Search for light dark particles at BESIII in China

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Outline

- The BESIII experiment in China
- Axion search results
- Dark photon search results
- Summary

3-Generations of experiments

BES→BESII→BESIII

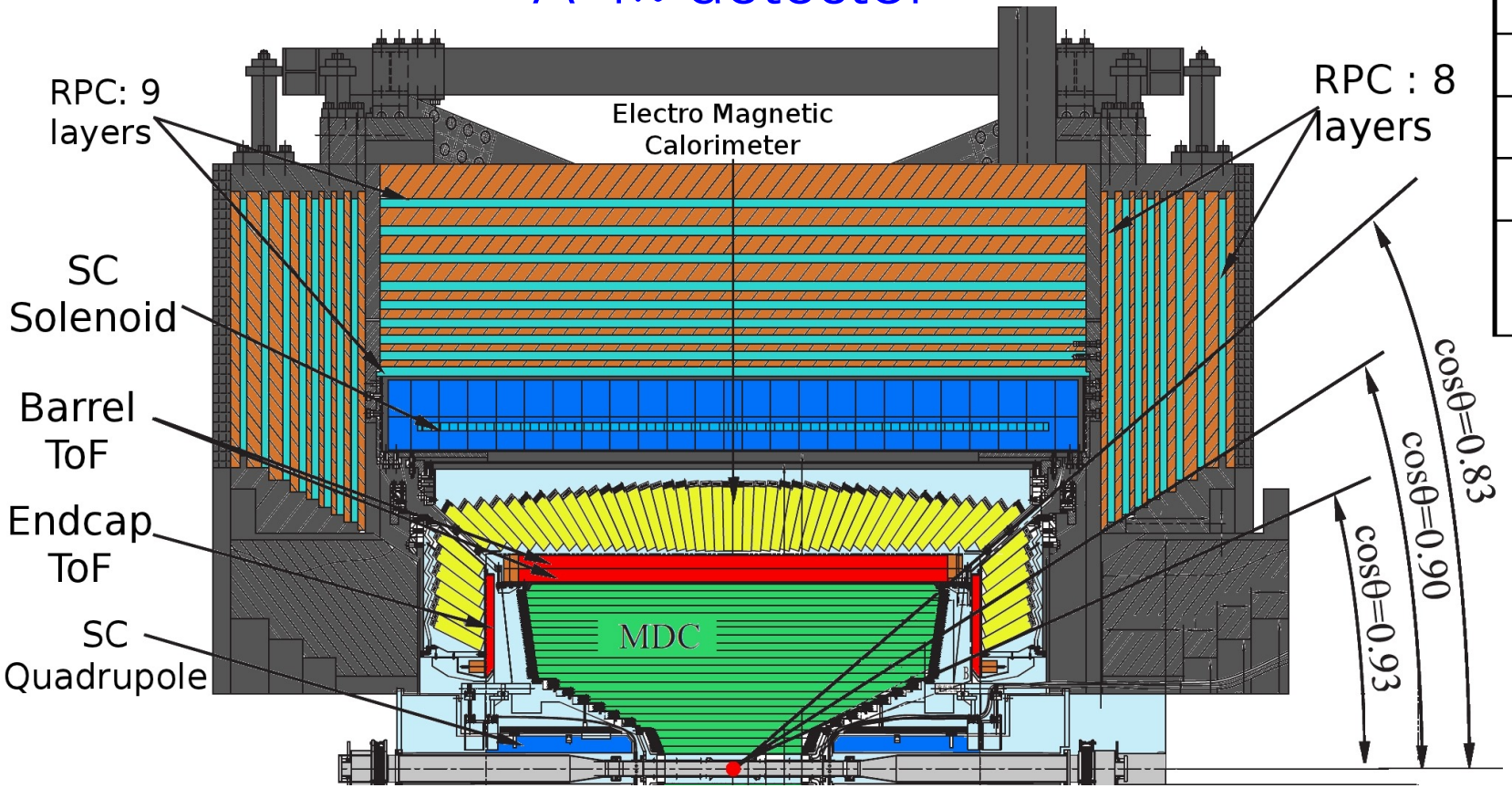
“An old newspaper picture”

1988年10月24日，邓小平同志“中国要在高科技领域占有一席之地”

The 3rd generation – BESIII

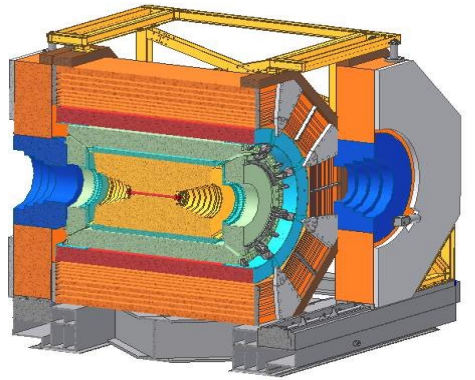
BEijing Spectrometer (BESIII)

A 4π detector



Exps.	MDC Spatial resolution	MDC dE/dx resolution	EMC Energy resolution
CLEO-c	110 μm	5%	2.2-2.4 %
BaBar	125 μm	7%	2.67 %
Belle	130 μm	5.6%	2.2 %
BESIII	130 μm	6%	2.5%

A modern general purposes multi-functional spectrometer!



BEPCII

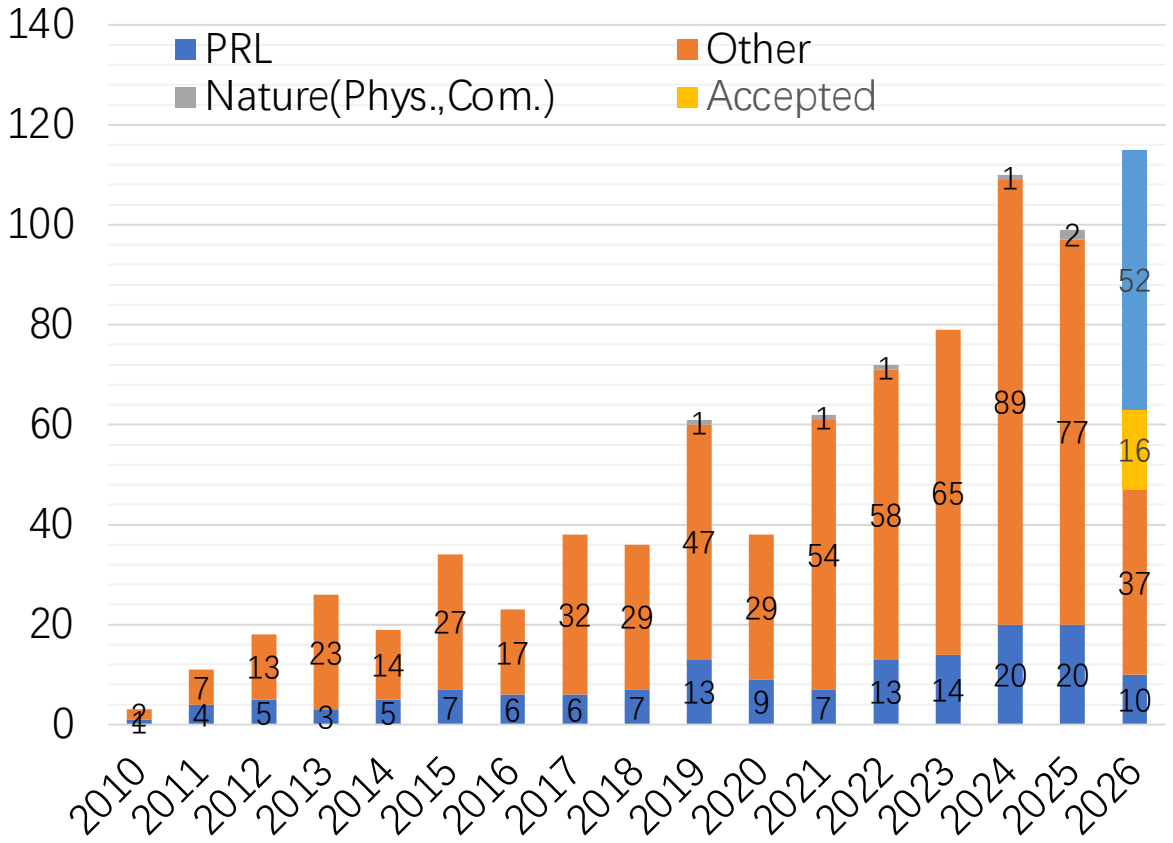
Beijing Electron Positron Collider (BEPCII)

- First collision in 2008 & physics run in 2009.
- $\sqrt{s}$ = 1.84 – 4.946 GeV (tau-charm factory).
- Design Luminosity $L_D=1\times10^{33}$ $cm^{-2}s^{-1}$ @ 3.773 GeV (2016 achieved; 2022-2024 achieved $1.1\times L_D$).
- Continuous injection (top-up mode).

> Among facilities of this kind, BEPCII currently has the highest luminosity in the world.
>
> —Luciano Maiani

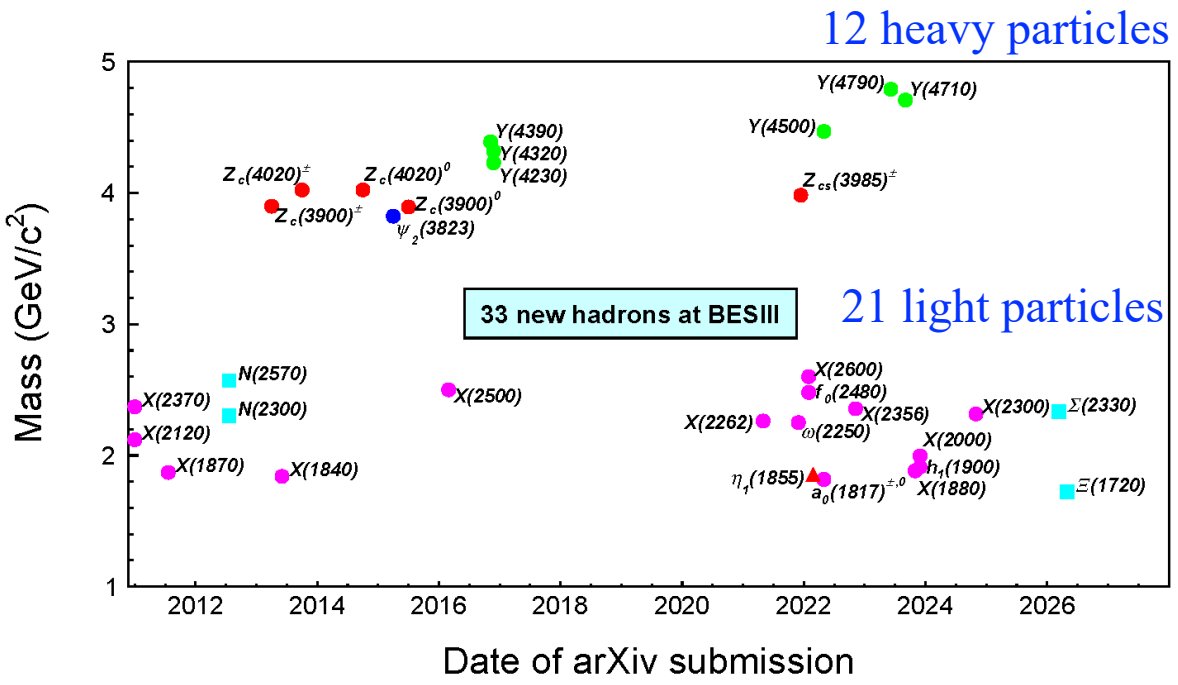
A productive experiment

Total: 844 = 776 + 16 (accepted) + 52 (submitted)



- 155 PRL+4 Nature(Physics)
- Fast growing (~100 / year)

Discover 33 new hadrons

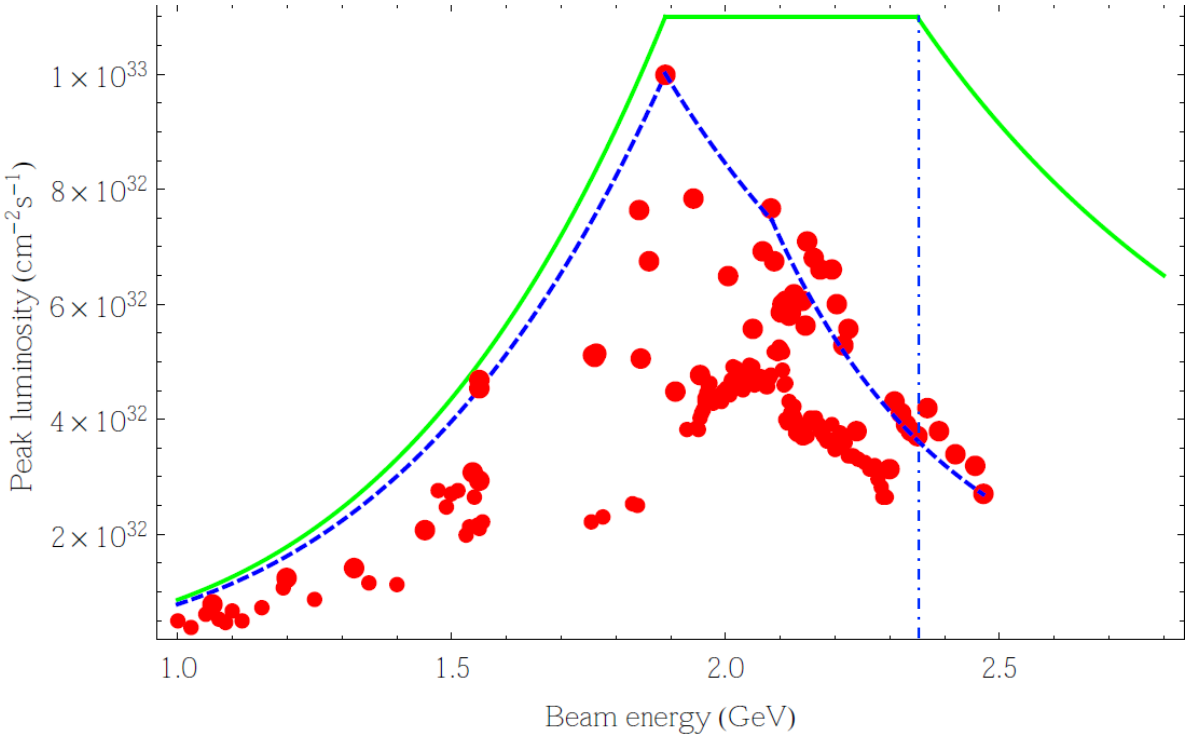


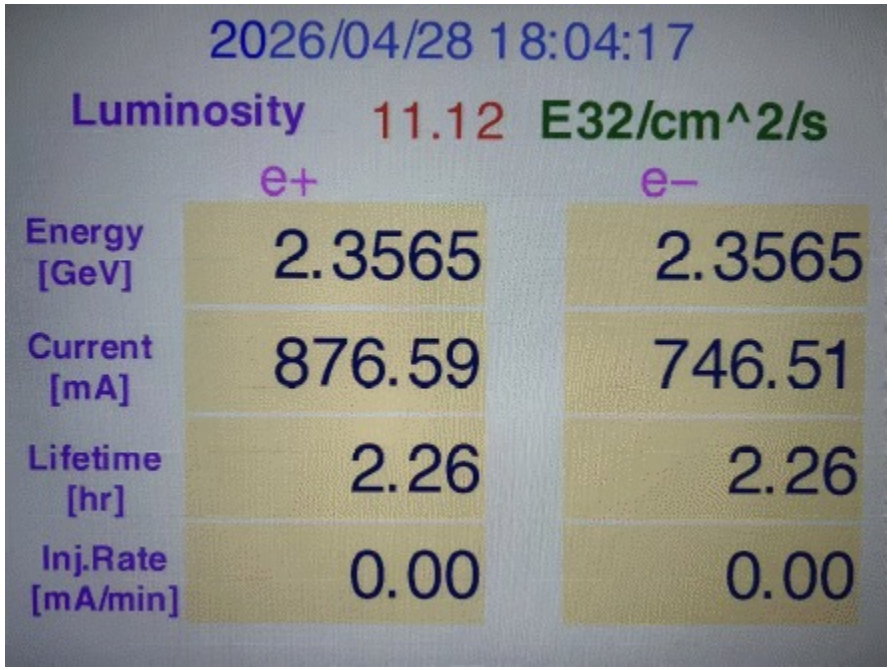
http://english.ihep.cas.cn/bes/re/pu/NewParticles/
Zhiqing Liu & Ryan Mitchell, Science Bulletin 68 (2023) 2148–2150

An upgraded machine commissioned

An upgraded machine BEPCII-U during 2023-2025

BEPCII-U vs. BEPCII



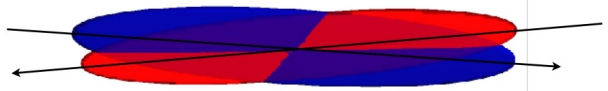


- Upgrade project approved by CAS in 2021.
- $\sqrt{s}$ up to 5.6 GeV; optimized @ 3.773 – 4.7 GeV.
- Luminosity enhanced by a factor of 3 @ 4.7 GeV.
- CGEM inner draft chamber installed.

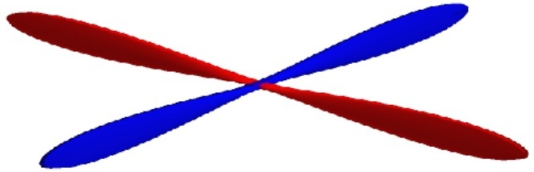
The new machine is ready to run !

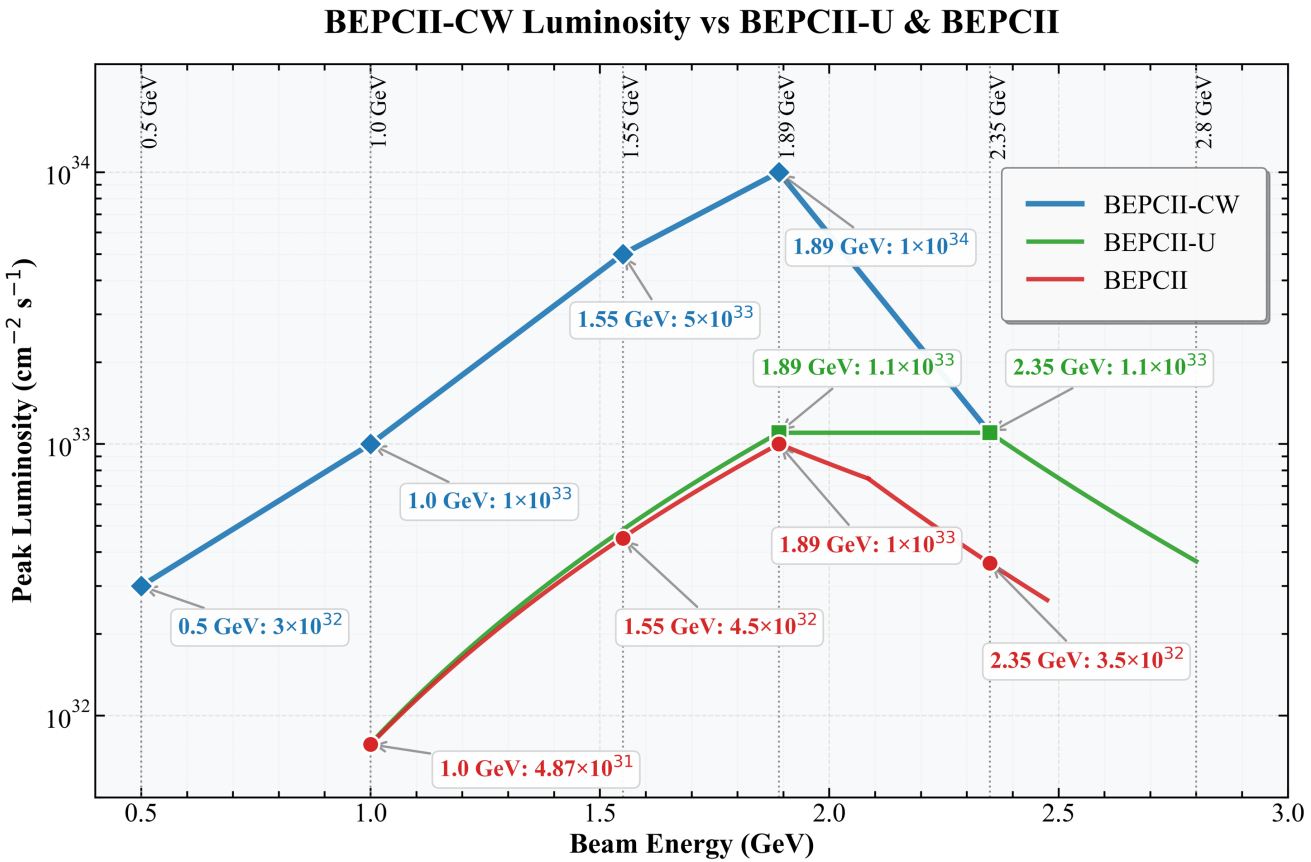
Our future – a crab-waist machine

Current BEPCII/U bunch



BEPCII crab-waist bunch





- Luminosity may increase by ×10 below 3.773 GeV.
- Operation below e+e- CM energy 1 GeV is enabled.
- Big chance for $(g\text{-}2)_\mu$, dark sector search etc.

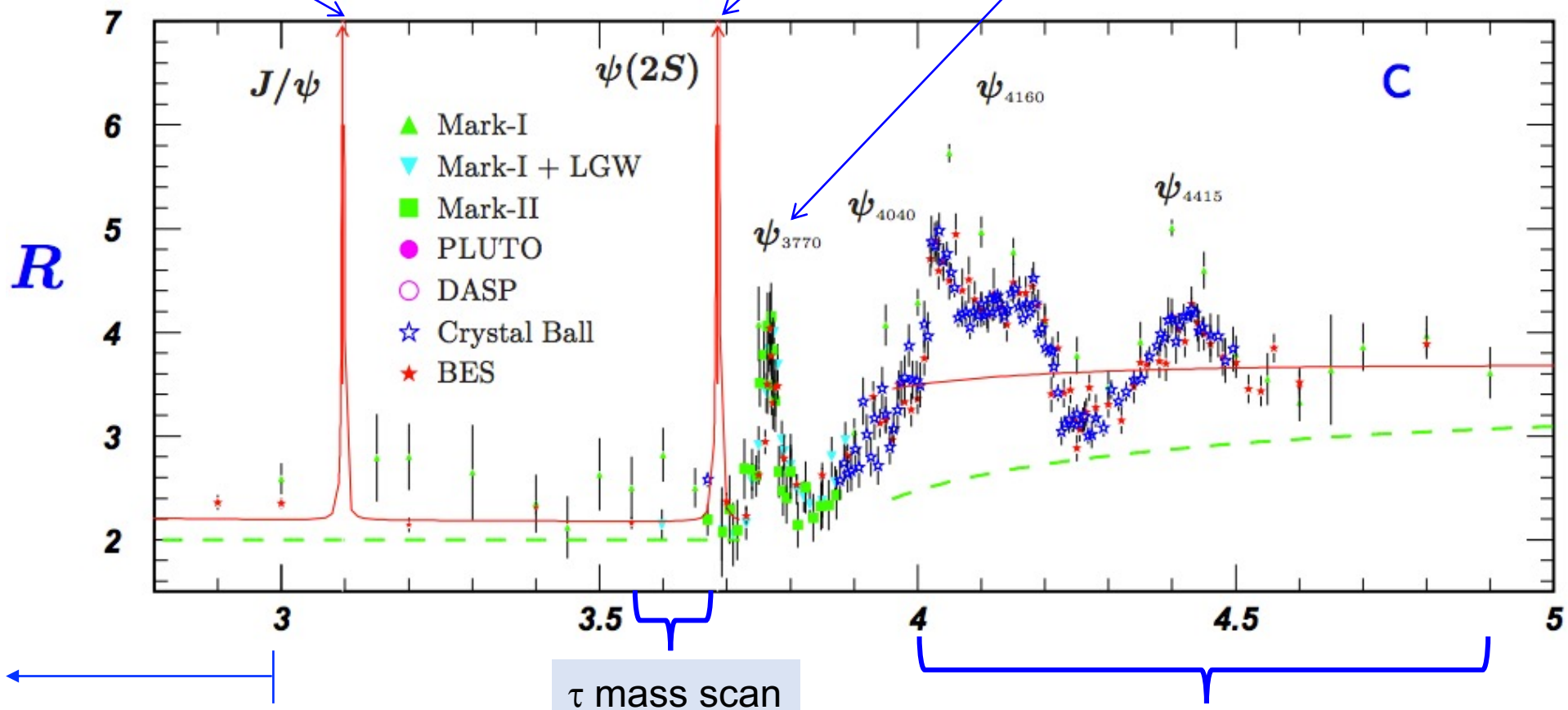
Search for dark sectors with our data

Data – On resonance & Scan

10 B J/ψ events: light hadron, hyperon

2.7 B ψ(2S) events: charmonium

20 fb^{-1} ψ(3770): D mesons



τ mass scan

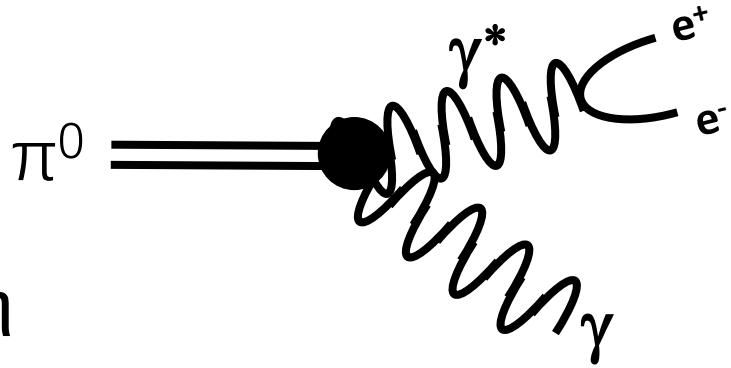
Low energy scan: R-value, baryon pair

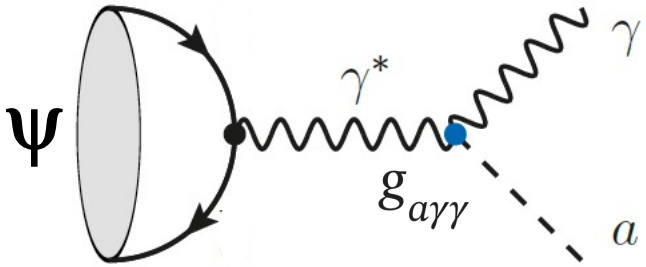
High luminosity scan: XYZ, Ds, Λ_c…

Sources & methods

Meson decay

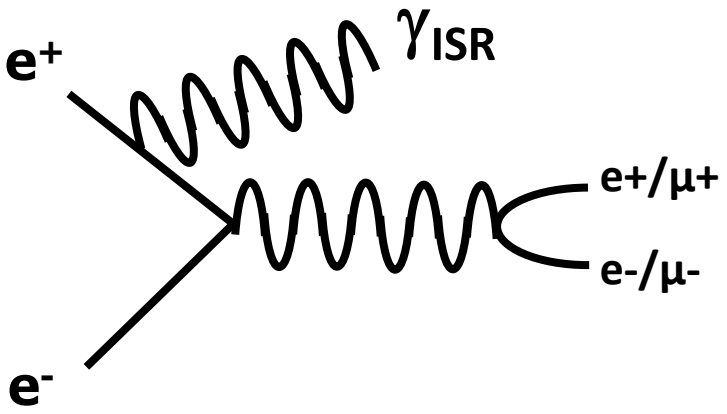
- $\eta/\pi^0 \to \gamma\,\gamma' \to \gamma\, e^+e^-$
- WASA, PHENIX, NA48
- BABAR & Belle/Υ(3S),B; KLOE/ϕ,η
- **BESIII / ψ, η, η'**

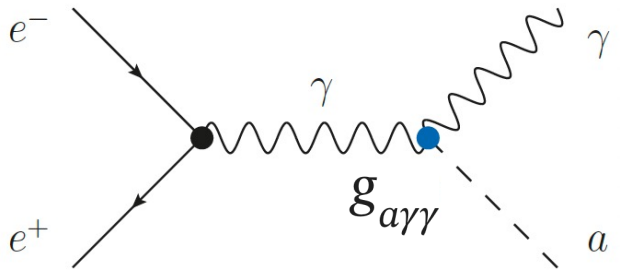




Initial State Radiation

- $e^+e^- \to \gamma\,\gamma' \to \gamma\, e^+e^-/\mu^+\mu^-$
- BABAR, KLOE, BESIII

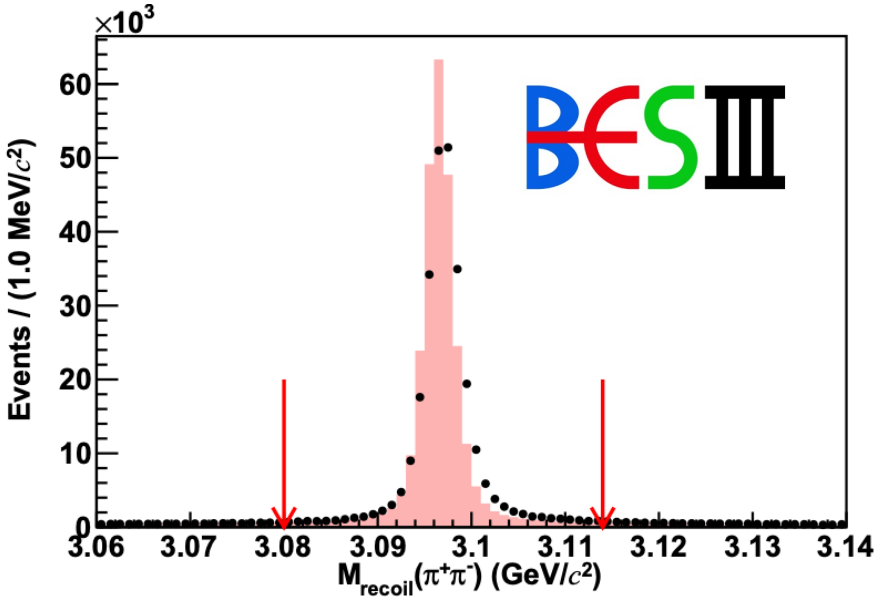




Search for Axion in J/ψ radiative decay

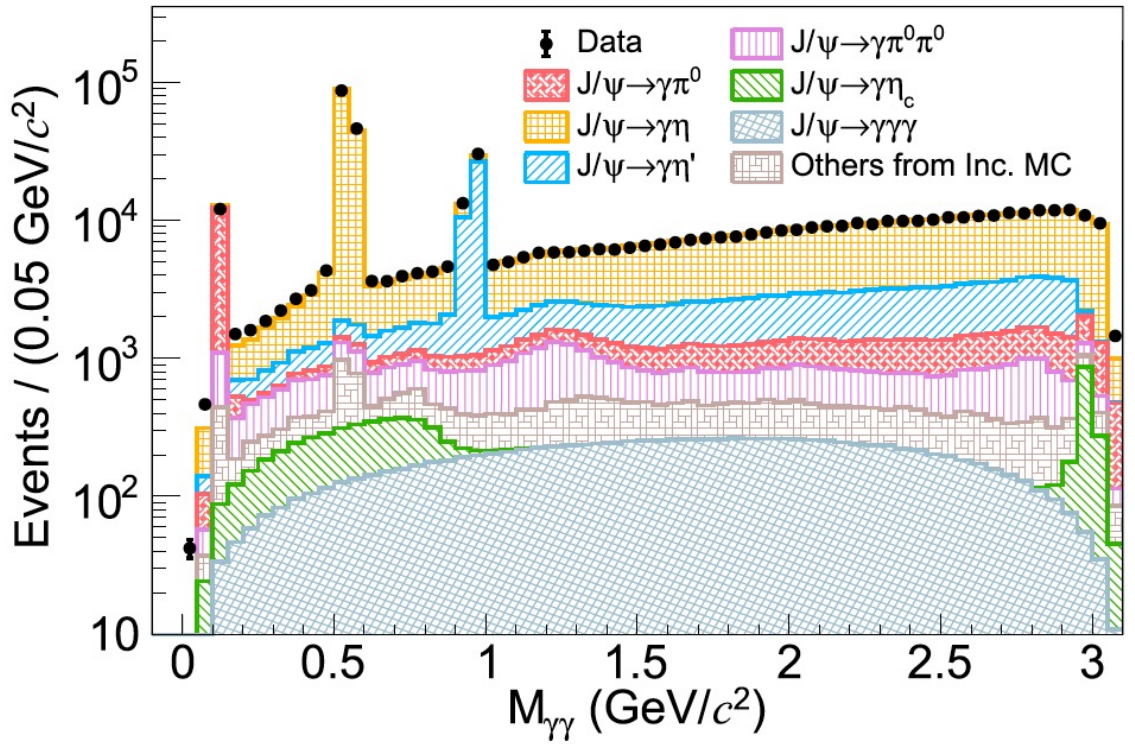
$\psi(2S) \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \gamma\, a, a \rightarrow \gamma\gamma$

- *Big sample (2.7 Billion × 35%~0.9 Billion)*
- *Relative clean background environment*
- *Avoid pollution from non-resonant axion production $e^+e^- \rightarrow \gamma\, a$ (model-independent)*



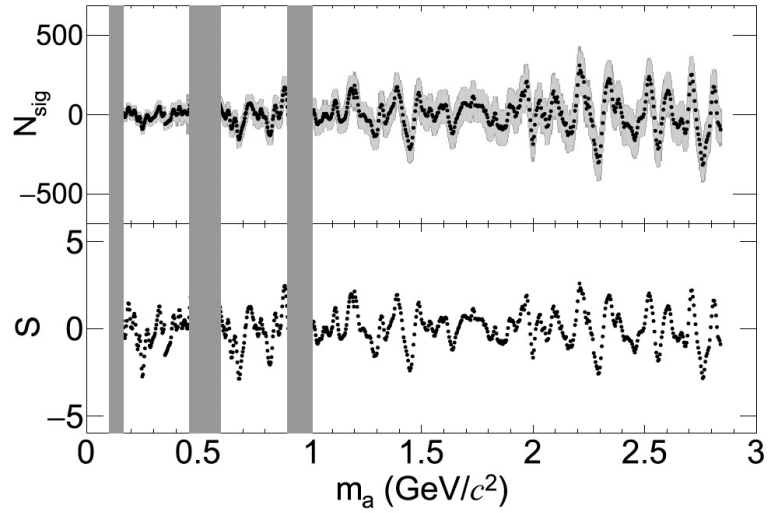
$M_{recoil}(\pi^+\pi^-)^2=(P_{e+e-} - P_{\pi+\pi-})^2$

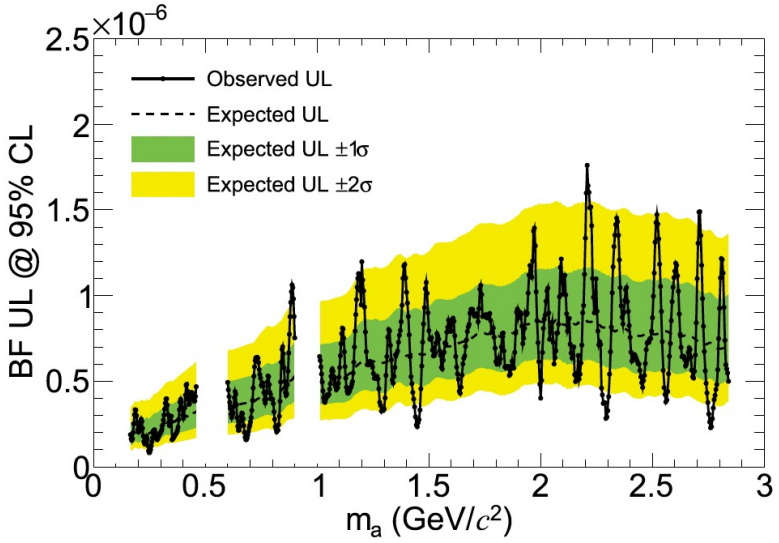
PLB 838 (2023) 137698



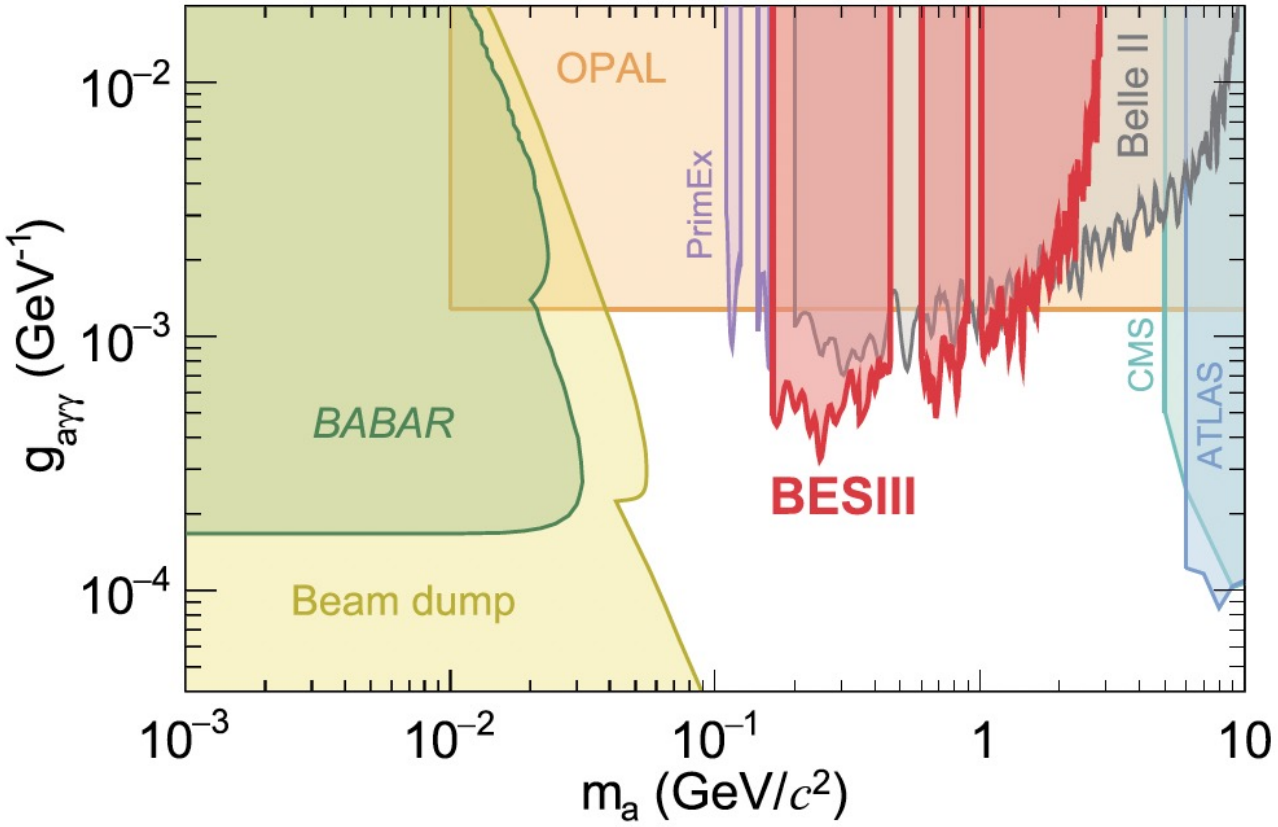
- Clear light-pseudo particles ($\gamma\pi^0$, $\gamma\eta$ and $\gamma\eta'$) → calibration and validations
- Scan $0.165<m_a<2.48$ GeV/c² in a 3 MeV step

Search for Axion in J/ψ radiative decay





PLB 838 (2023) 137698



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

B(J/ψ→γa)@95% C.L is obtained [assuming B(a →γγ)=100%]

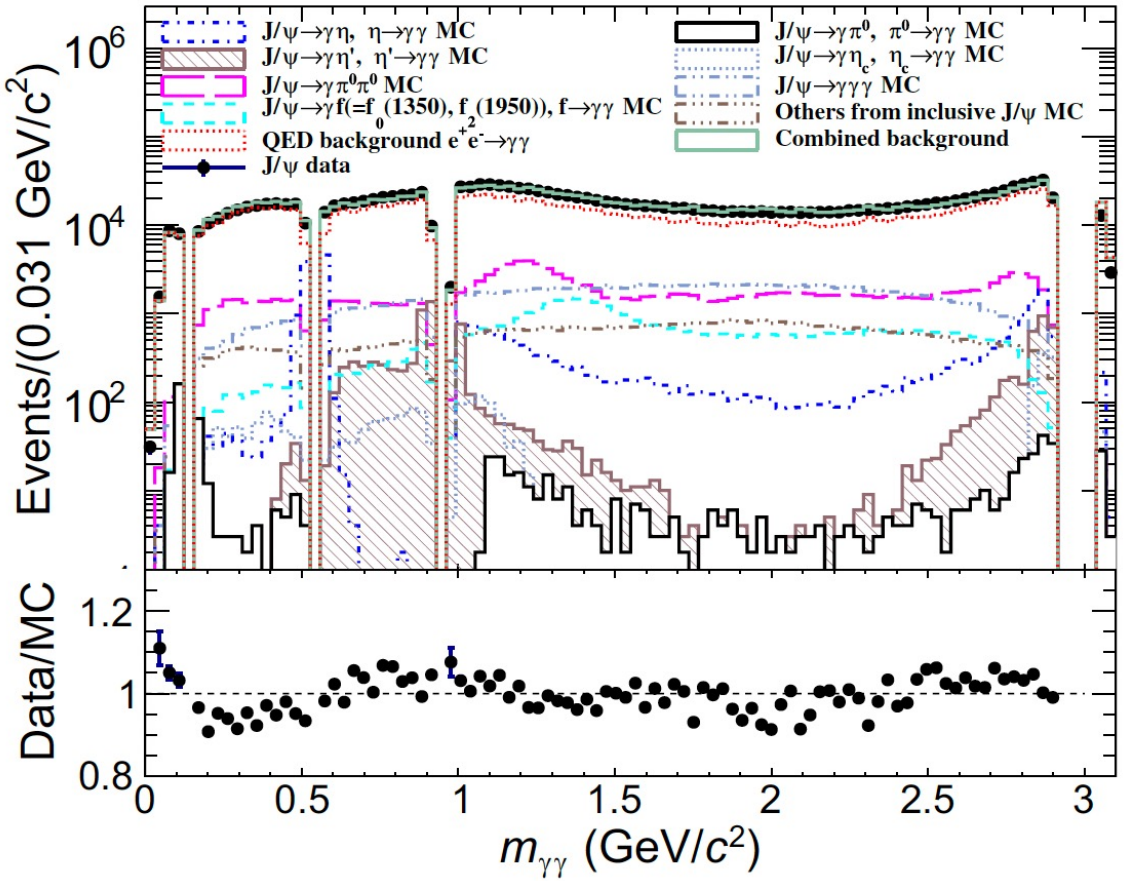
Search for Axion in J/ψ radiative decay

$J/\psi \rightarrow \gamma\, a,\ a \rightarrow \gamma\gamma$

- *Huge sample (10 Billion events)*
- *More complicated background (pure neutral final state…QED background dominant…)*
- *Possible non-resonant axion production $e+e-\rightarrow\gamma\, a$*
- *Benefit from good beam resolution, 4.4% of resonant contribution → negligible*

BESIII

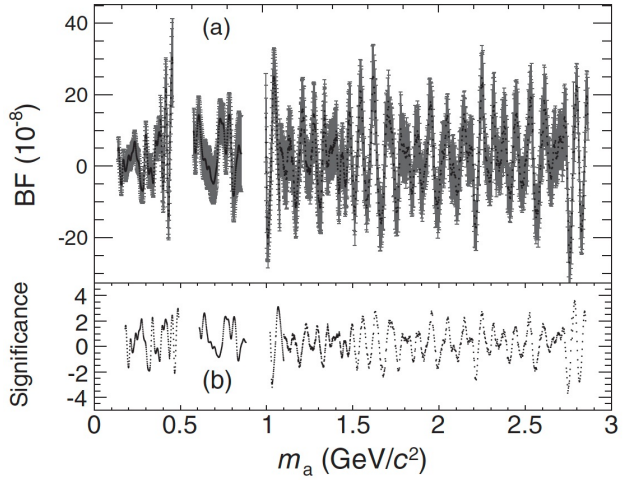
PRD 110, L031101 (2024)

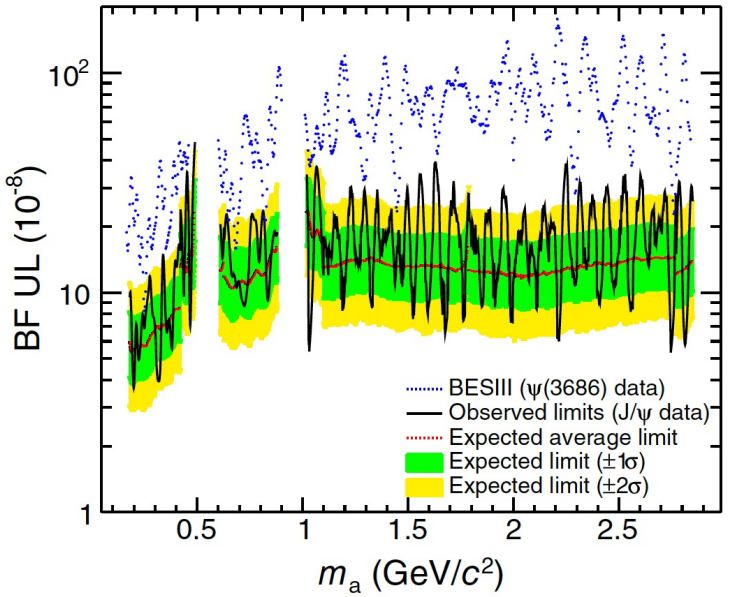


m_a range (GeV/c^2)	$m_{\gamma\gamma}$ fit interval (GeV/c^2)	Polynomial function order
0.180–0.420	0.16, 0.46	Fourth
0.421–0.490	0.39, 0.51	Fifth
0.610–0.880	0.59, 0.90	Fifth
1.020–1.099	1.00, 1.20	Fifth
1.100–2.770	$m_a - 0.10$, $m_a + 0.10$	Third
2.772–2.850	2.70, 2.88	Fourth

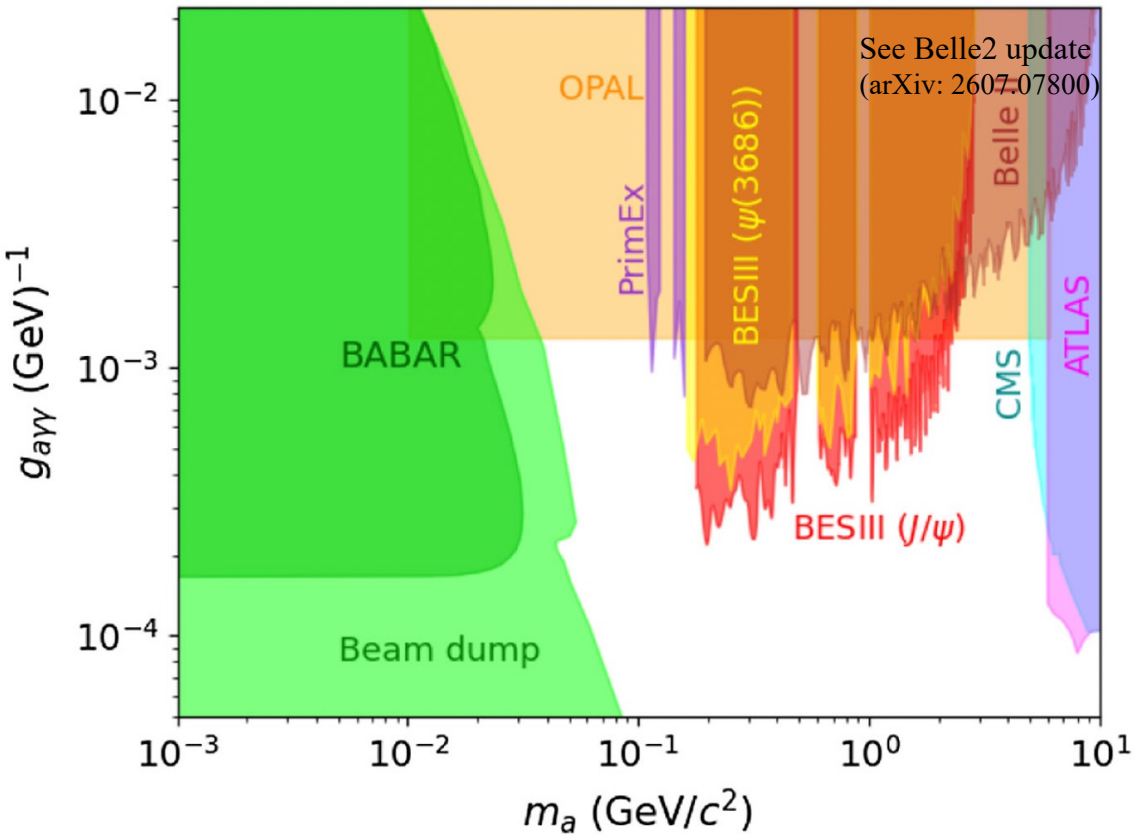
Scan m($\gamma\gamma$) in 1-2 MeV step to search for an axion signal

Search for Axion in J/ψ radiative decay





PRD 110, L031101 (2024)



$$\mathcal{B}(J/\psi \to \gamma a) \times \mathcal{B}(a \to \gamma\gamma) = \frac{N_{\rm sig}}{\epsilon N_{J/\psi}}$$

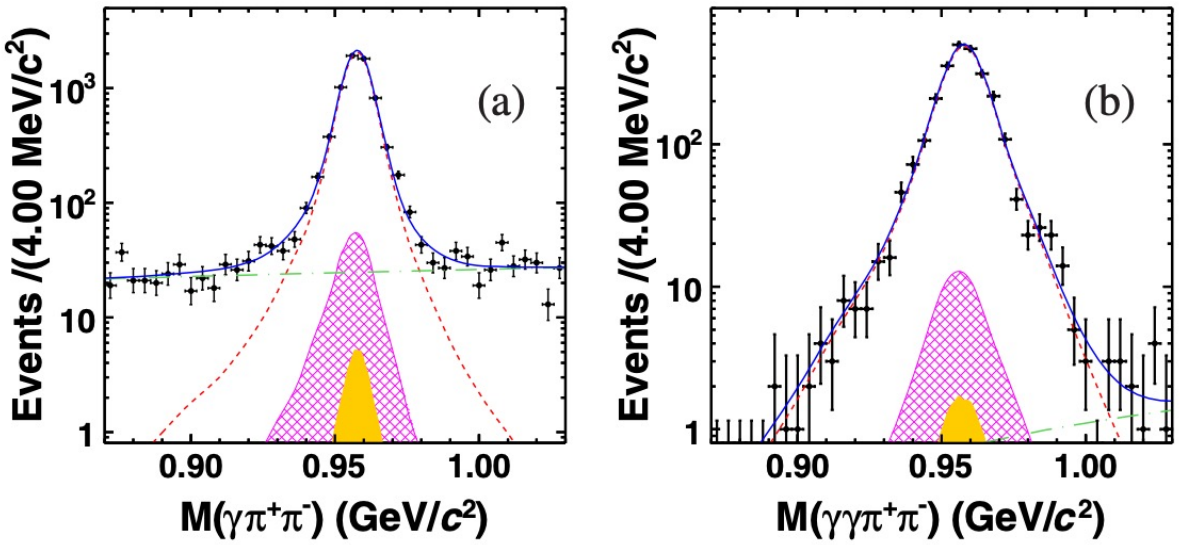
$$\frac{\mathcal{B}(J/\psi \to \gamma a)}{\mathcal{B}(J/\psi \to e^+e^-)} = \frac{m_{J/\psi}^2}{32\pi\alpha} g_{a\gamma\gamma}^2 \left(1 - \frac{m_a^2}{m_{J/\psi}^2}\right)^3$$

$B(J/\psi \to \gamma a)$@95% C.L is obtained [assuming $B(a \to \gamma\gamma)$=100%]

Search for dark photon in J/ψ→γ'η'

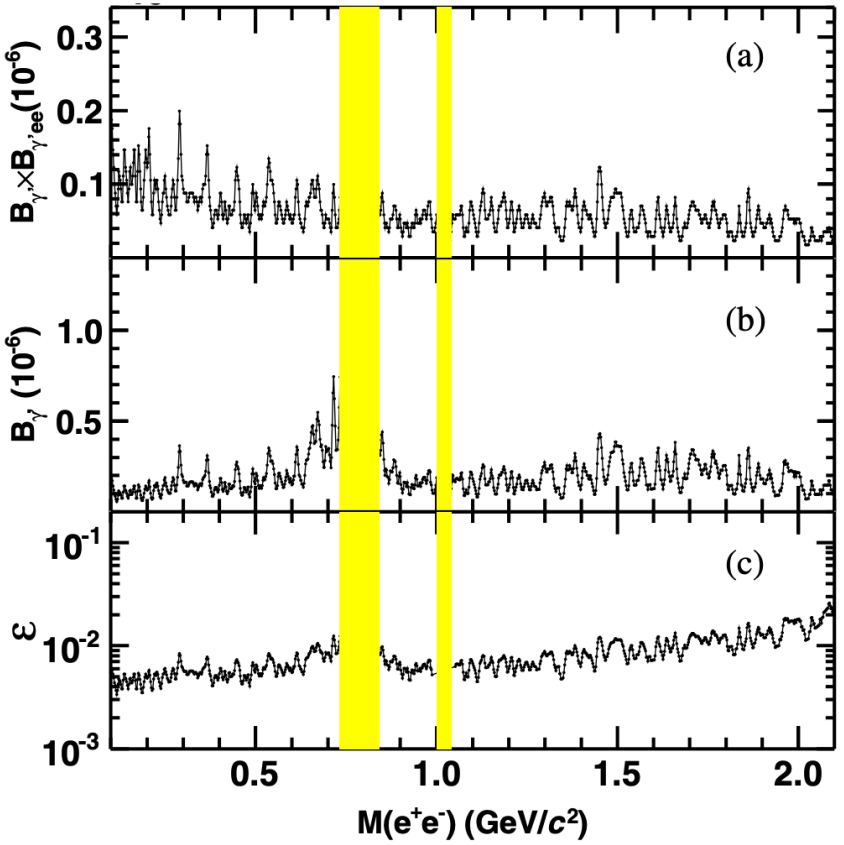
- N(J/ψ)=1.3 Billion
- Br(J/ψ→γη') ~ $5*10^{-3}$
- Yield ~6.5 Million
- Update with 10 Billion ongoing
- J/ψ→e+e-η'

PRD 99, 012013 (2019)



6443 events

2498 events



$\varepsilon < [3.4\times10^{-3}, 2.6\times10^{-2}]$

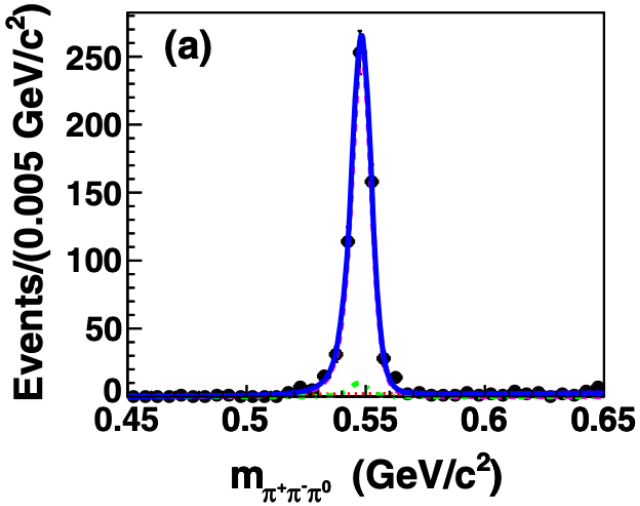
JHEP07(2009)051

$$\frac{\mathcal{B}(J/\psi \to \eta'\gamma')}{\mathcal{B}(J/\psi \to \eta'\gamma)} = \varepsilon^2 |F(m_{\gamma'}^2)|^2 \frac{\lambda^{3/2}(m_{J/\psi}^2, m_{\eta'}^2, m_{\gamma'}^2)}{\lambda^{3/2}(m_{J/\psi}^2, m_{\eta'}^2, 0)}$$

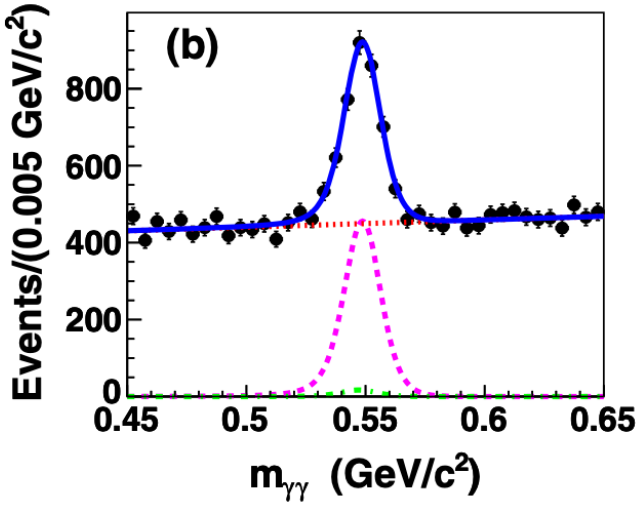
Search for dark photon in J/ψ→γ'η

- N(J/ψ)=1.3 Billion
- Br(J/ψ→γη) ~ 1*10^{-3}
- Yield ~1.3 Million
- Update to 10 Billion ongoing
- J/ψ→e+e-η

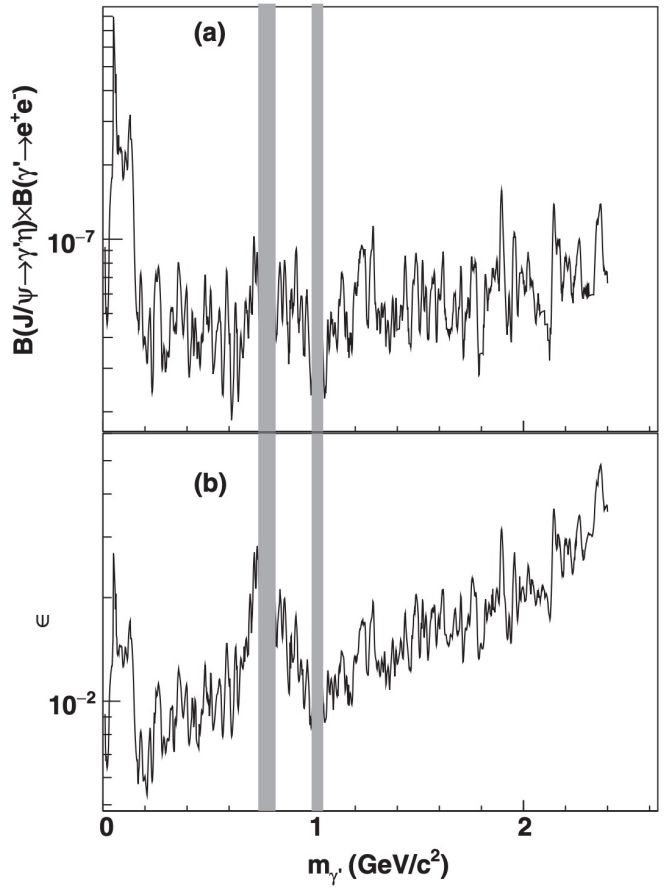
PRD 99, 012006 (2019)



595 events



1877 events



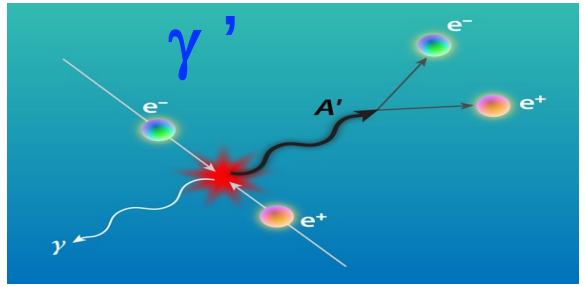
$\varepsilon < [10^{-2}, 10^{-3}]$

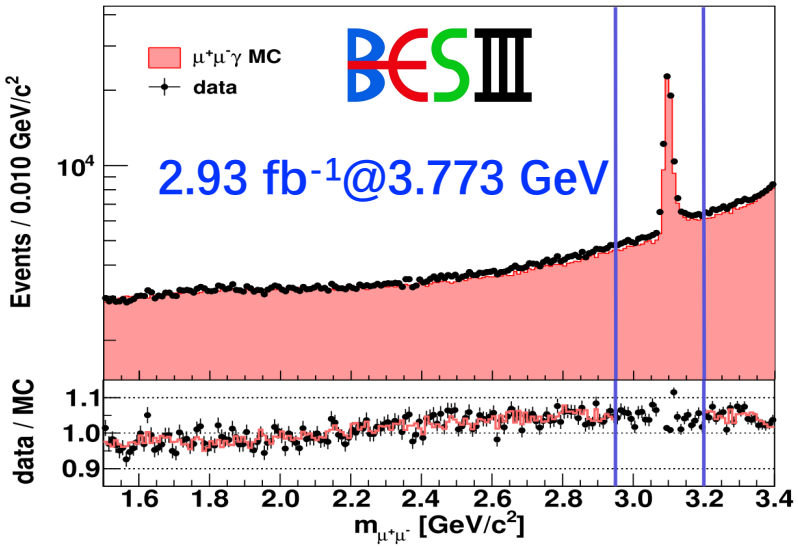
JHEP07(2009)051

$$\frac{\mathcal{B}(J/\psi \to \eta'\gamma')}{\mathcal{B}(J/\psi \to \eta'\gamma)} = \varepsilon^2 |F(m_{\gamma'}^2)|^2 \frac{\lambda^{3/2}(m_{J/\psi}^2, m_{\eta'}^2, m_{\gamma'}^2)}{\lambda^{3/2}(m_{J/\psi}^2, m_{\eta'}^2, 0)}$$

Dark photon via ISR $e^+e^-/\mu^+\mu^-$

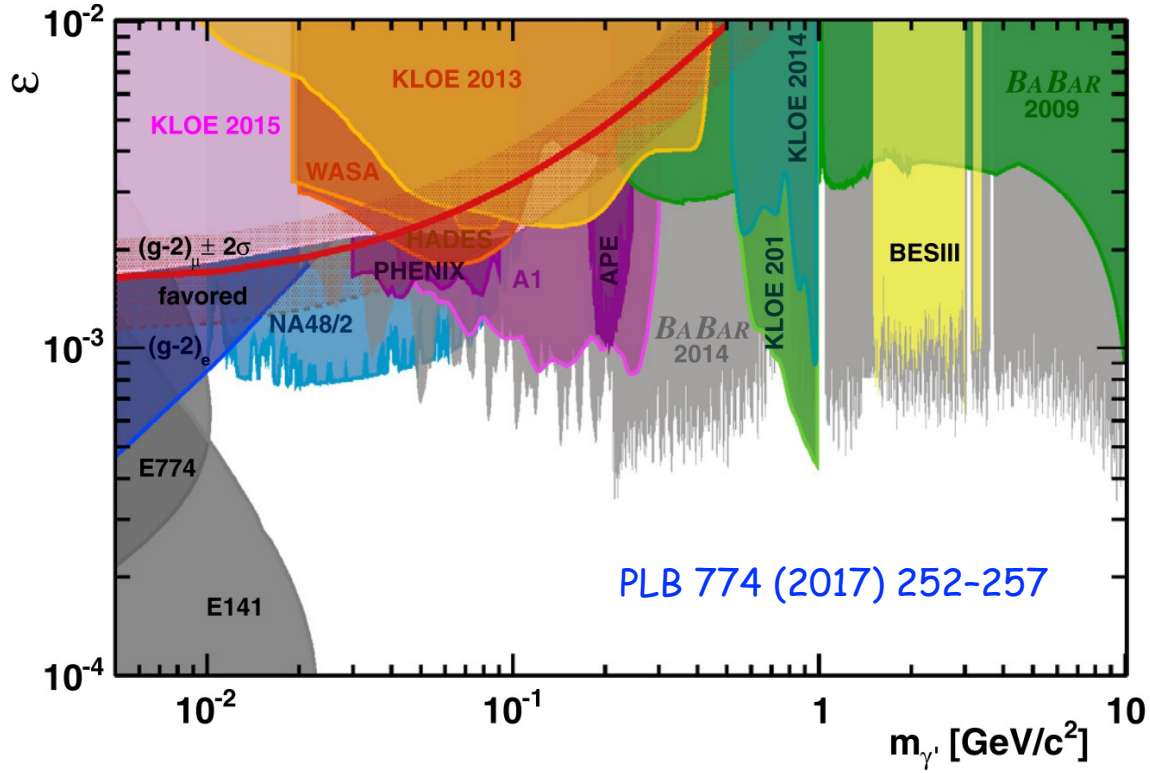
https://physics.aps.org/articles/v7/115





- Untagged photon method
- ISR μ+μ− events dominate

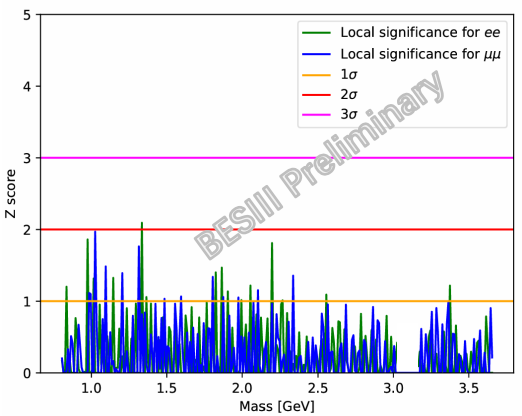
- BaBar measurement [PRL113, 201801 (2014)]
- Coupling strength exclusion limit @ 90% C.L.
- $\varepsilon < [10^{-3}, 10^{-4}]$
- Comparable to BABAR in same mass region

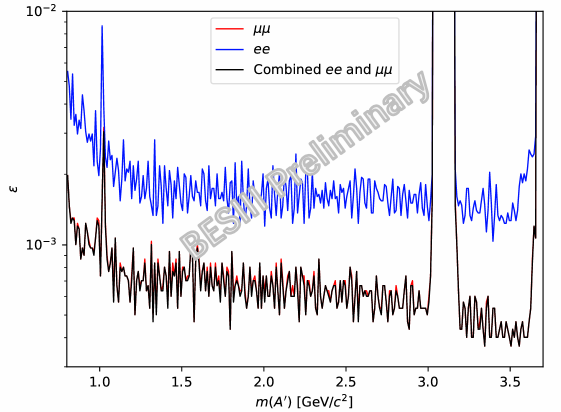


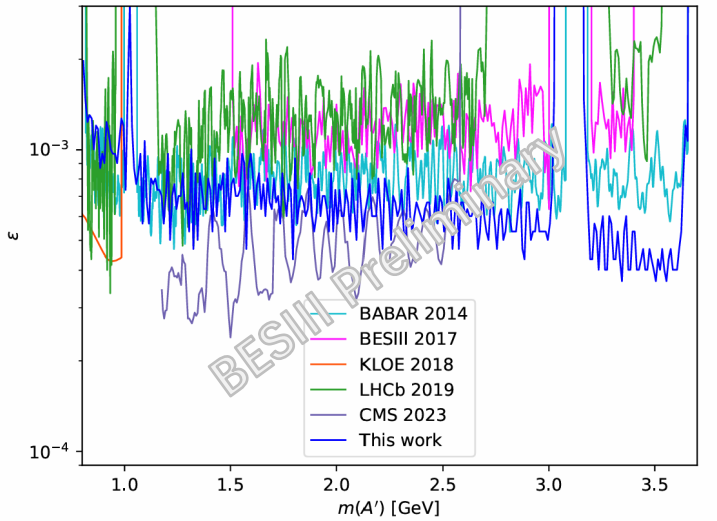
$$\Gamma_{ll} = \frac{\alpha\varepsilon^2}{3m_{\gamma'}^2}(m_{\gamma'}^2 + 2m_l^2)\sqrt{m_{\gamma'}^2 - 4m_l^2}$$

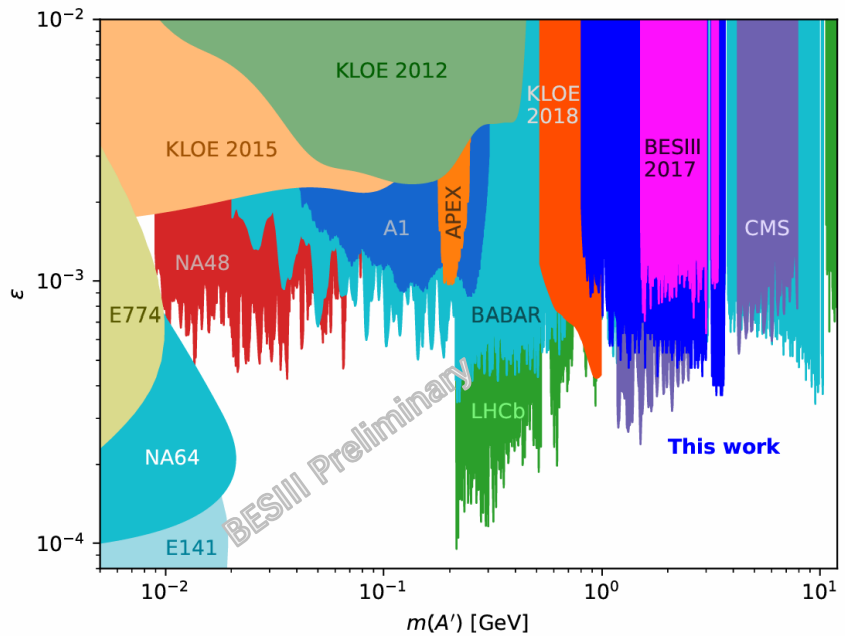
$$\Gamma_{tot} = \Gamma_{ee} + \Gamma_{\mu\mu} \cdot (1 + R(\sqrt{s})) ,$$

Dark photon via ISR $e^+e^-/\mu^+\mu^-$





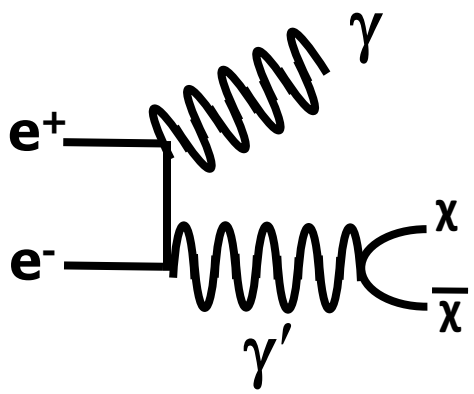




- A full update of dark photon search in di-lepton mass spectra using ISR with 20 fb^{-1} data @ 3.773 GeV
- Semi-blinded analysis and cross-checks:
  - BESIII 2017 analysis of $2.9\ \mathrm{fb}^{-1}$
  - $s + b$ likelihood vs. CL_s methods
- $m = 0.8 - 3.66\ \mathrm{GeV}$
- No globally significant dark photon signal
- ε exclusion limits improve upon previous BESIII, BABAR, and LHCb limits
  ⇒ complements CMS limits for
  $m = 2.54\ -\ 3.64\ \mathrm{GeV}$

Dark photon invisible decay

Consider now: 2M(χ) < M(γ'), dark Photon decays dominantly into Light Dark Matter (LDM) $\alpha_D >> \alpha\varepsilon^2$!



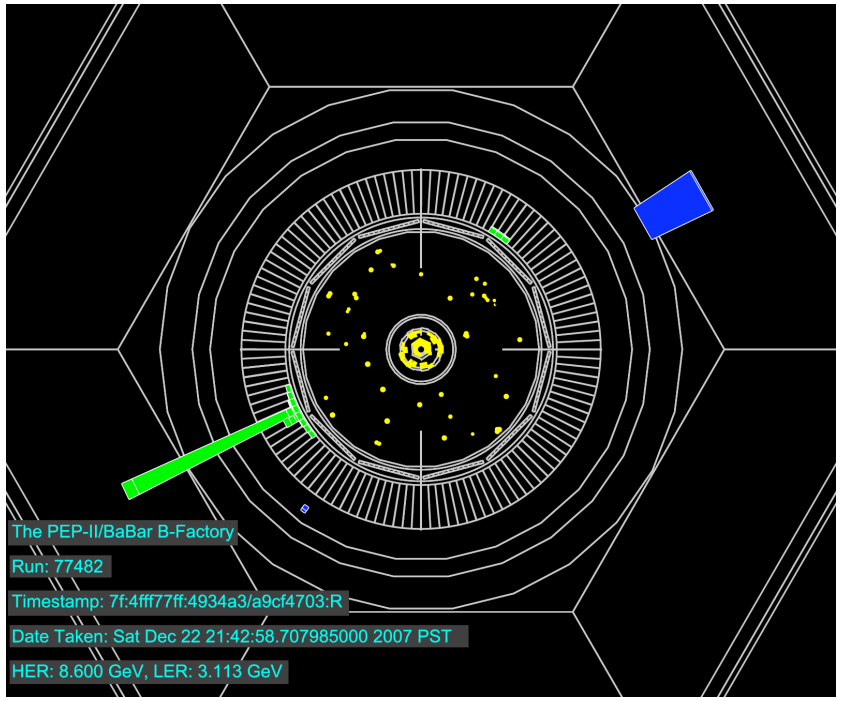
Strategy: Missing mass (energy) measurement

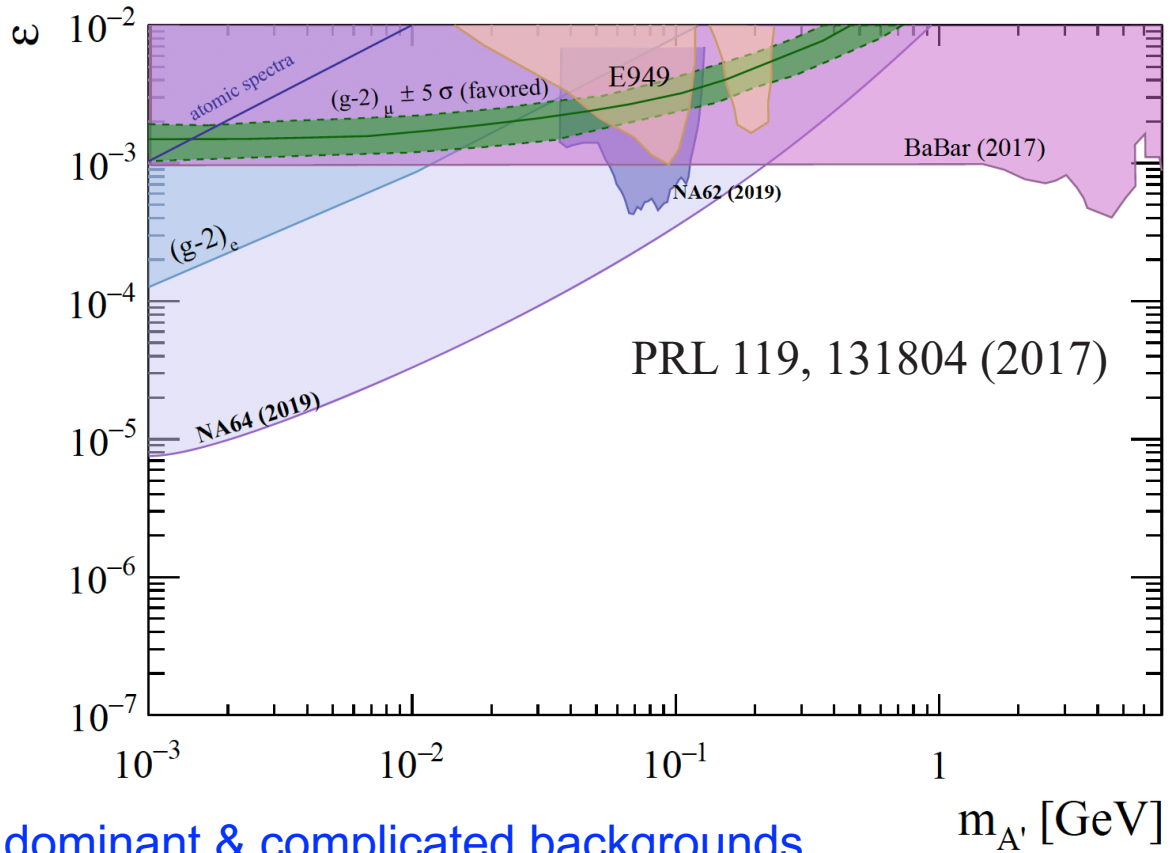
$$M_{miss}^2 = (P^4_{e-} + P^4_{e+} - P^4_{\gamma})^2$$

Invisible decay

For single photon signals, usually complicated background & active trigger needed !

One photon penetrate the calorimeter in the BABAR detector

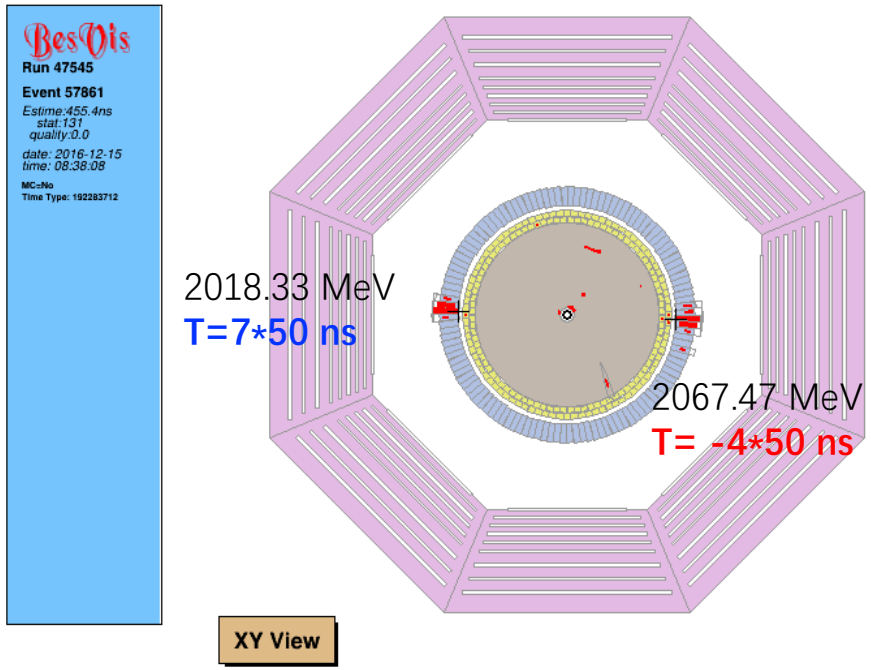


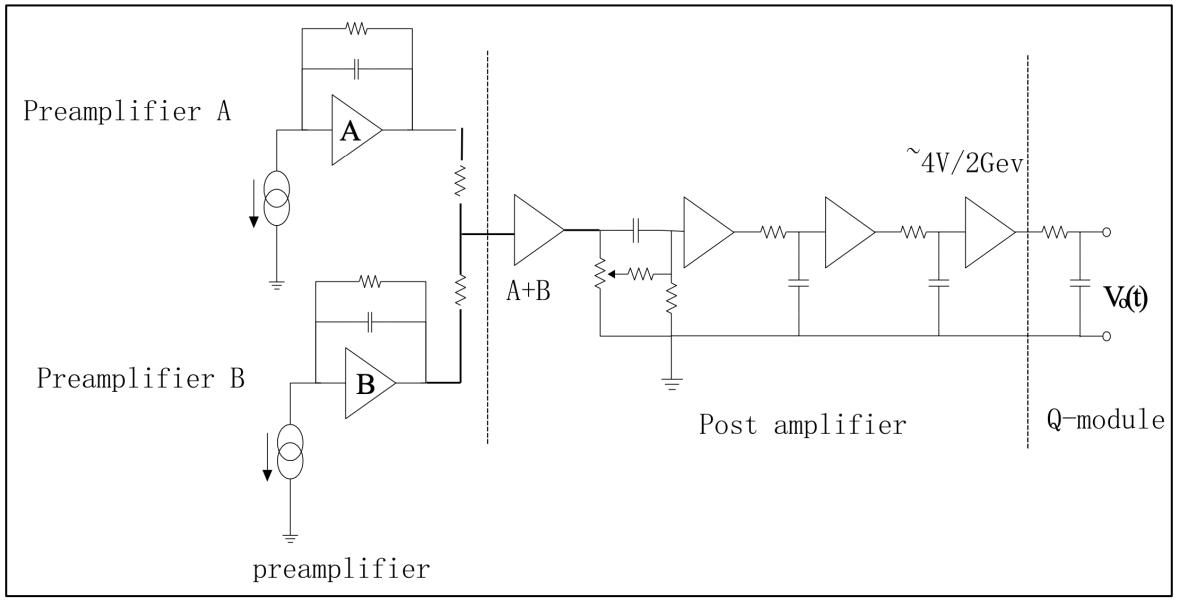


- $e^+e^- \rightarrow \gamma\gamma$ events are dominant & complicated backgrounds
- 53 fb^{-1}, BaBar achieve exclusion limit $\varepsilon < [10^{-4}, 10^{-3}]$

BESIII invisible dark photon decay

- Event start time not precise
- Induce $e^+e^- \rightarrow \gamma\gamma$ background

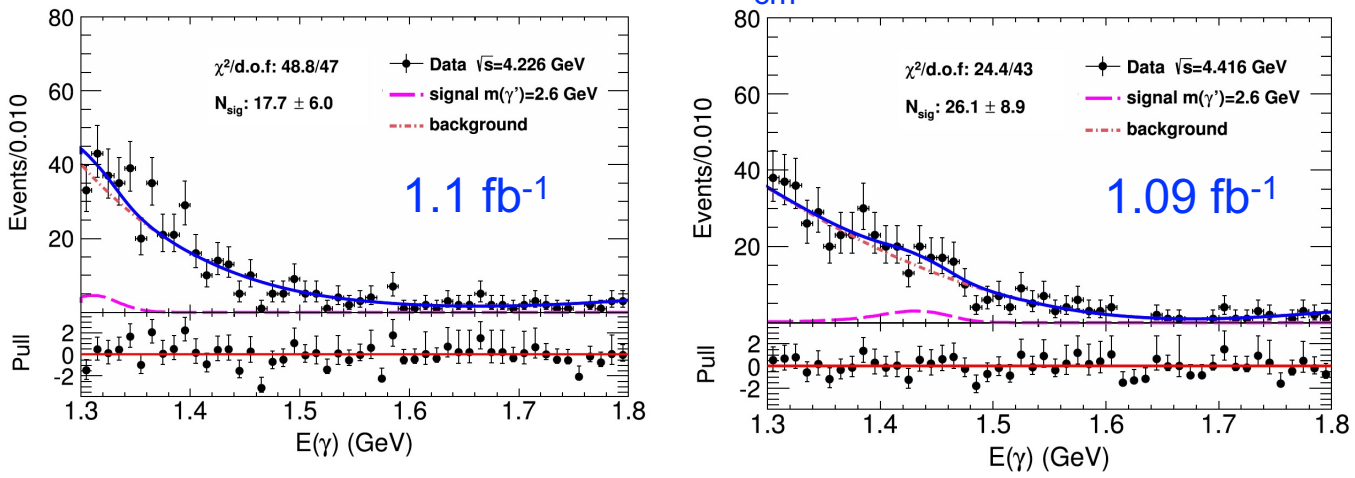


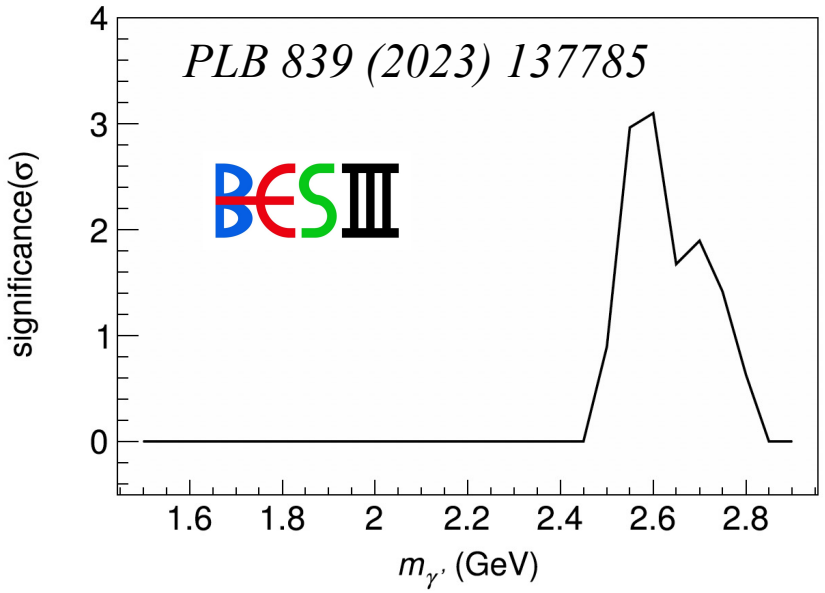


- EMC electronics saturate for >2 GeV photon
- Can not explore low mass region (→high energy γ)

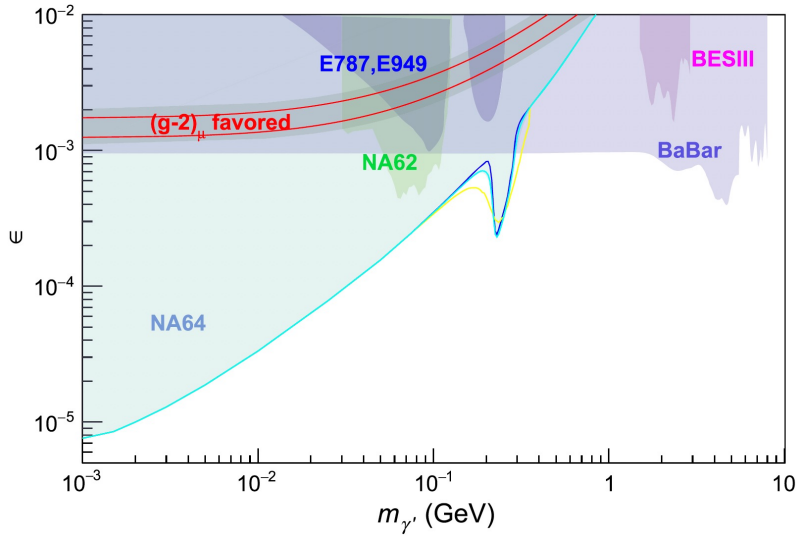
BESIII invisible dark photon decay

In total Lum=14.9 fb^{-1} from E_{cm}=4.13 – 4.60 GeV





$$E_\gamma = \frac{s - m_{\gamma'}^2}{2\sqrt{s}} \qquad \sigma(e^+e^- \to \gamma\gamma') = \frac{2\pi\alpha^2}{s}\epsilon^2(1-x)\left(\left(1+\frac{2x}{(1-x)^2}\right)\Theta - 2\cos\theta_c\right) \qquad \cos\theta_c = 0.6$$



- BESIII search for an invisible decay dark photon
- High energy data with E_{cm}>4 GeV is used first
- Scan the high mass region m(γ') in [1.5, 2.9] GeV
- Upgrade with 17 fb^{-1} E_{cm}=3.773 GeV data is already ongoing…

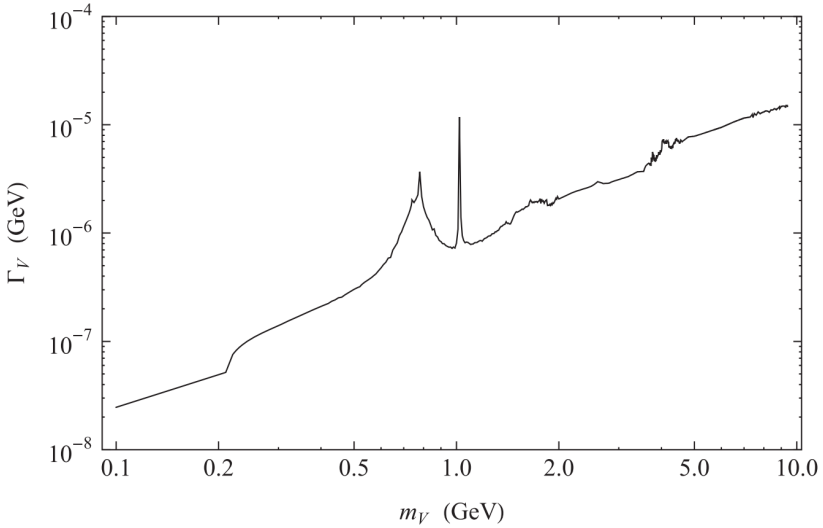
Summary

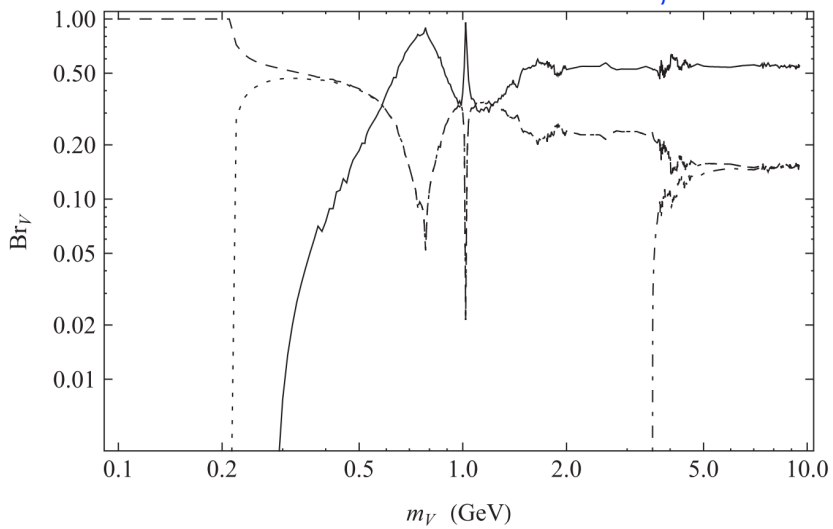
- BESIII is an active running & promising e^+e^- machine operated in China.
- Fruitful achievements in hadron physics, as well as for dark sectors search & NP.
- Conduct axion searches & dark photon searches via various approaches, producing cutting-edge results.
- Future upgrade will have significant impact on the low energy frontier.

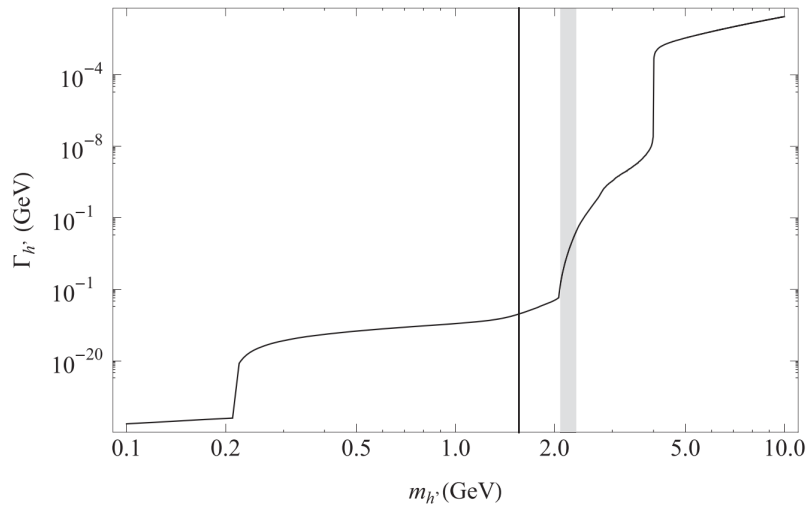
Thanks for your attention !

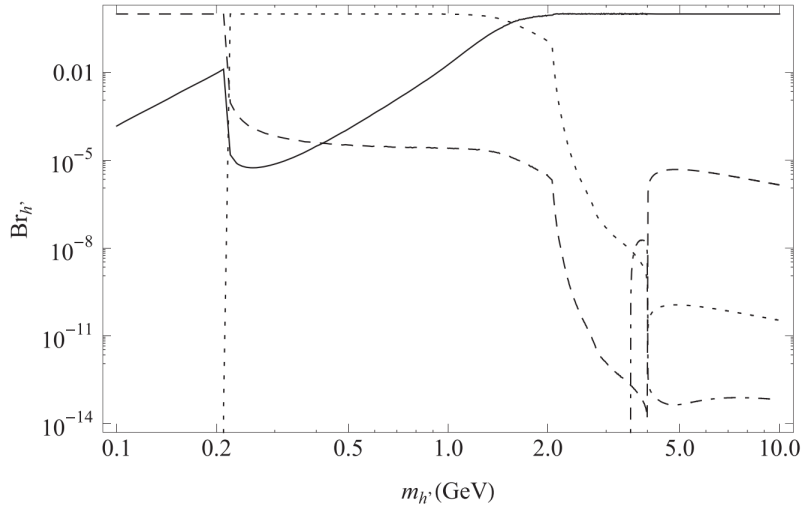
Dark photon branching ratio

PRD 79, 115008 (2009)









Dark forces at KLOE

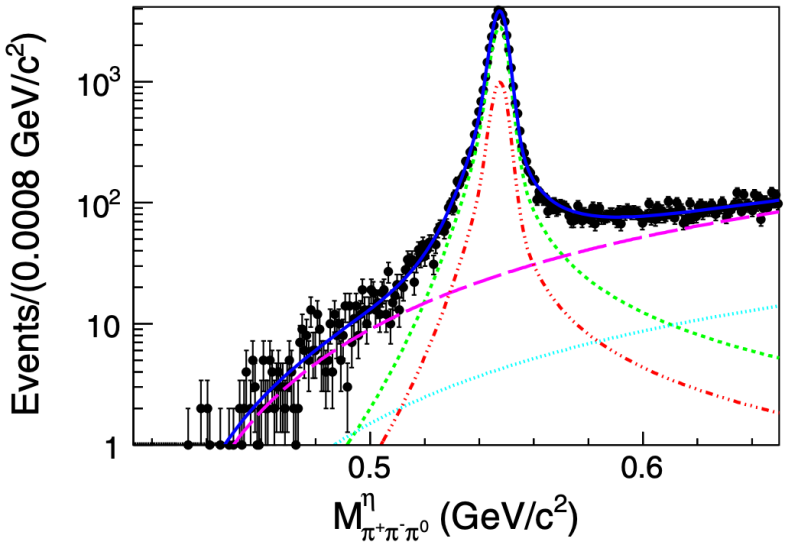
From Xiaoling Kang

- Decay of the ϕ meson into a U boson + pseudoscalar η
  - $\phi \to U\eta, U \to e^+e^-, \eta \to \pi\pi\pi$ Phys. Lett. B706 (2012) 251 Phys. Lett. B720 (2013) 111
- Associated Uγ production:
  - $e^+e^- \to U\gamma \; with \; U \to \mu^+\mu^-$ Phys. Lett. B736 (2014) 459
  - $e^+e^- \to U\gamma \; with \; U \to e^+e^-$ Phys. Lett. B750 (2015) 633
  - $e^+e^- \to U\gamma \; with \; U \to \pi^+\pi^-$ Phys. Lett. B757 (2016) 356
  - Combined analysis $\mu^+\mu^-$ and $\pi^+\pi^-$ Phys. Lett. B 784 (2018) 336
- Higgsstrahlung process, in the m(h')<m(U) scenario, with an invisible Higgs:
  - $e^+e^- \to Uh', with \; h' \to invisible \; and \; U \to \mu^+\mu^-$ Phys. Lett. B 747 (2015) 365
- Leptophobic B boson search (ongoing)

$\omega/\phi \rightarrow$ invisible

- N(J/ψ)=1.3 Billion
- Br(J/ψ→ηω/ηϕ) ~ 17.4/7.5*10^{-4}
- Yield ~ 1 – 5 Million
- Will update to 10 Billion

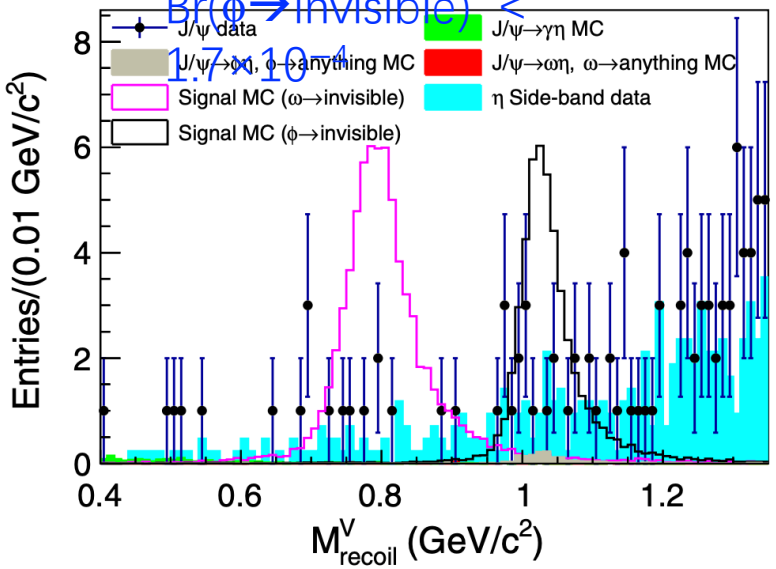
Phys. Rev. D 98, 032001 (2018)



Reconstruct η→$\pi^+\pi^-\pi^0$ decay

Br(ω→invisible) < 7.3×10^{-5}

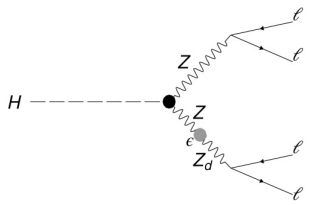
Br(ϕ→invisible) < 1.7×10^{-4}

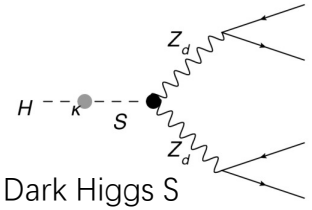


- Search for a signal in recoil side
- Maybe converted to dark photon coupling…

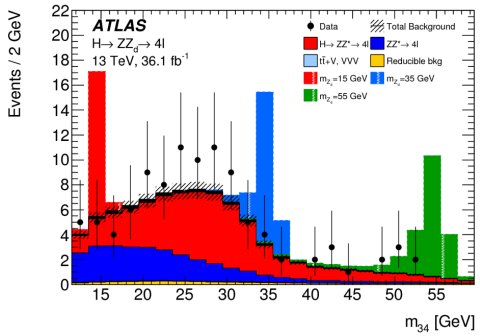
ATLAS search

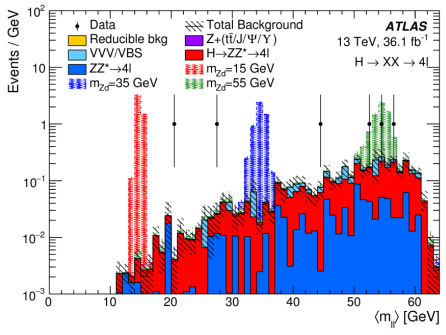
JHEP 06 (2018) 166

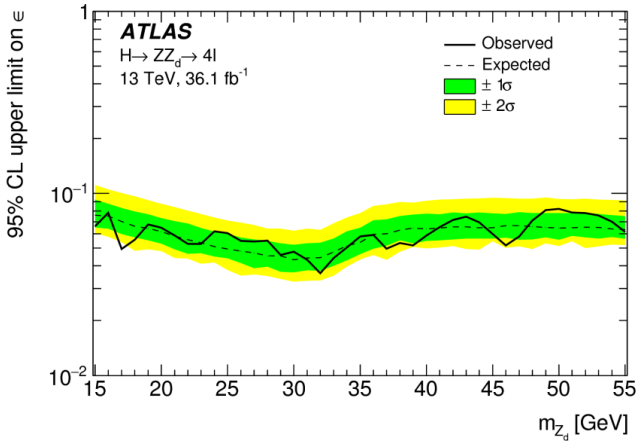




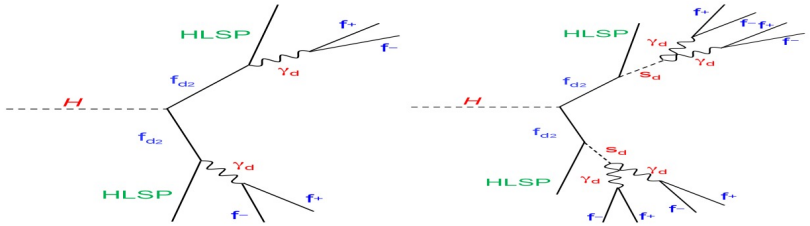
Dark Higgs S



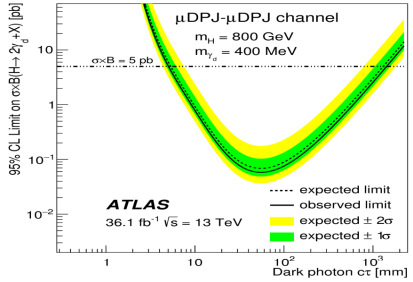


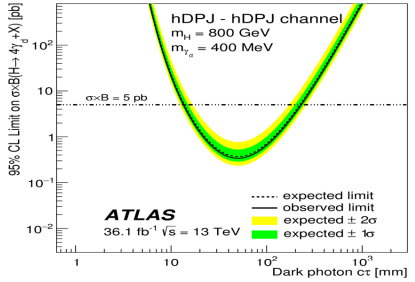


Eur. Phys. J. C 79 (2019) 481

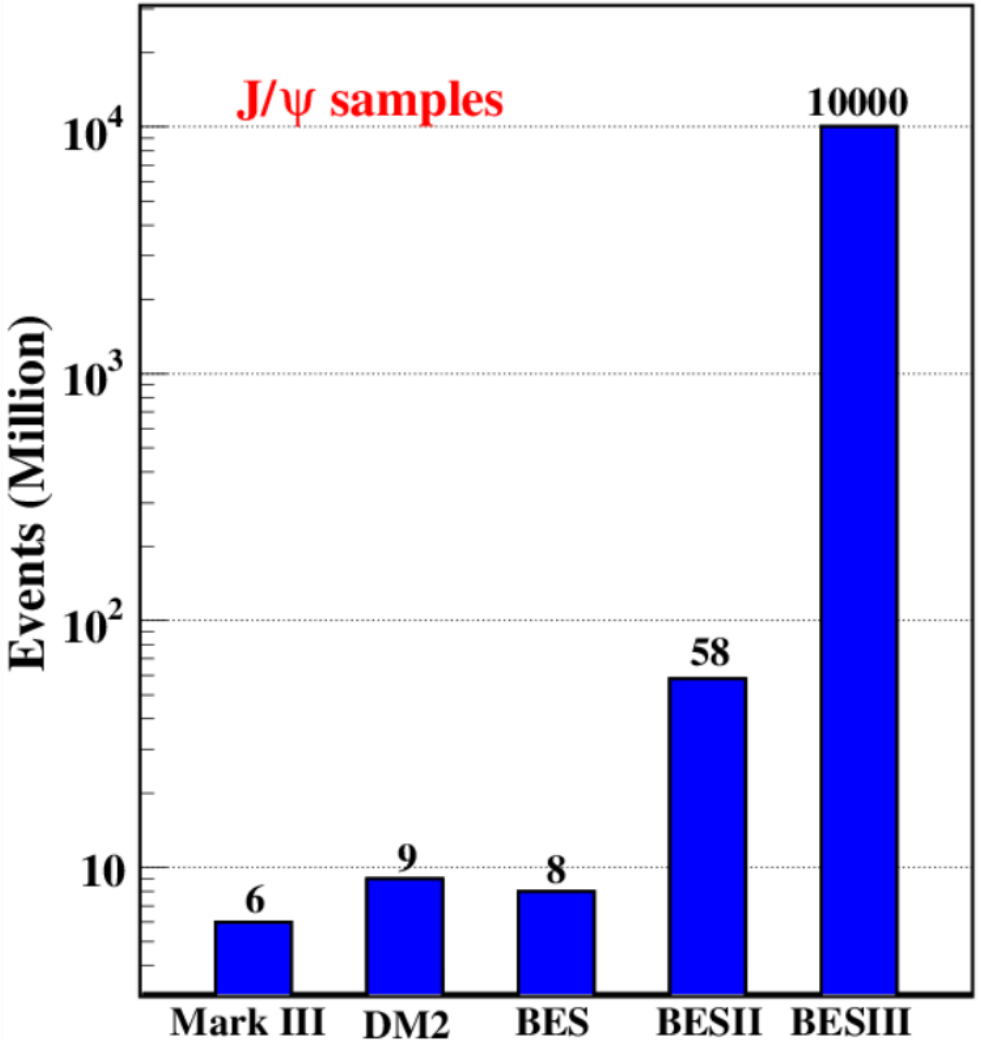


Dark fermion fd2
hidden lightest stable particle
Dark scalar sd & dark photon γd





BESIII – A Hyperon/light meson factory



- Br(J/ψ→γη') ~ 5*10^{-3}, η' yield ~50 Million
- Br(J/ψ→γη) ~ 1*10^{-3}, η yield ~10 Million
- Br(J/ψ→ΛΛ) ~ 1.9*10^{-3}; Λ yield ~20 Million
- Br(J/ψ→$\Sigma^+\Sigma^-/\Sigma^0\Sigma^0$) ~ 1.2*$10^{-3}$; Λ yield ~12 Million
- Br(J/ψ→$\Xi^-\Xi^+/\Xi^0\Xi^0$) ~ 1*10^{-3}; Λ yield ~10 Million

Polarization / NP Search (CP violation, EDM) / Decay dynamics

backup