

Dark photon search in e^+e^- collision

Zhiqing Liu (刘智青)

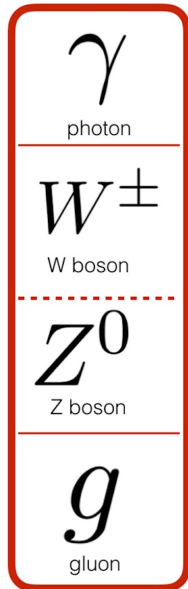
Shandong University

SPCS2021, Nov. 20th Shanghai

Outline

- Introduction
- BESIII experiment and datasets
- Dark photon visible search
- Dark photon invisible search
- Summary

Dark photon

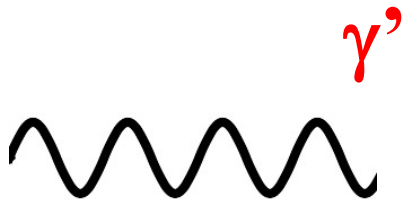


SM gauge bosons

- Spin-1 particles
- EM interaction $\rightarrow$ U(1) gauge group

Hypothetical massive force carrier of extra U(1)_d gauge group; predicted in many theories beyond the Standard Model

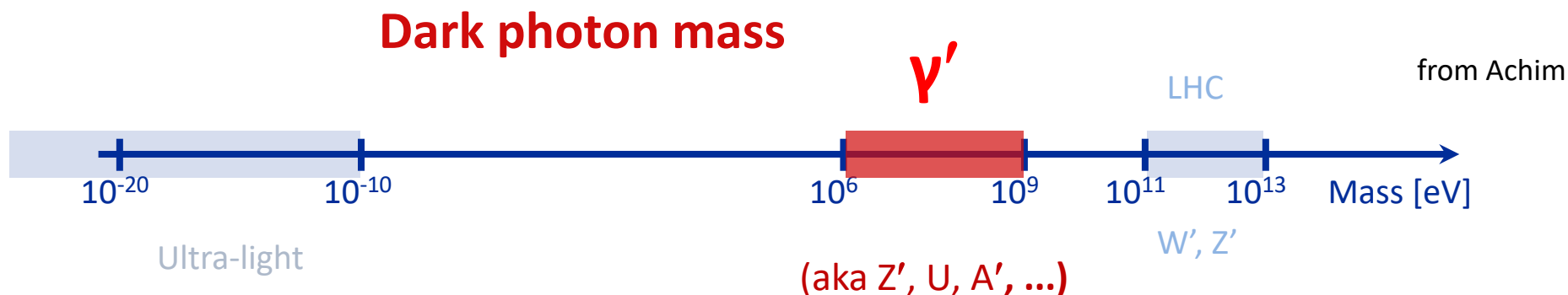
- *Para-photon, U-boson, hidden-sector, secluded photon etc.*
- Now dark photon ($\gamma' \rightarrow$ BESIII convention)



Fayet, PLB 95,285 (1980)
NPB 347,743 (1990)
Holdom, PLB 166,196 (1986)

Dark photon mass

- **Massless kind:** do not couple directly with SM current → not our topic today

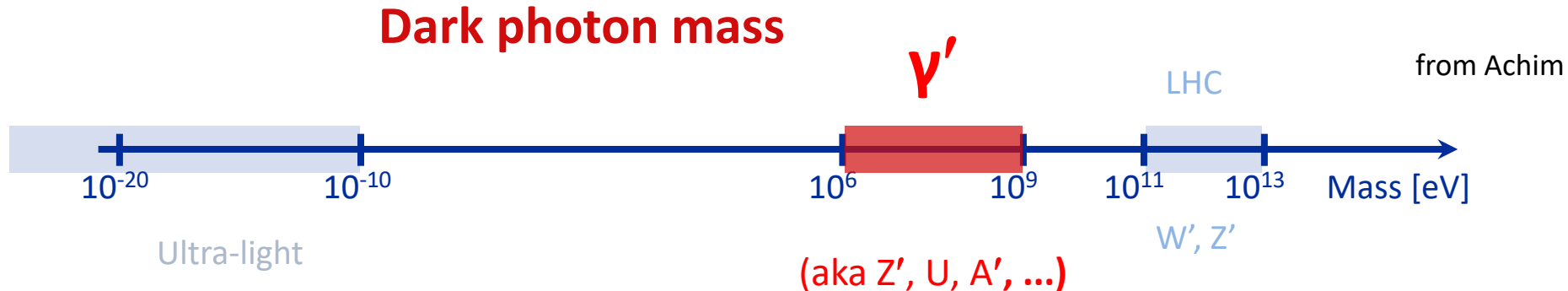


- **Massive kind:** can couple to ordinary matter

- Ultra-light dark photon ($<10^{-10}$ eV): Cavendish-type experiment (test Coulomb's law), CMB cosmological constraints, planet (earth, Jupiter) magnetic field → Maxwell's equations
- Light dark photon: XENON10...
- $\mathcal{O}(\text{GeV}/c^2)$ dark photon: particle detector search (BaBar, Belle, BESIII etc.)

Dark photon mass

- **Massless kind:** do not couple directly with SM current → not our topic today

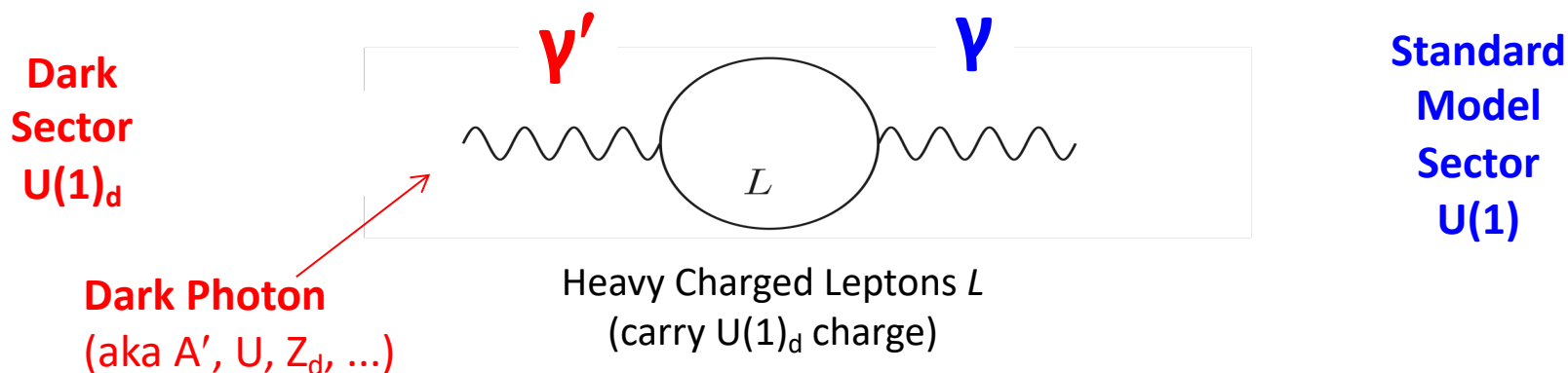


Search for the $O(\text{GeV}/c^2)$ mass scale in a world-wide effort

- Could explain large number of **astrophysical anomalies** AMS-02
Arkani-Hamed et al. (2009) → AMS positron flux excess... PRL122, 041102 (2019)
- Could explain some SM deviations: e.g. **$(g-2)_\mu$ deviation** between Standard Model prediction and direct $(g-2)_\mu$ measurement
Pospelov(2008) → large parameter space has been ruled out...

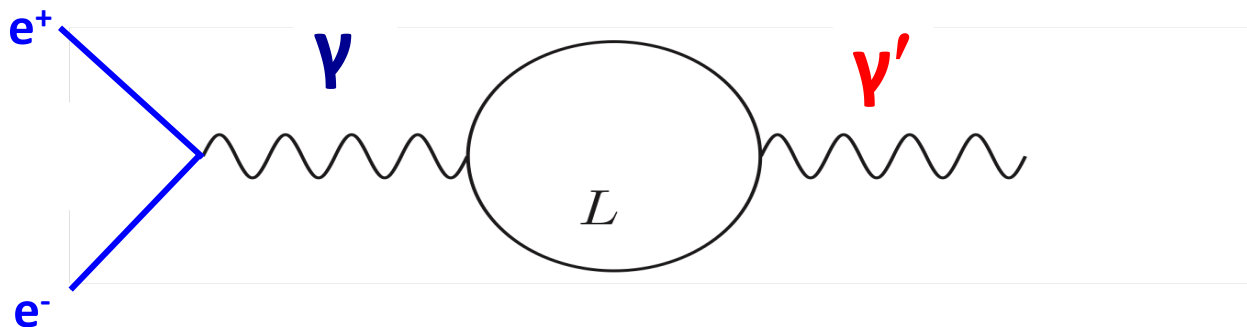
Mixing

A way to relate the dark sector to the SM (coupling $\sim \epsilon^2$)



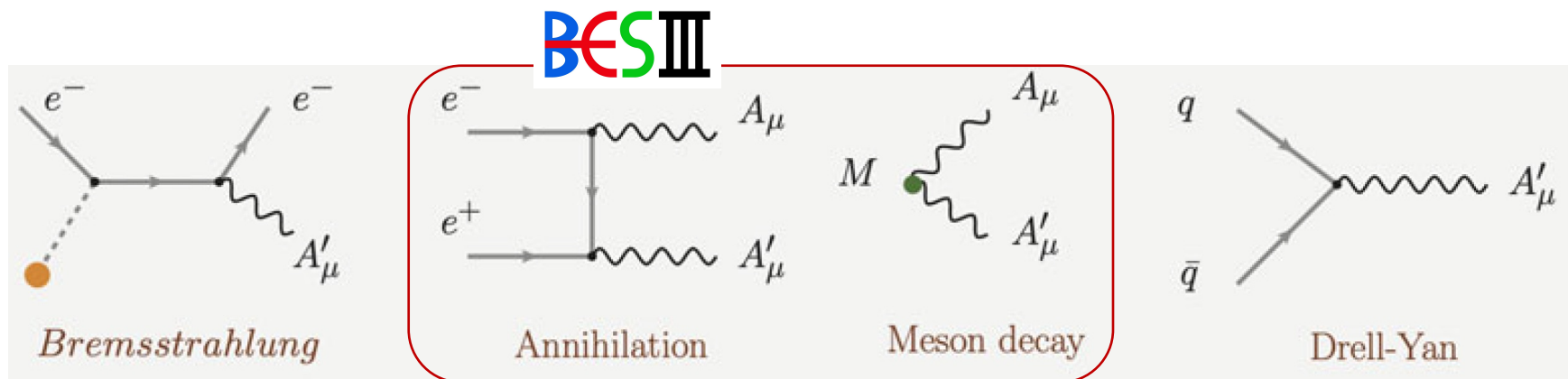
$$\mathcal{L} = -\epsilon e J^\mu A'_\mu,$$

Production in e^+e^- collider

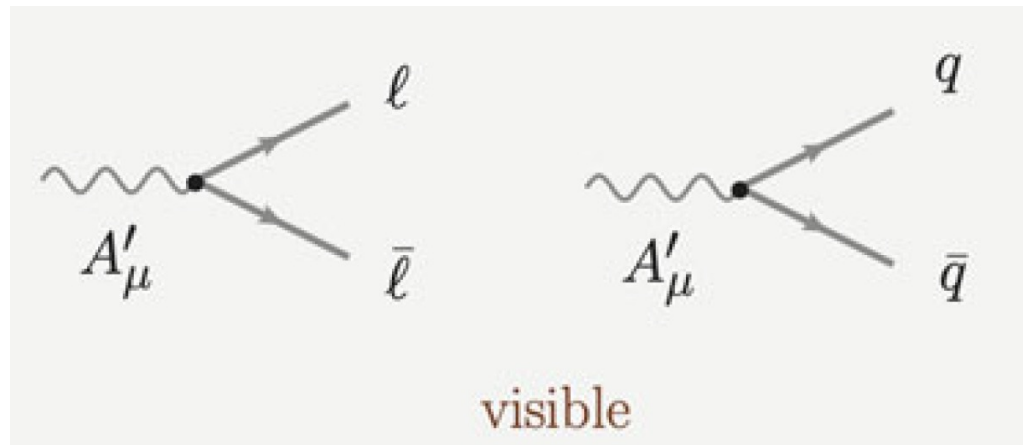


Suppression of Dark Photon coupling by a factor ε

$$\alpha' = \varepsilon^2 \cdot \alpha_{em}$$



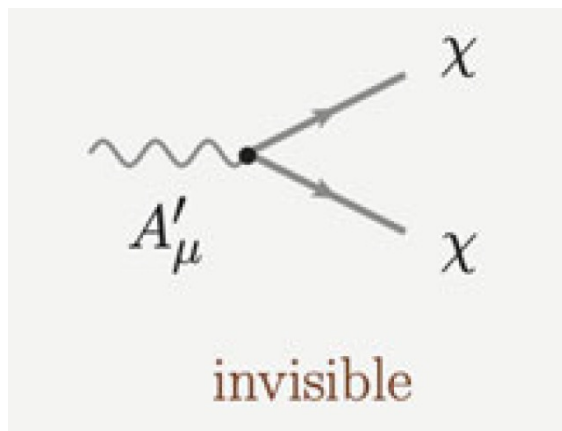
Decay



If $m(\gamma') < 2m(\chi)$, visible decay

- Leptons ($e+e^-$ etc)
- Quarks (hadrons)
- Branching ratios are calculated

PRD 79, 115008 (2009)



If $m(\gamma') > 2m(\chi)$, invisible decay (dominate)

$$\alpha_D \gg \alpha \varepsilon^2$$

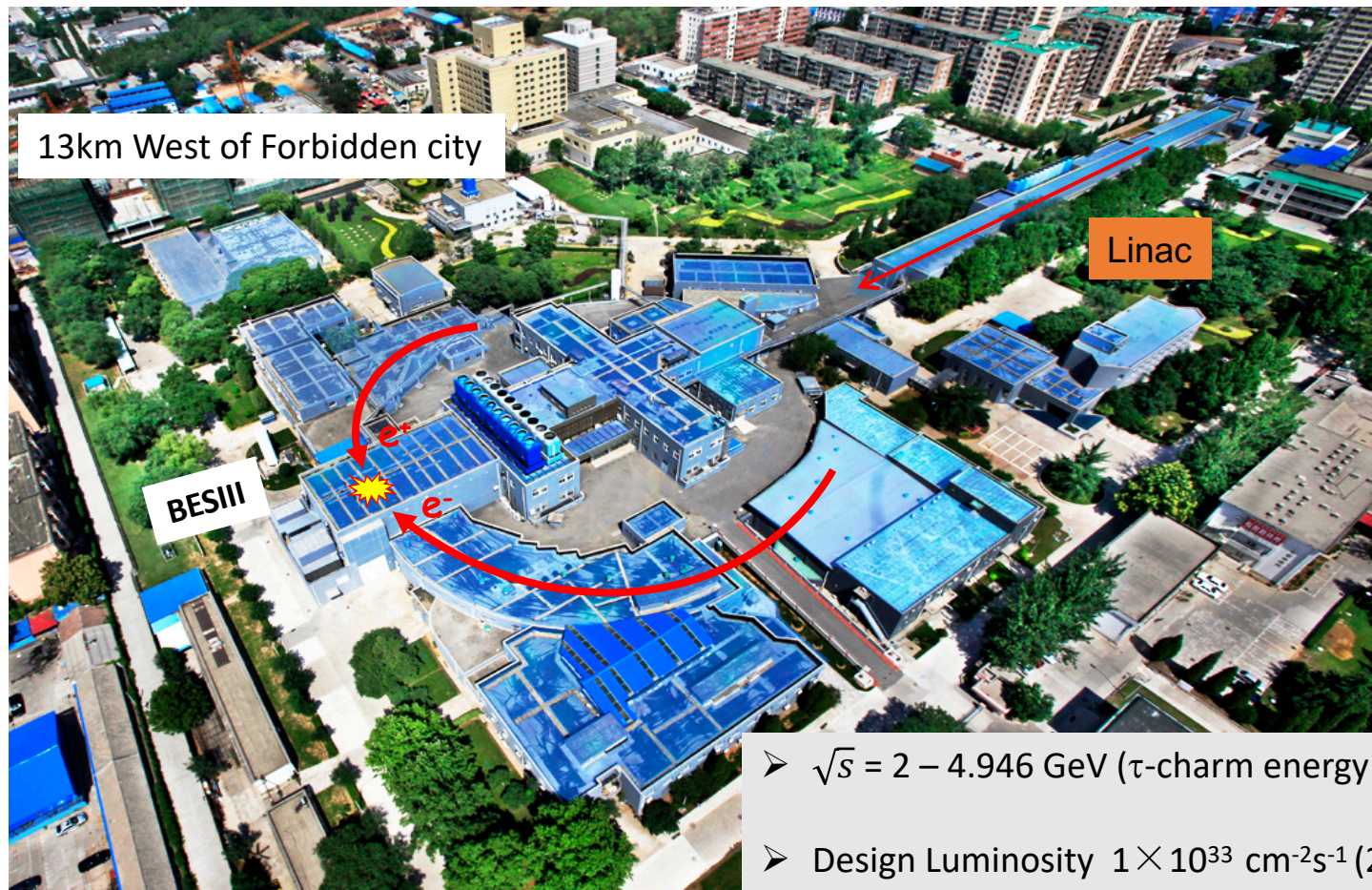
The BESIII experiment

1988年10月16日 北京正负电子对撞机对撞成功

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”

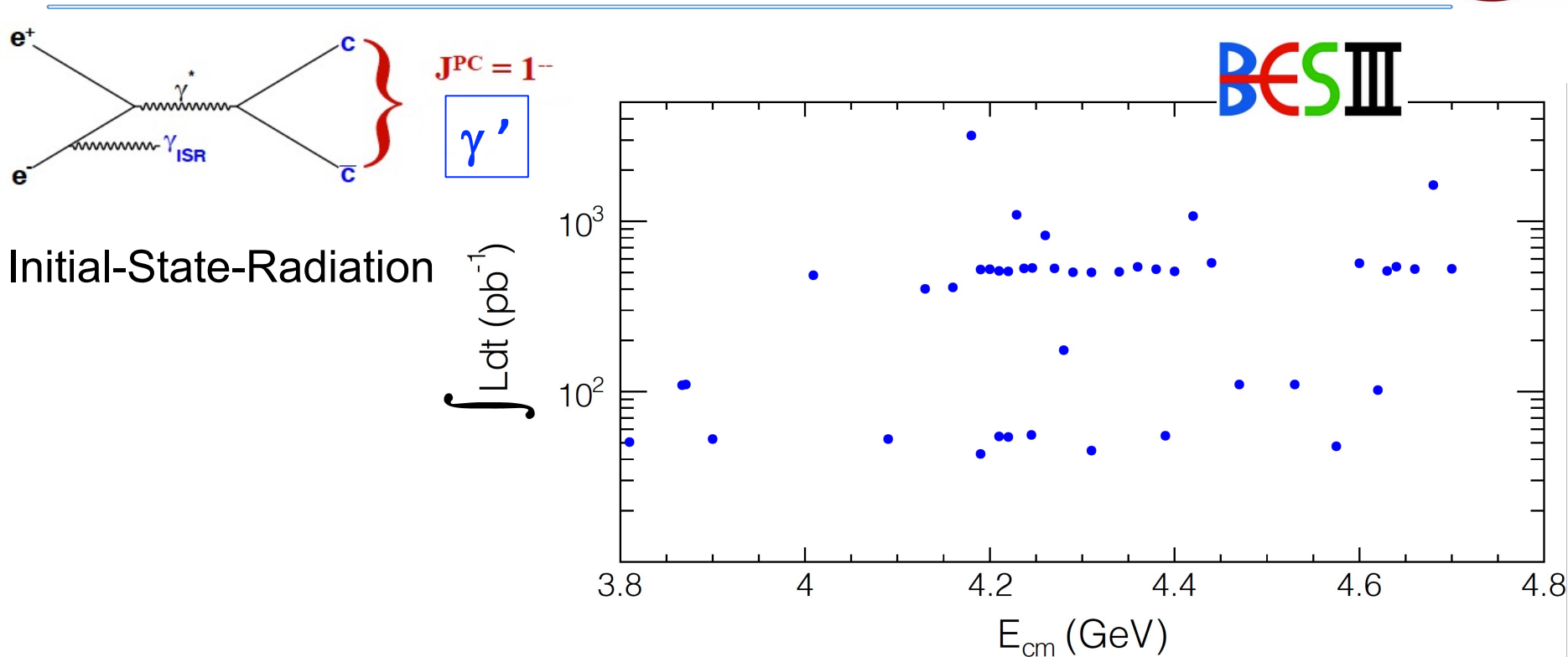


Beijing Electron Positron Collider (BEPCII)



- $\sqrt{s} = 2 - 4.946 \text{ GeV}$ (τ -charm energy region)
- Design Luminosity $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ (2016 achieved)

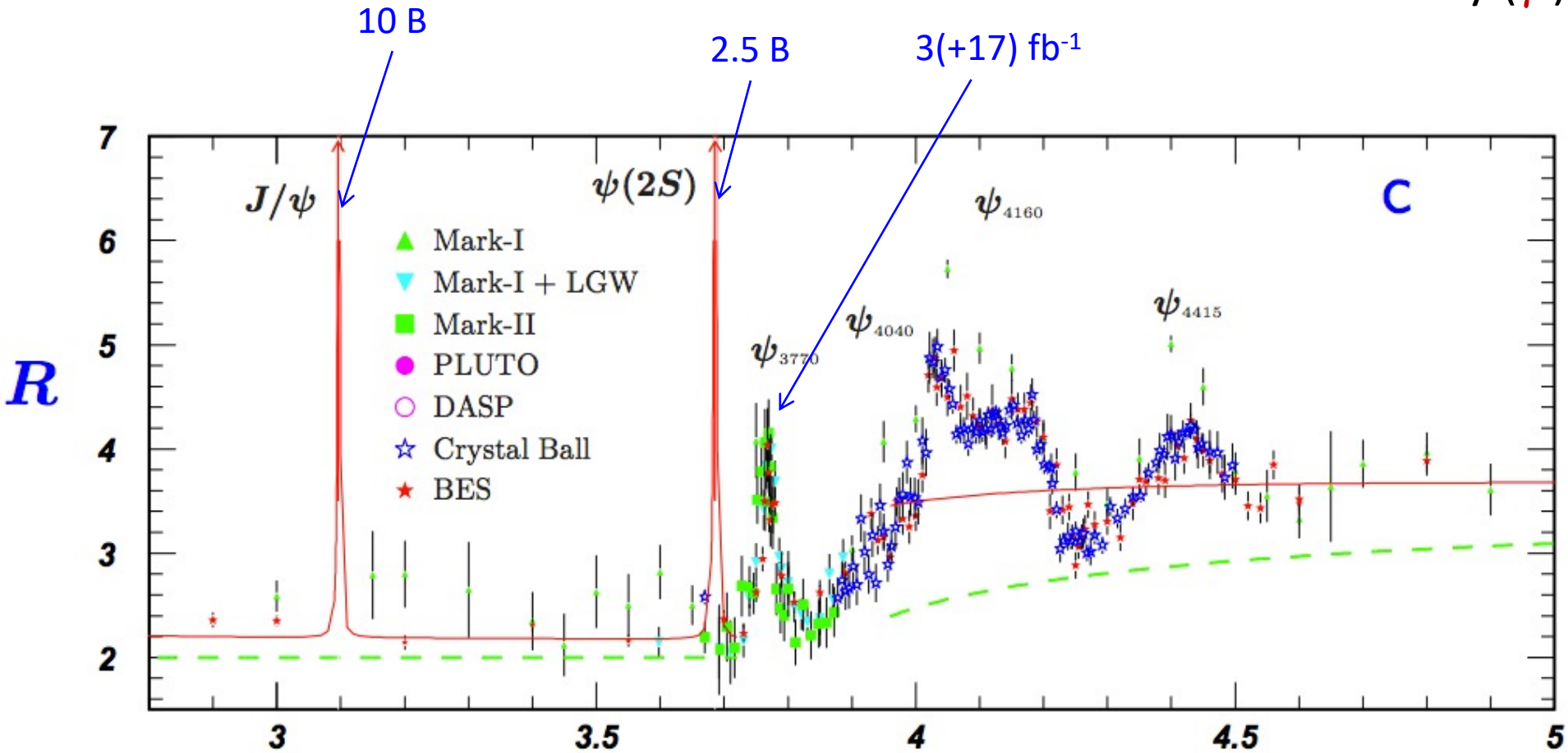
Data Sets (I)



- A scan experiment for vector charmonium-(like) states studies
- Over 20 fb^{-1} data between 3.8 – 4.7 GeV during last 7 years

Data Sets (II)

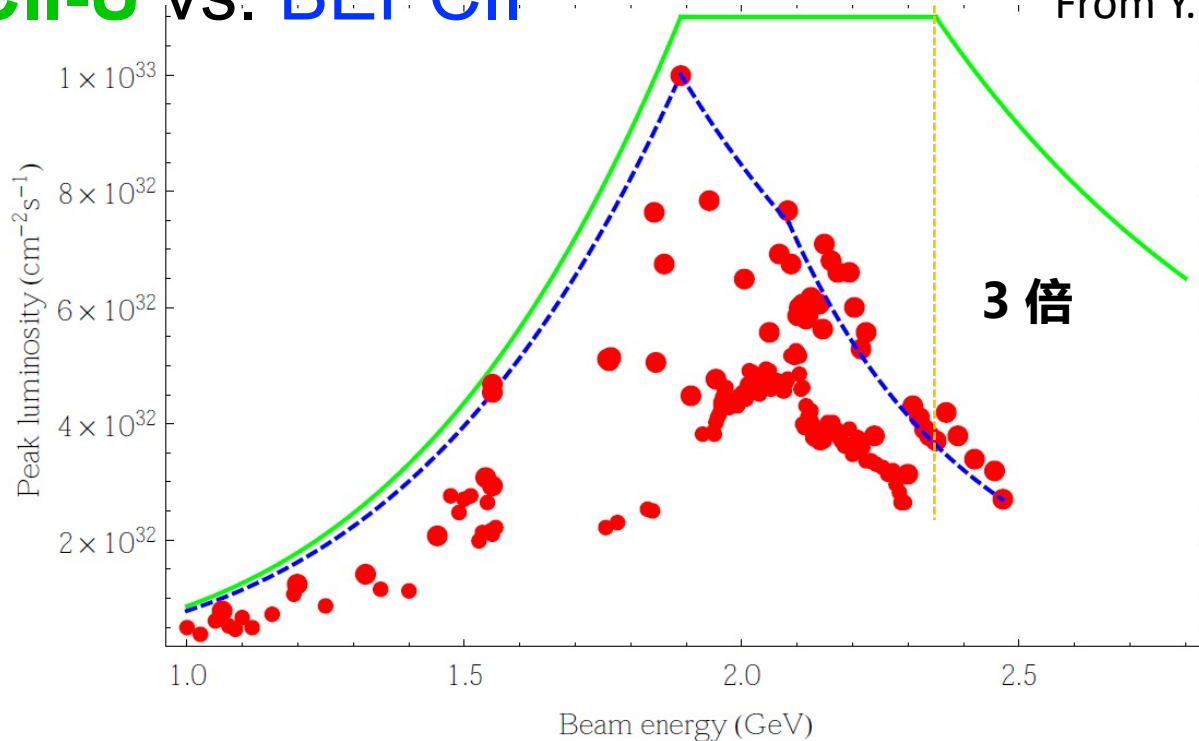
- Meson decay (γ')



BEPCII-Upgrade

BEPCII-U vs. BEPCII

From Y. Zhang @ FPCP2021



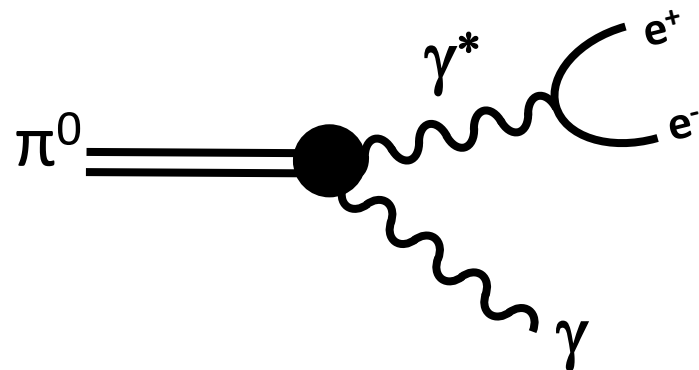
- Not a new machine, but an upgrade machine
- Luminosity increased by a factor of 3 @ 2.35 GeV
- Beam energy up to 2.8 GeV
- Start running in 2025...

Visible dark photon search

Sources

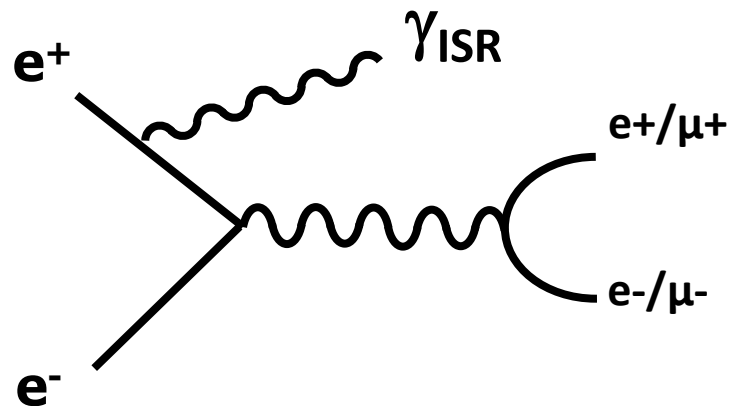
Meson decay

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



Initial State Radiation

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



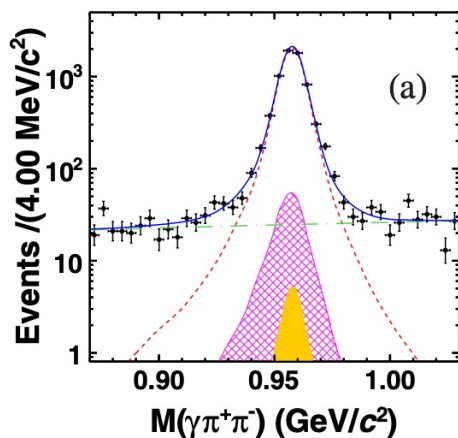
$J/\psi \rightarrow \gamma' \eta'$

PRD 99, 012013 (2019)

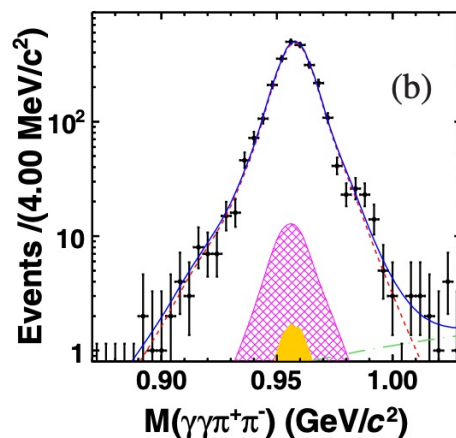
- $N(J/\psi) = 1.3$ Billion
- $\text{Br}(J/\psi \rightarrow \gamma \eta') \sim 5 \cdot 10^{-3}$
- Yield ~ 6.5 Million
- Will update to 10 Billion

BESIII

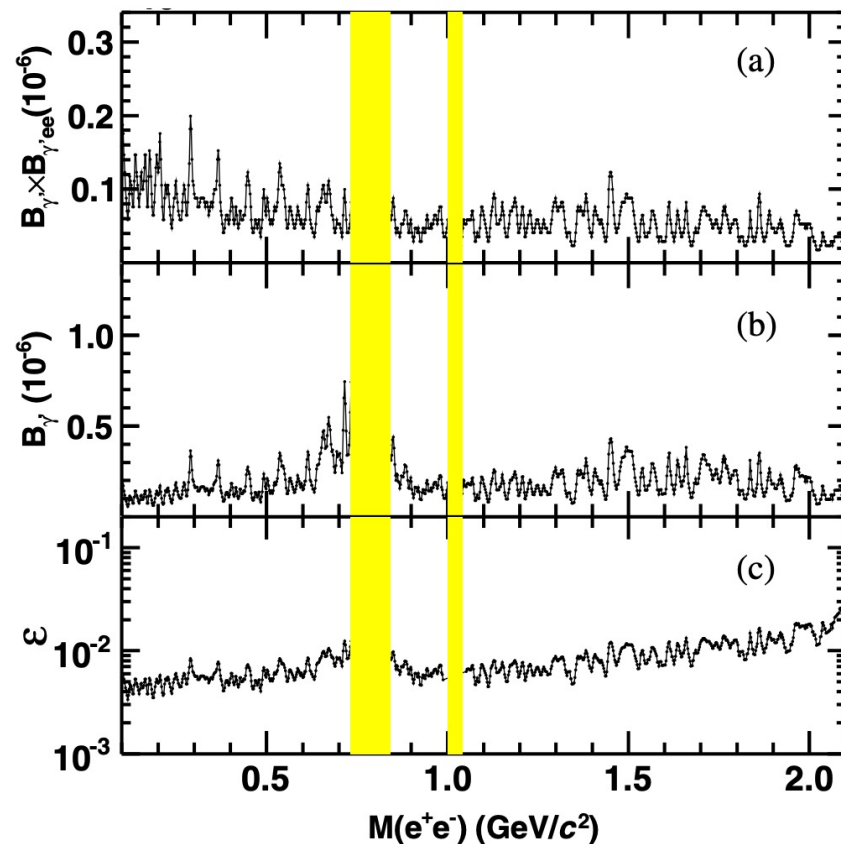
- $J/\psi \rightarrow e^+ e^- \eta'$



6443 events



2498 events



$$\epsilon < [3.4 \times 10^{-3}, 2.6 \times 10^{-2}]$$

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

JHEP07(2009)051

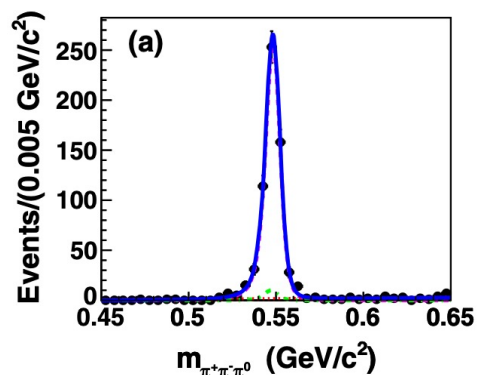
$J/\psi \rightarrow \gamma' \eta$

PRD 99, 012006 (2019)

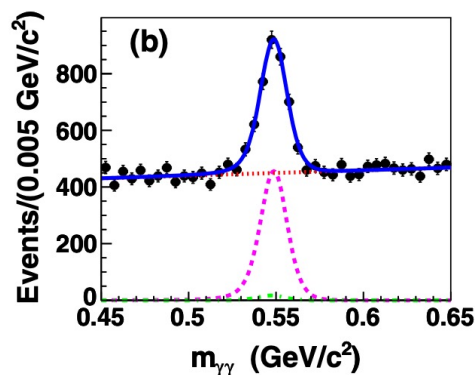
- $N(J/\psi) = 1.3$ Billion
- $\text{Br}(J/\psi \rightarrow \gamma \eta) \sim 1 \cdot 10^{-3}$
- Yield ~ 1.3 Million
- Will update to 10 Billion

BESIII

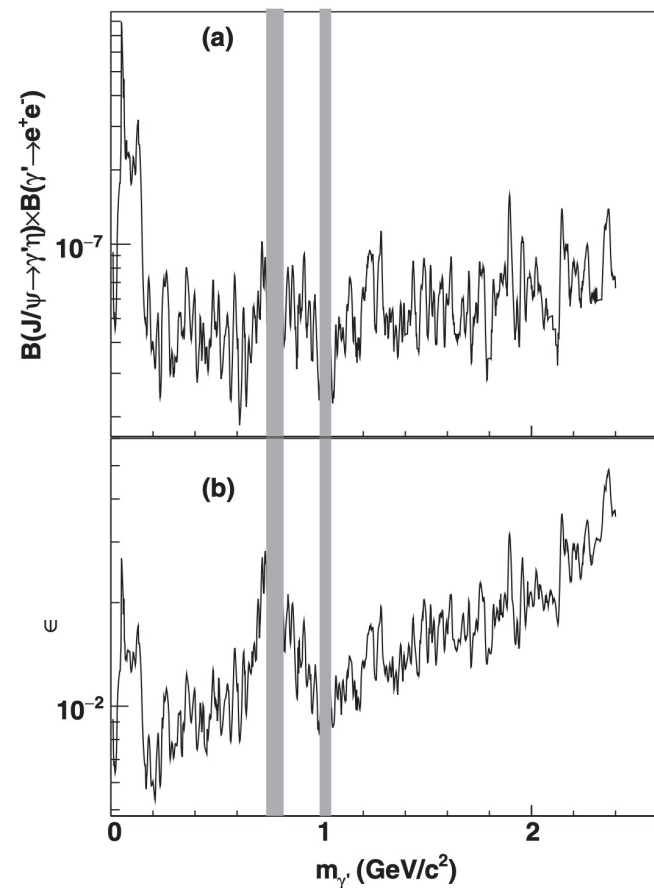
- $J/\psi \rightarrow e^+e^- \eta$



595 events



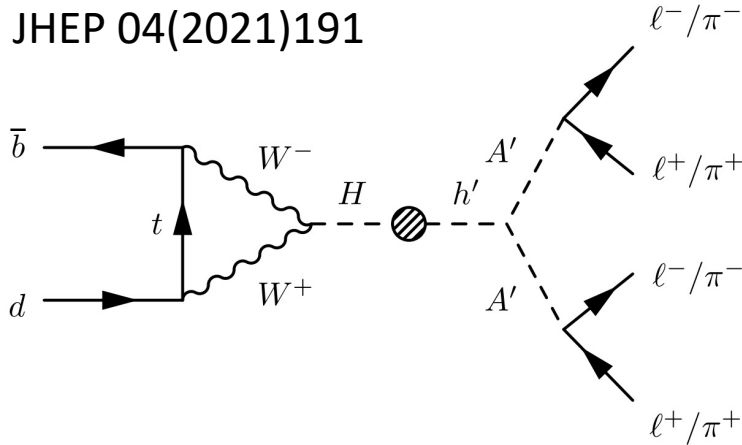
1877 events



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

B-meson decay

JHEP 04(2021)191

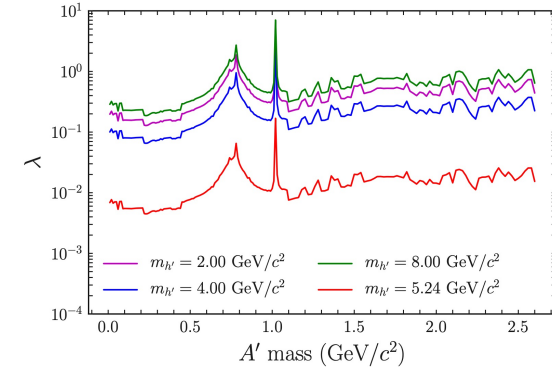
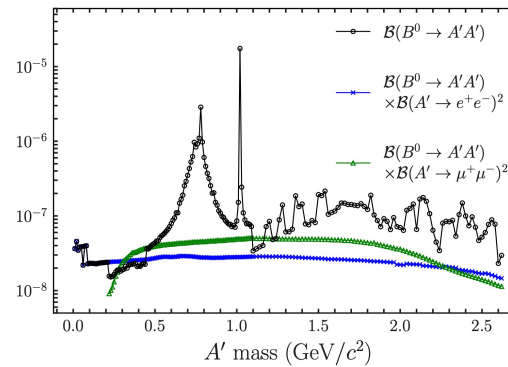
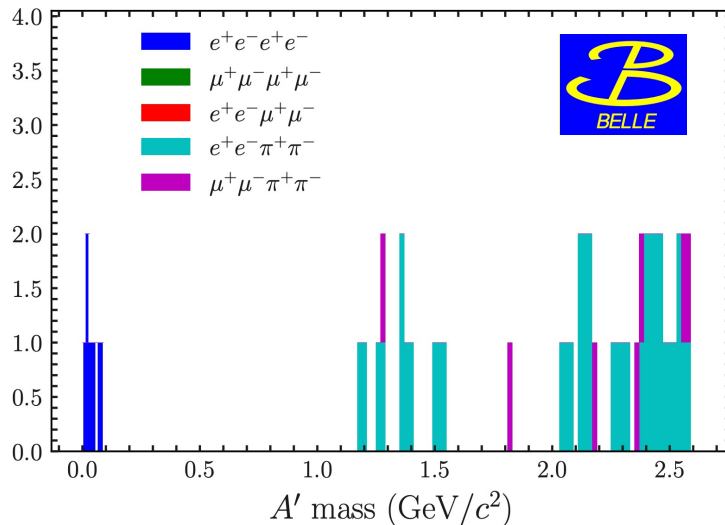


- B meson decay mediated by dark Higgs h'
- SM background $\text{Br}(B^0 \rightarrow 4\ell) \sim \mathcal{O}(10^{-12}) \rightarrow \text{clean}$

$$\Gamma_{A' \rightarrow \ell^+ \ell^-} = \frac{1}{3} \alpha \varepsilon_{\text{mix}}^2 m_{A'} \sqrt{1 - 4m_\ell^2/m_{A'}^2} (1 + 2m_\ell^2/m_{A'}^2),$$

$$\Gamma_{A' \rightarrow \text{hadrons}} = \Gamma_{A' \rightarrow \mu^+ \mu^-} \times R(s = m_{A'}^2), \quad \text{PRD 79, 115008 (2009)}$$

772*0.486=375 M B^0 pairs

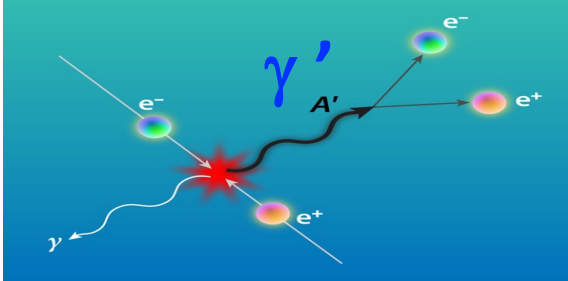


- Translate into branching ratios $\text{Br}[B^0 \rightarrow \gamma' \gamma'] < [10^{-8}, 10^{-5}]$
- Higgs coupling $\lambda < [10^{-2}, 10^{-1}]$

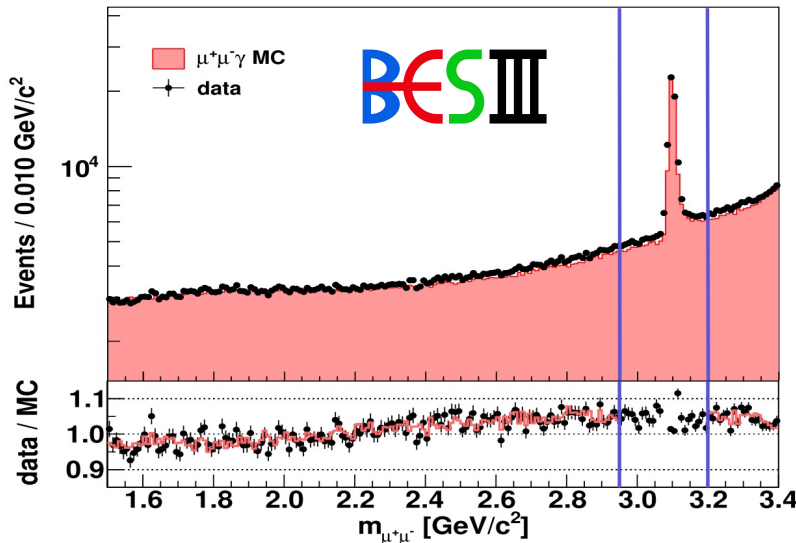
$$B(B^0 \rightarrow A'A') \simeq 7 \times 10^{-7} \times \lambda^2 \times V_{A'A'}^{1/2} \times \frac{V_{A'A'} + 12m_{A'}^4/m_{B^0}^4}{(1 - m_{h'}^2/m_{B^0}^2)^2}$$

ISR $e^+e^-/\mu^+\mu^-$

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



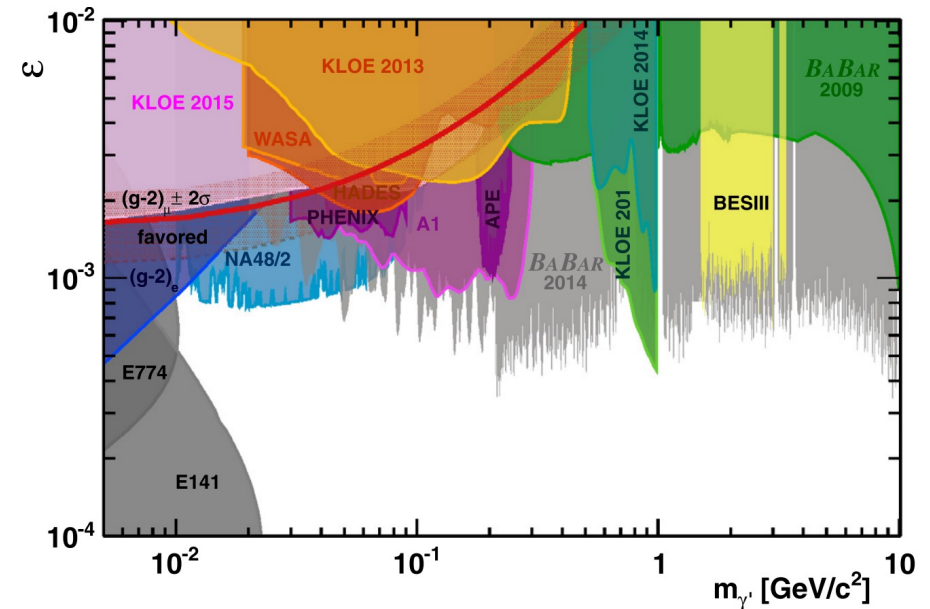
- 2.93 fb⁻¹ @ 3.773 GeV (17 fb⁻¹ coming...)



- Untagged photon
- ISR $\mu^+\mu^-$ events dominate

PLB 774 (2017) 252-257

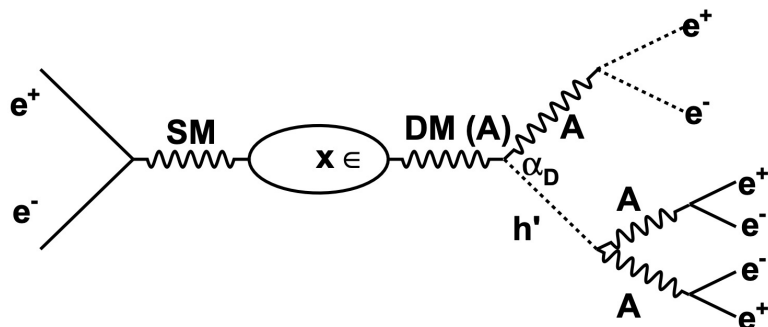
- BaBar measurement [PRL113, 201801 (2014)]
- Coupling strength exclusion limit @ 90% C.L.
- $\varepsilon < [10^{-3}, 10^{-4}]$
- Comparable to BABAR in same mass region



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

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

$$e^+e^- \rightarrow \gamma' h' \rightarrow 3\gamma'$$



a) $m(h') < m(\gamma')$

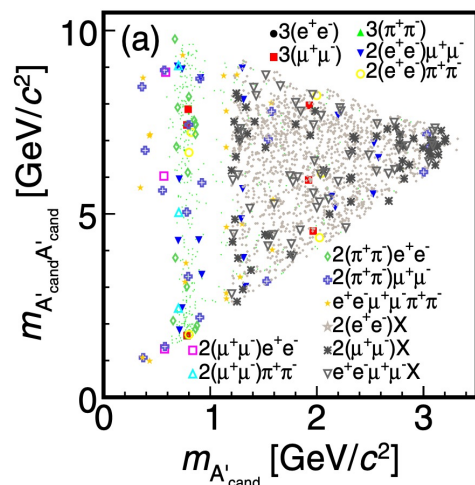
b) $m(\gamma') < m(h') < 2m(\gamma')$

c) $m(h') > 2m(\gamma')$

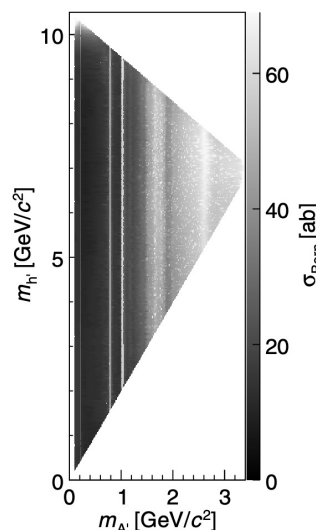
With (γ') decay to SM particles

➤ Suffer less QED background

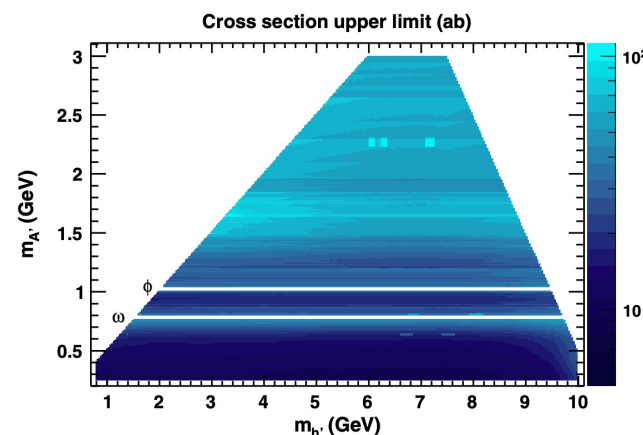
➤ If α_D is large, more sensitive than radiative production



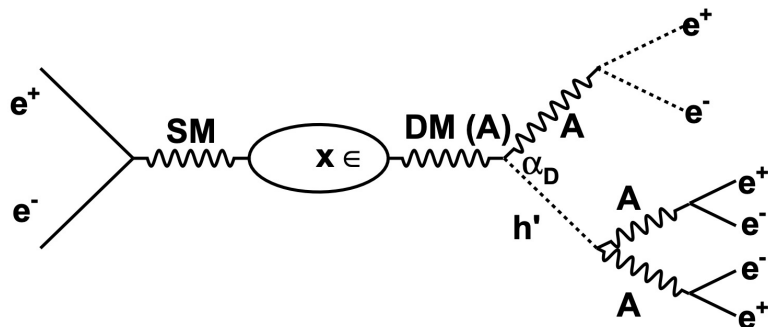
977 fb⁻¹ & 13 channels @ Belle
PRL 114, 211801 (2015)



516 fb⁻¹ & 11 channels @ BaBar
PRL 108, 211801 (2012)



$$e^+e^- \rightarrow \gamma' h' \rightarrow 3\gamma'$$



a) $m(h') < m(\gamma')$

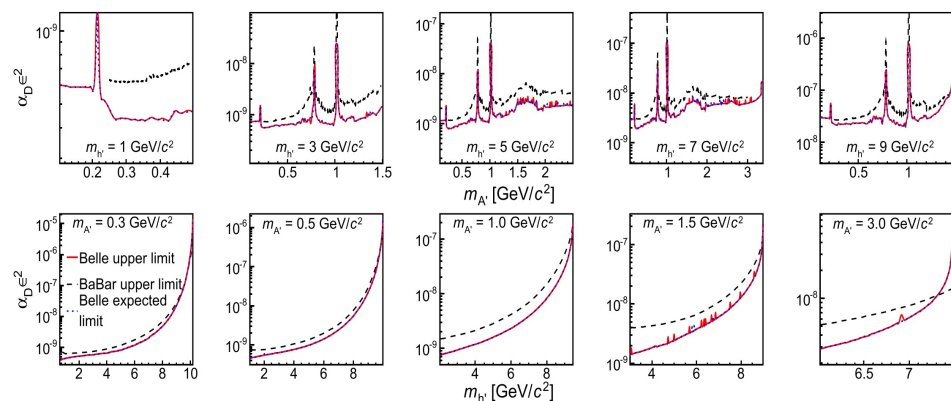
b) $m(\gamma') < m(h') < 2m(\gamma')$

c) $m(h') > 2m(\gamma')$

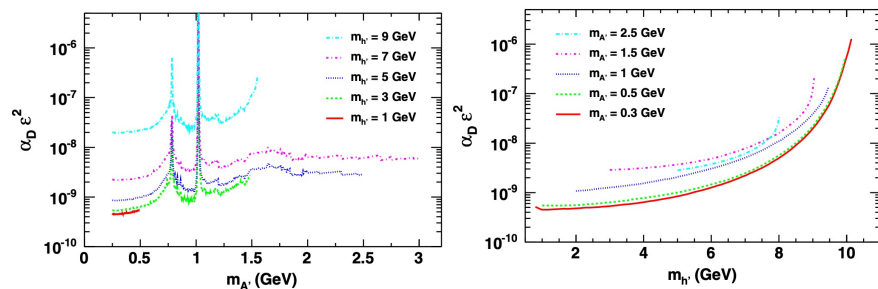
With (γ') decay to SM particles

- Less QED background
- If α_D is large, more sensitive than radiative production

977 fb⁻¹ & 13 channels @ Belle
PRL 114, 211801 (2015)

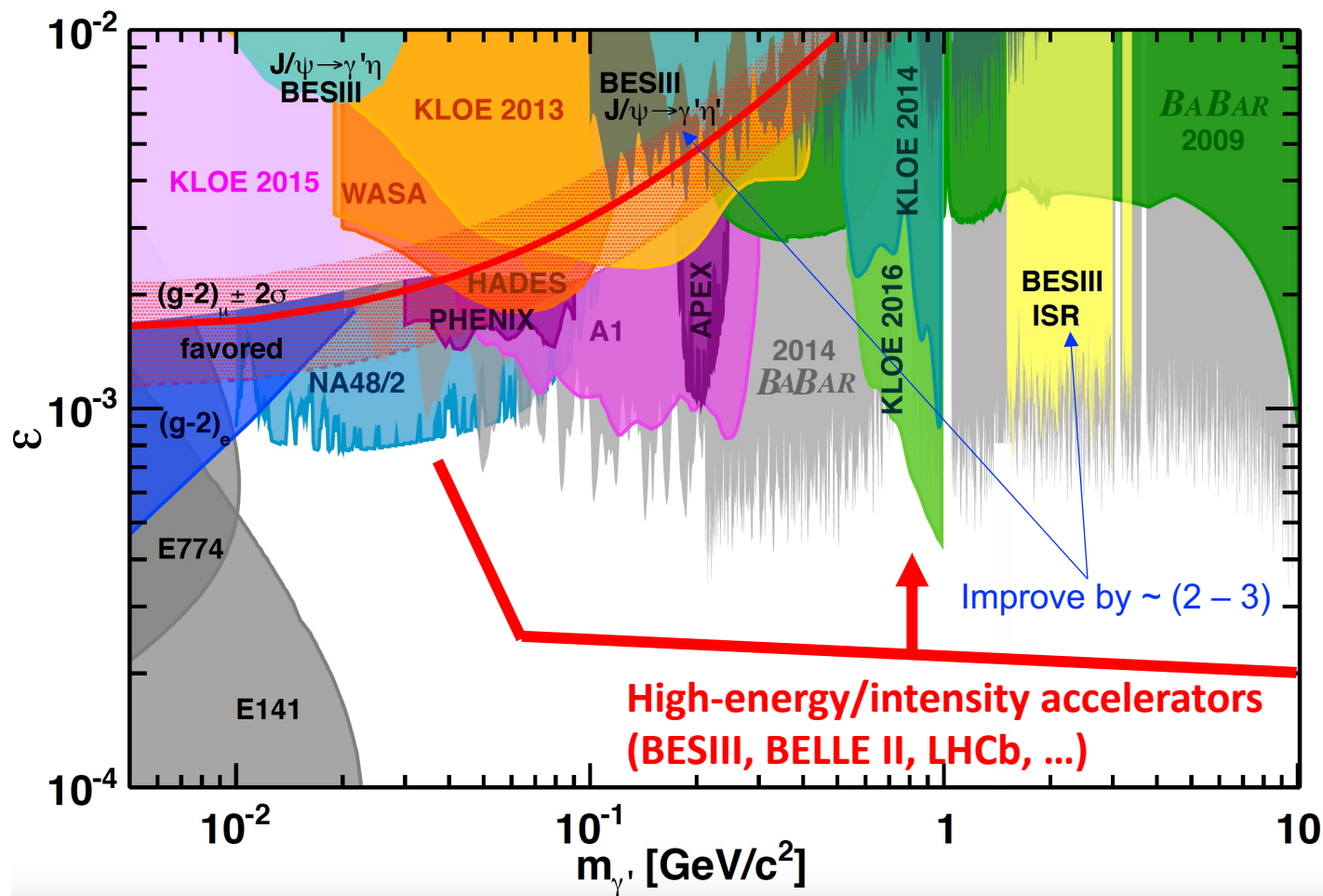


516 fb⁻¹ & 11 channels @ BaBar
PRL 108, 211801 (2012)



- Assuming $\alpha_D \sim \alpha$
- Exclusion limit $\epsilon < [10^{-4}, 10^{-3}]$

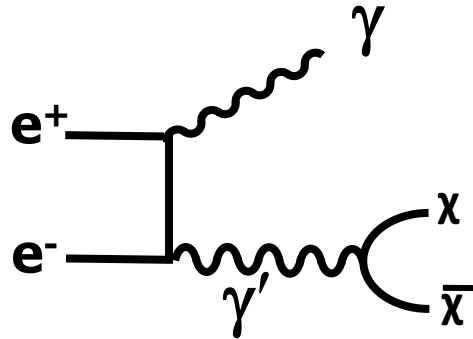
Dark photon exclusion limits



Invisible dark photon search

Invisible decay

Consider now: $2M(\chi) < M(\gamma')$, dark Photon decays dominantly into Light Dark Matter (LDM) $\alpha_D \gg \alpha \epsilon^2$!



Strategy: Missing mass (energy) measurement

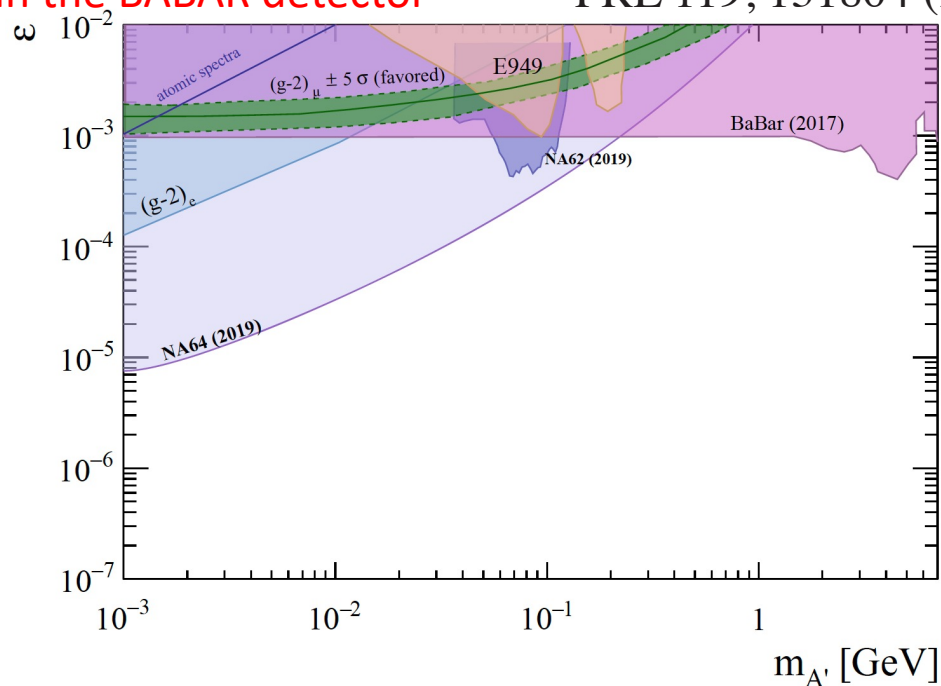
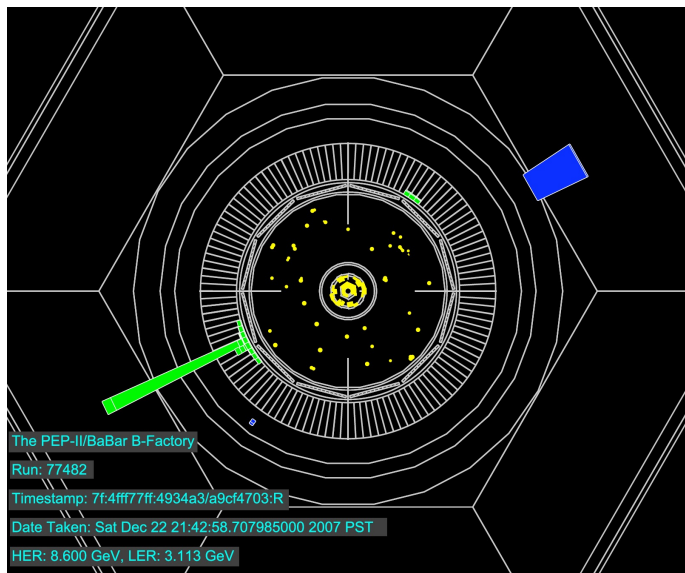
$$M_{\text{miss}}^2 = (\mathbf{P}_{e^-}^4 + \mathbf{P}_{e^+}^4 - \mathbf{P}_{\gamma}^4)^2$$

Invisible decay

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

One photon penetrate the calorimeter in the BABAR detector

PRL 119, 131804 (2017)

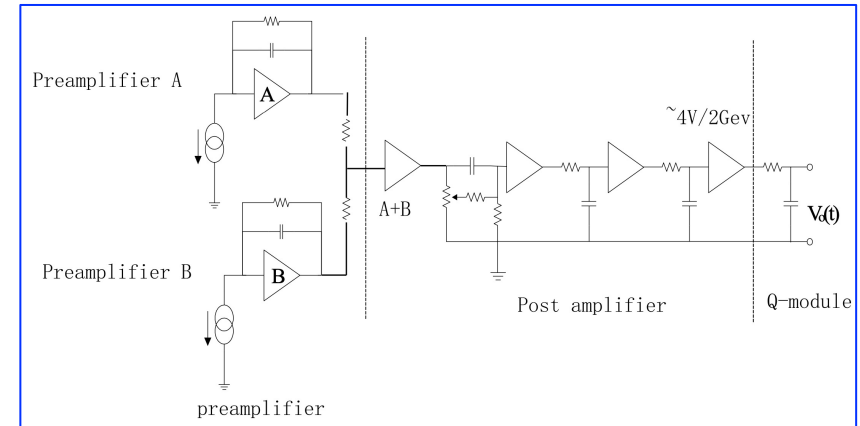
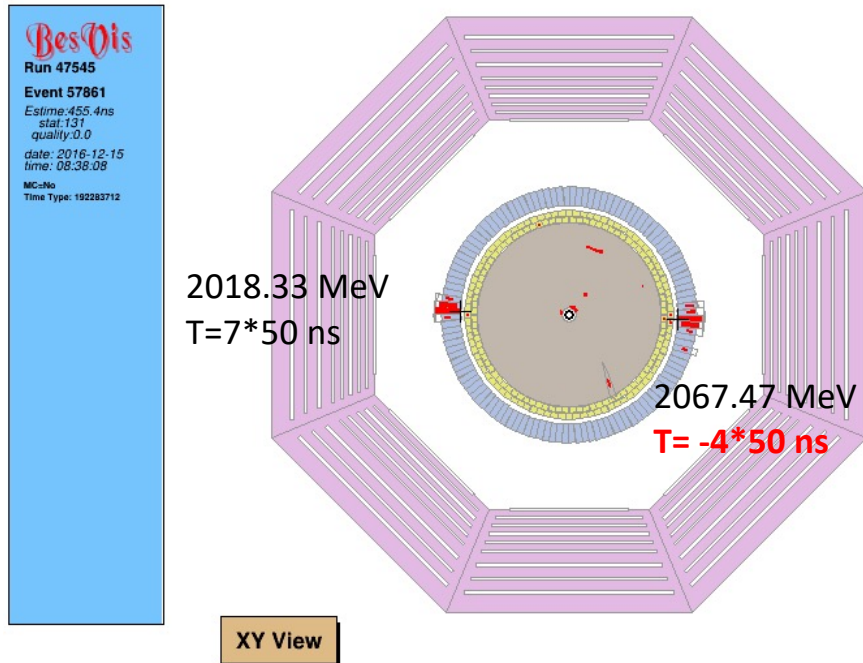


➤ $e^+e^- \rightarrow \gamma\gamma$ events are dominant backgrounds

➤ 53 fb^{-1} , BaBar achieve exclusion limit $\varepsilon < [10^{-4}, 10^{-3}]$

BESIII invisible

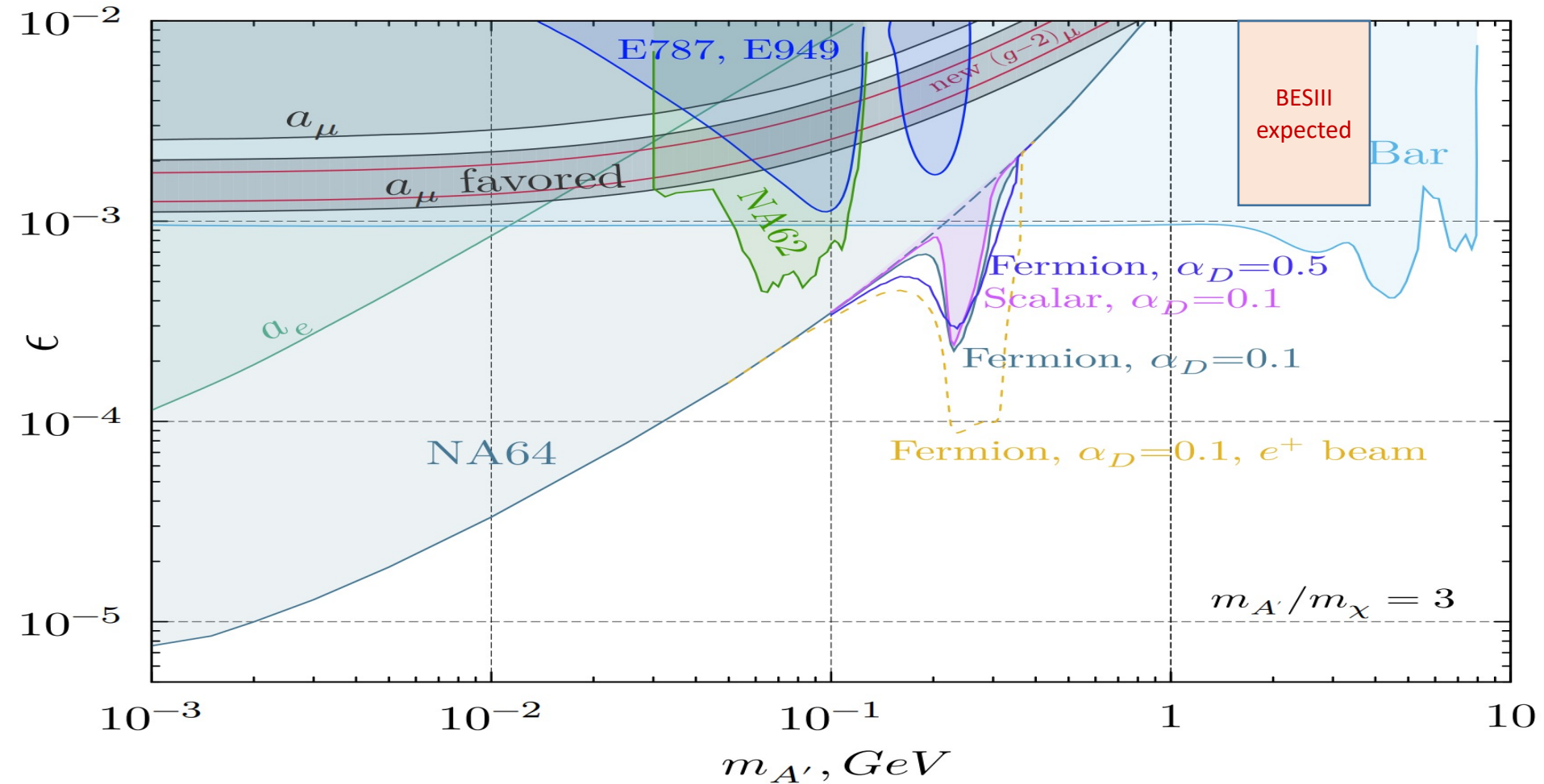
- Event start time not precise
- Induce $e^+e^- \rightarrow \gamma\gamma$ background
- EMC electronics saturate for 2 GeV photon
- Can not explore low mass region for high energy data



Analysis ongoing and expect results soon...

Exclusion limits

BESIII will achieve a comparable exclusion limit as BaBar [1.5 - 2.9] GeV region



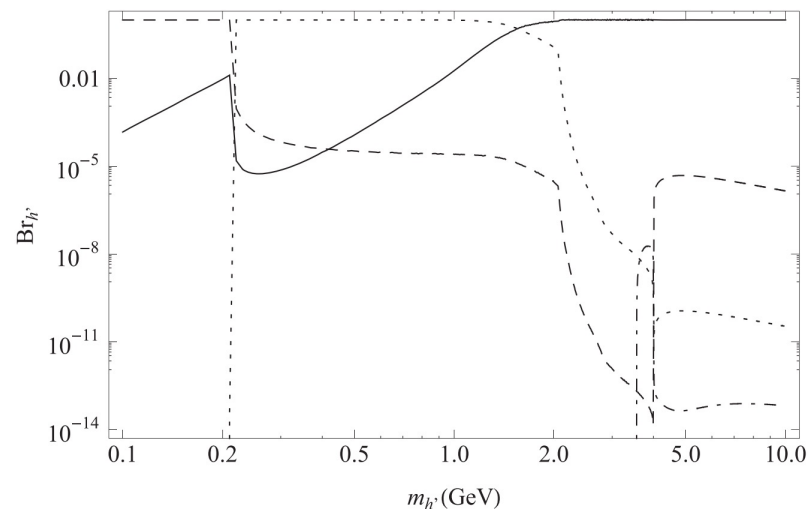
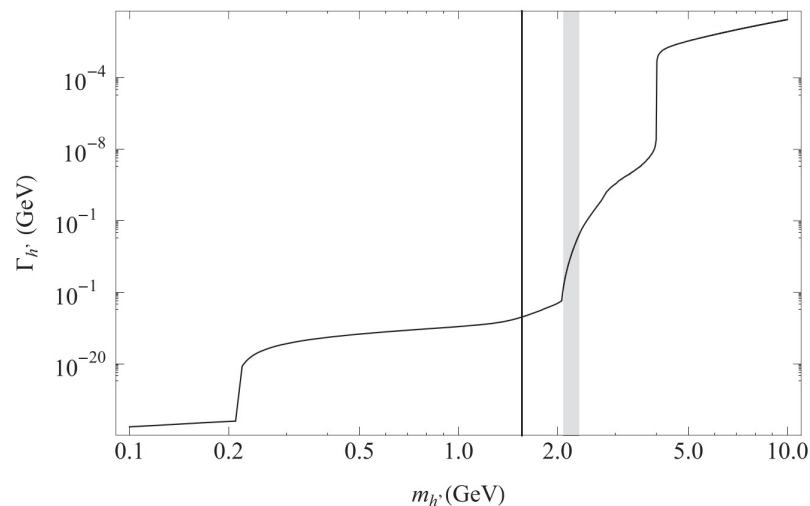
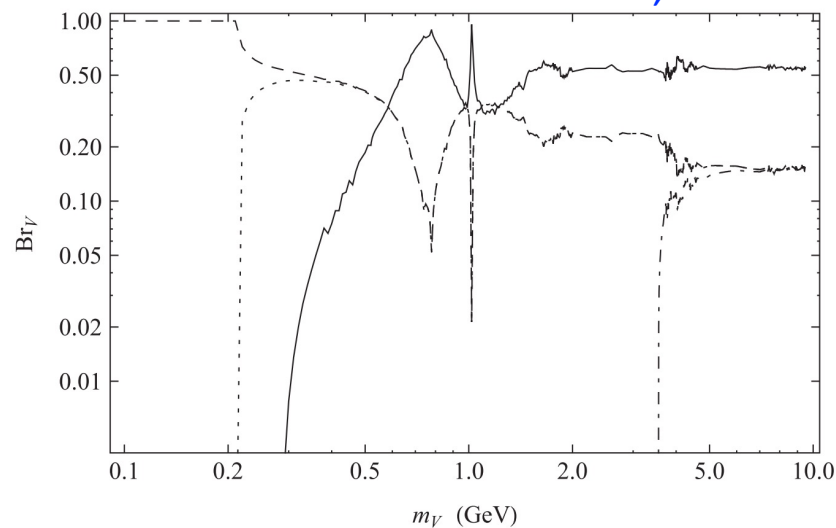
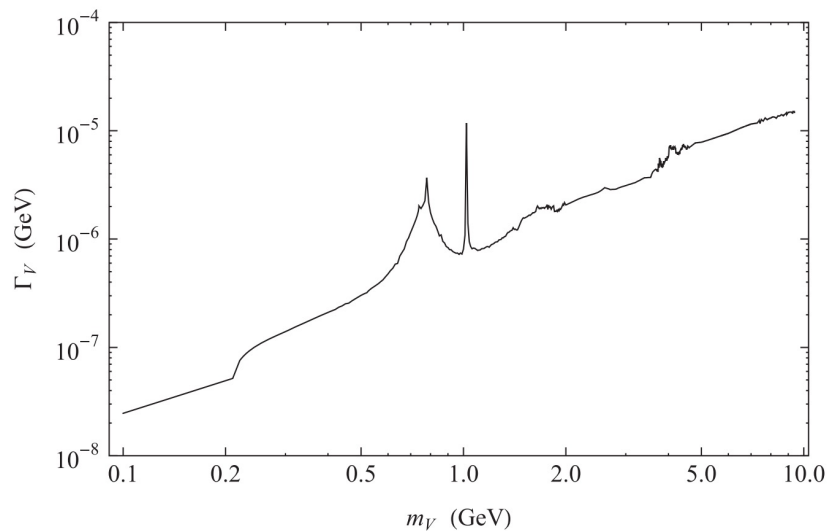
Summary

- Dark photon is a prime candidate for NP & world wide efforts to search for it
- BESIII is an active experiment (multi-purpose) in China
- Conduct dark photon searches via visible & invisible approach
- Sensitivity is similar to B-factory...

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**
 - $\phi \rightarrow U\eta, U \rightarrow e^+e^-, \eta \rightarrow \pi\pi\pi$ [Phys. Lett. B706 \(2012\) 251](#)
[Phys. Lett. B720 \(2013\) 111](#)
- **Associated $U\gamma$ production:**
 - $e^+e^- \rightarrow U\gamma$ with $U \rightarrow \mu^+\mu^-$ [Phys. Lett. B736 \(2014\) 459](#)
 - $e^+e^- \rightarrow U\gamma$ with $U \rightarrow e^+e^-$ [Phys. Lett. B750 \(2015\) 633](#)
 - $e^+e^- \rightarrow U\gamma$ with $U \rightarrow \pi^+\pi^-$ [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:**
 - $e^+e^- \rightarrow Uh',$ with $h' \rightarrow$ invisible and $U \rightarrow \mu^+\mu^-$ [Phys. Lett. B 747 \(2015\) 365](#)
- **Leptophobic B boson search (ongoing)**

$\omega/\phi \rightarrow \text{invisible}$

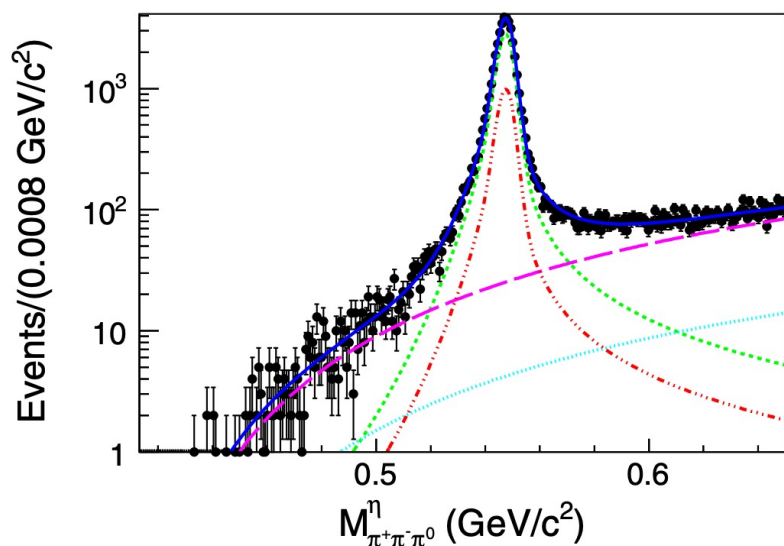
- $N(J/\psi) = 1.3$ Billion
- $\text{Br}(J/\psi \rightarrow \eta\omega/\eta\phi) \sim 17.4/7.5 \times 10^{-4}$
- Yield $\sim 1 - 5$ Million
- Will update to 10 Billion

BESIII

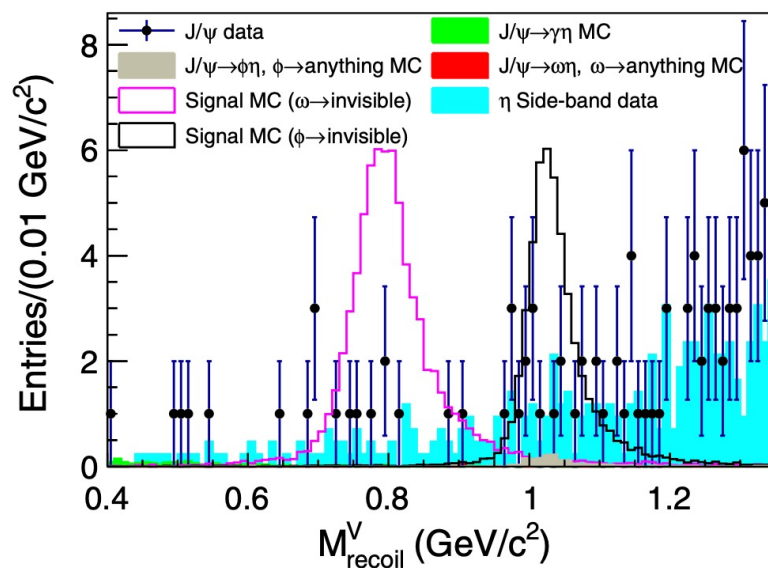
Phys. Rev. D 98, 032001 (2018)

$$\text{Br}(\omega \rightarrow \text{invisible}) < 7.3 \times 10^{-5}$$

$$\text{Br}(\phi \rightarrow \text{invisible}) < 1.7 \times 10^{-4}$$



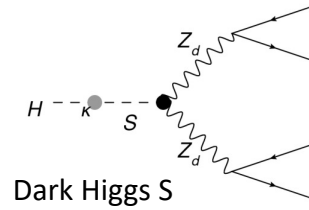
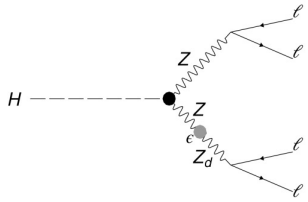
Reconstruct $\eta \rightarrow \pi^+\pi^-\pi^0$ decay



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

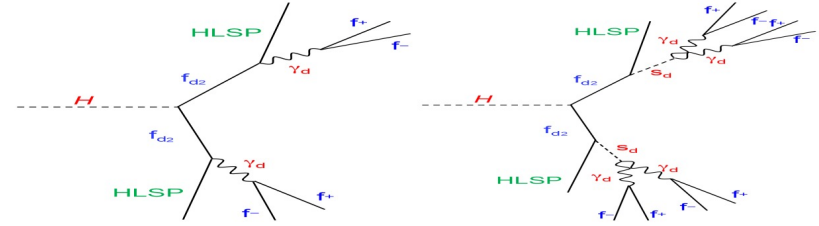
ATLAS search

JHEP 06 (2018) 166

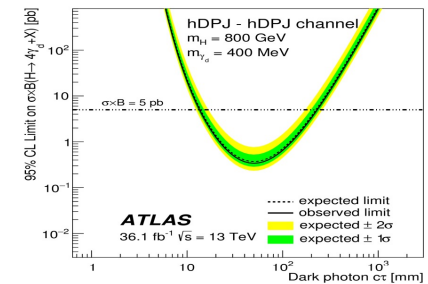
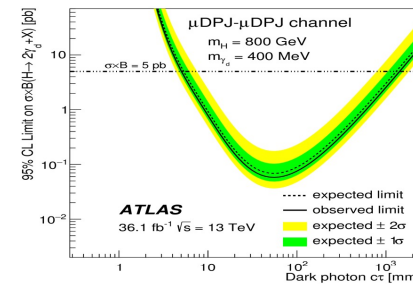
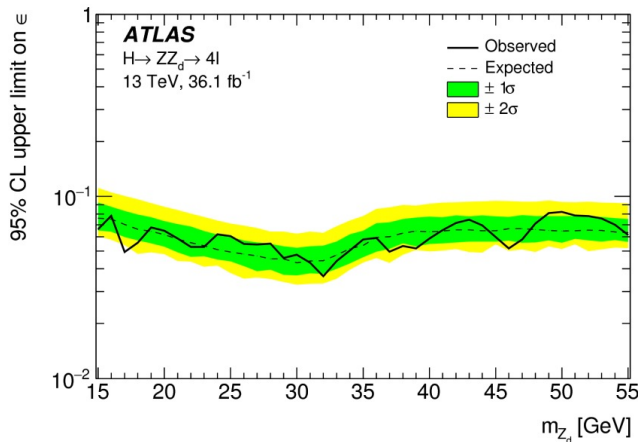
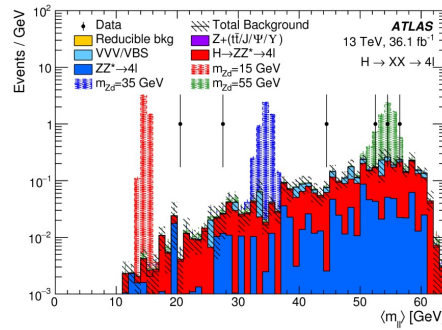
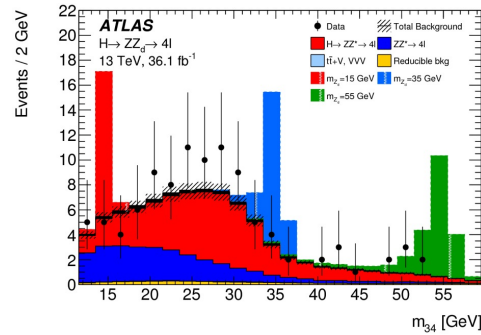


Dark Higgs S

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



Dark fermion fd_2
hidden lightest stable particle
Dark scalar sd & dark photon γ_d



Backup

