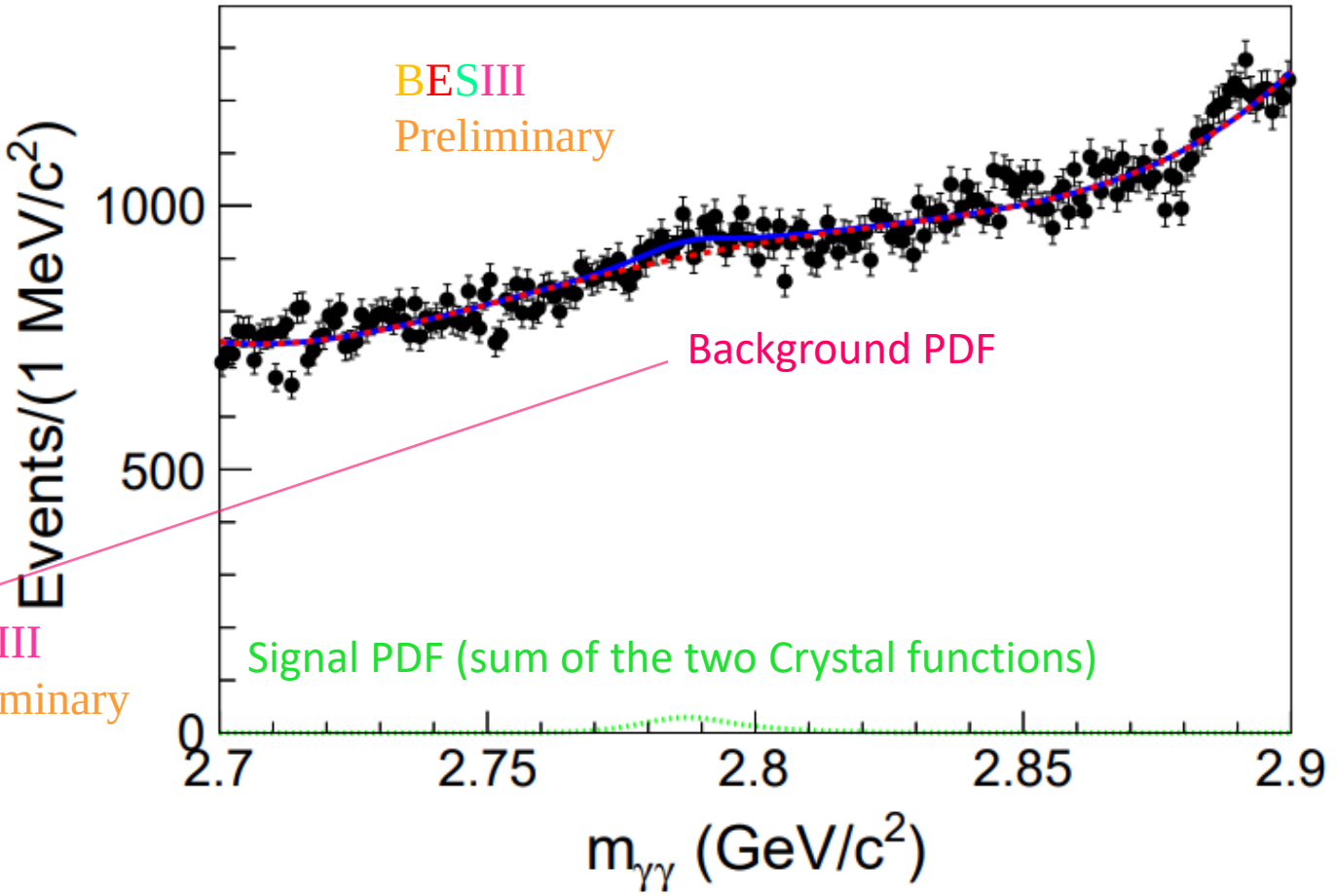
Search for an Axion-like particle

BESIII
Preliminary

Maximum Likelihood fit

Signal yield is extracted by performing a series of unbinned extended maximum likelihood fit to $m_{\gamma\gamma}$ distribution

m_a points (GeV/c^2)	$m_{\gamma\gamma}$ fit interval (GeV/c^2)	Order of Polynomial function
$0.18-0.42$	$0.16, 0.46$	4^{th}
$0.421-0.49$	$0.39, 0.51$	5^{th}
$0.61-0.88$	$0.59, 0.90$	5^{rd}
$1.02-1.099$	$1.0, 1.20$	5^{th}
$1.10-2.77$	$m_a-0.10, m_a+0.10$	3^{rd}
$2.772-2.85$	$2.70, 2.90$	4^{th}



Search for an Axion-like particle

BESIII Preliminary

Final sources of the systematic uncertainties

Source	Uncertainties	
	$J/\psi \to \gamma a$	Axion
Additive systematic uncertainty (events)		
Fit bias	9.2	9.2
Total	9.2	9.2
Multiplicative systematic uncertainties (%)		
Photon detection efficiency	0.6	0.6
χ^2_{4C}	2.3	2.3
ΔE_{ij}	0.1	0.1
$\Delta\phi_{ij}$	0.1	0.1
$B(J/\psi \to e^+e^-)$		0.5
Contamination of $e^+e^- \to \gamma a$		4.4
J/ψ counting	0.44	0.44
Total	2.4	5.1

BESIII Preliminary

We calculate the final systematic uncertainty as $\sqrt{\sigma_{add}^2 + (\sigma_{mult} \times N_{sig})^2}$.