New Physics Searches at BESIII

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(On behalf of the BESIII Collaboration)

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Outline

1. Search for New Physics at BESIII
2. BSM Phenomena
   - Dark photon
   - Invisible quarkonium decay
   - Light Higgs boson
3. Forbidden Processes
4. Summary and Prospects

Outline

BEPCII and BESIII at IHEP, Beijing

Beijing Electron Positron Collier II

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Beijing Electron Positron Collier II

Beam energy: $1.0 - 2.3\,\text{GeV}$

Peak luminosity: $1.00 \times 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$

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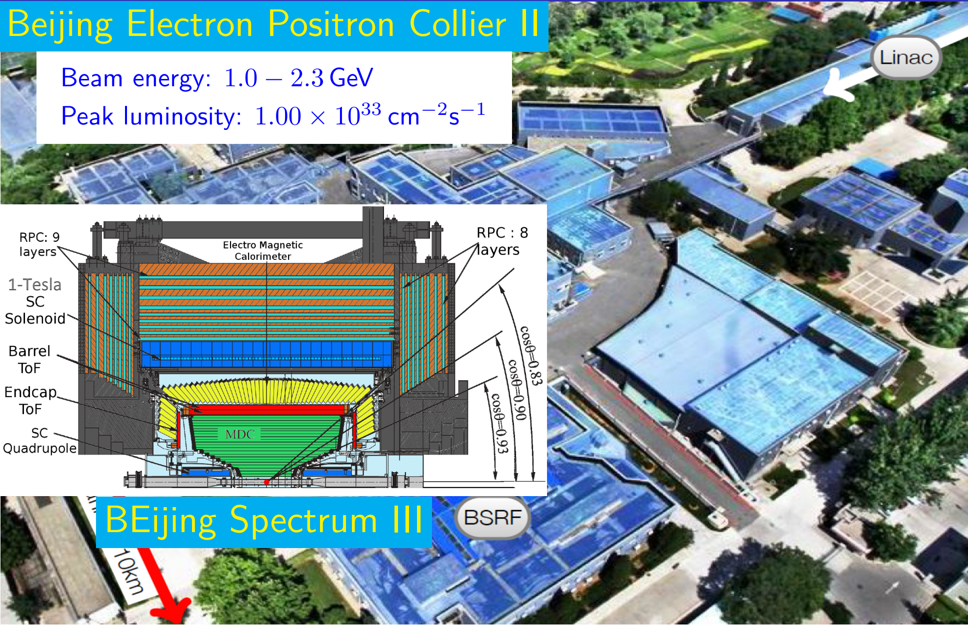

BEijing Spectrum III

BEPCII and BESIII at IHEP, Beijing

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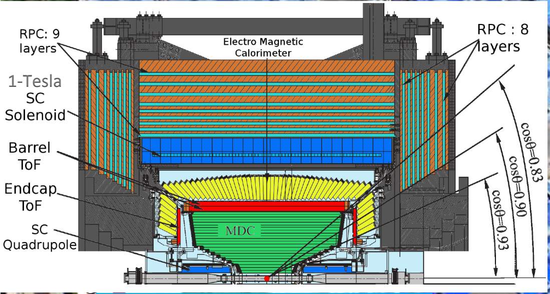


BEijing Spectrum III

NIM A **614**, 345 (2010)

Good detector performance

MDC: $\frac{\sigma_p}{p} = 0.5\%$ @ 1 GeV/c

$\mathrm{d}E/\mathrm{d}x = 6\%$

$\sigma_{xy} = 120\,\mu$m

EMC: $\frac{\Delta E}{E} = 2.5\%$ @ 1 GeV

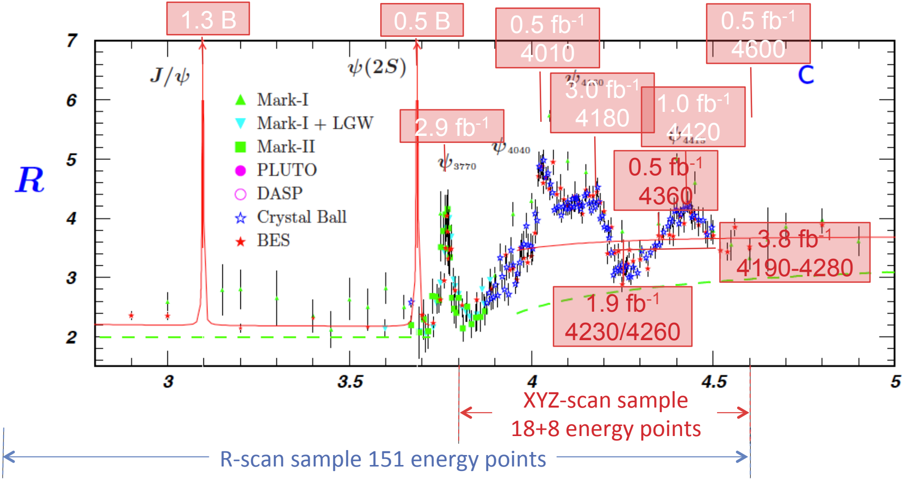
$\sigma = 0.6$ cm

TOF: $\sigma_T =$ 80 ps (Barrel)

110 ps (Endcap)

60 ps for ETOF since 2015

Data samples



- World largest data samples on J/ψ, $\psi(2S)$, $\psi(3770)$, unique XYZ
- More J/ψ data were taken in 2018, available for physics study soon

Highlights of new physics searches at BESIII

- BSM phenomena – BSM resonances, invisible quarkonium decays
  - ✔ $e^+e^- \to \gamma_{\text{ISR}}\gamma', \gamma' \to e^+e^-$ — Dark photon
  - ✔ $J/\psi \to \eta/\eta'\,\gamma', \gamma' \to e^+e^-$ — Dark photon
  - ✔ $J/\psi \to \eta\,\omega/\phi, \omega/\phi \to$ invisible — Invisible quarkonium decay
  - ✔ $J/\psi \to \gamma A^0, A^0 \to \mu^+\mu^-$ — Light Higgs boson
- Forbidden processes – Baryon/lepton number, lepton flavor violations
  - ✔ $J/\psi \to \Lambda_c^+ e^- + \text{c.c.}$ — BNV+LNV
- Rare processes – FCNC, weak decays of charmonium $c \to d, c \to s$
  - ✔ $\psi(2\text{S}) \to \Lambda_c^+ \bar{p} e^+ e^-$ — FCNC
  - ✔ $\psi(n\text{S}) \to D^0 e^+ e^-$ — FCNC
  - ✔ $D \to h(h')e^+e^-$ — FCNC

  See Dayong Wang, Peking University, July 7
- Precision measurements – e.g. lepton universality test

Outline

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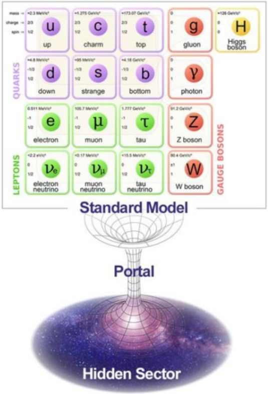
Dark sector and portal

- Numerous astrophysical observations strongly suggest the existence of DM, which provides a hint of dark sector (hidden sector)
- There could exist many dark sectors that communicate with the SM sector via portals



R. Essig et al., arXiv:1311.0029 (2013)

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	$y_N L H N$

Dark photon

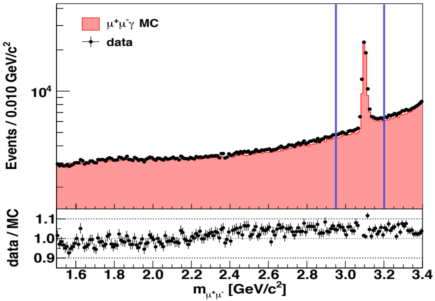
- Postulate an extra $\mathrm{U}(1)$ gauge symmetry, and the corresponding gauge boson is called dark photon or U boson, γ', A', Z'_d
- It can decay into light DM particles $\chi\chi$ (invisible decays)
- or decay into the SM $q\bar{q}, \ell^+\ell^-, \nu\bar{\nu}$ (visible/invisible decays)
  - ✔ direct and very weak interaction
  - ✔ kinetic mixing with the SM photon, or mass mixing with the Z

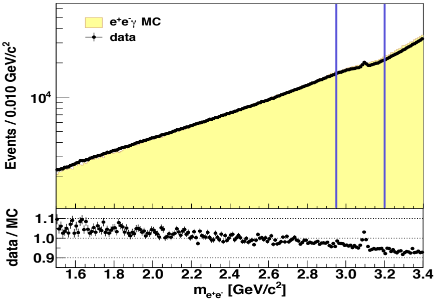
$$\mathcal{L}_{\text{int}} = -\left(\varepsilon e J_\mu^{\text{EM}} + \varepsilon_Z \frac{g}{2\cos\theta_W} J_\mu^{\text{NC}}\right) Z_d^\mu$$

  - mixing strength $\varepsilon = \sqrt{\alpha'/\alpha} \sim 10^{-2} - 10^{-5}$ (could be smaller)
  - mass ranges: $\mathrm{MeV}/c^2 - \mathrm{GeV}/c^2$ (ε_Z suppressed by $(m_{A'}/m_Z)^2$)

A resonant structure in the invariant mass spectrum

- Initial state radiation process: $e^+e^- \to \gamma_{\text{ISR}}\gamma', \gamma' \to \ell^+\ell^-, \ell = e, \mu$
- Search for a narrow structure in $m_{\ell^+\ell^-}$ on top of the continuum QED background ($e^+e^- \to \gamma_{\text{ISR}}\ell^+\ell^-$)
  - ✔ Mass range b/w 1.5 & $3.4\,\text{GeV}/c^2$ is studied
  - ✔ J/ψ region excluded





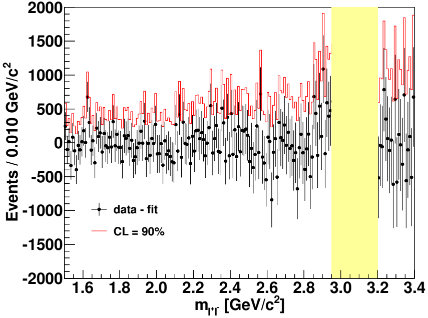
Dark photon search (1)

$e^+e^- \to \gamma_{\text{ISR}}\gamma', \gamma' \to \ell^+\ell^-$

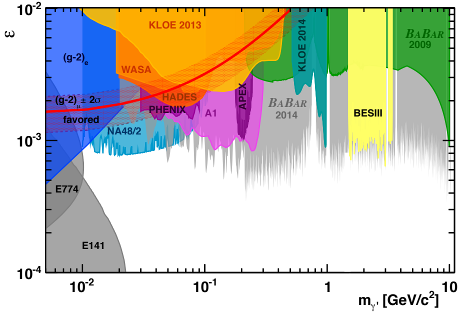
Phys. Lett. B **774**, 252 (2017)

$2.93\,\text{fb}^{-1}$ $\psi(3770)$

- Fit $m_{\mu^+\mu^-}$ and $m_{e^+e^-}$ of data (4^{th} order polynomials)
- Calculate mass differences b/w data & fit for μ and e respectively
- No peaking structure is observed in the combined "(data − fit)"



- Upper limits on ε @ 90% C.L.: $10^{-3} - 10^{-4}$ (comparable to BaBar)



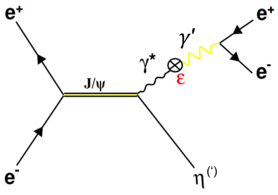
Dark photon search (2)

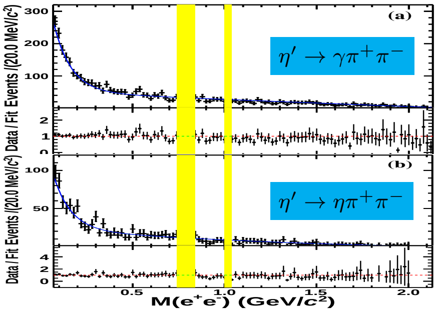
$J/\psi \to \eta'/\eta\gamma', \gamma' \to e^+e^-$

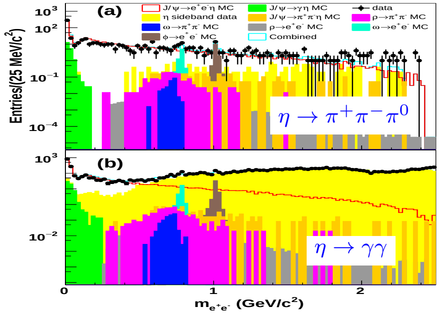
BESIII Preliminary (2018)

$1310.6 \times 10^6 \ J/\psi$

- First search for γ' in E.M. Dalitz decays:
  - $J/\psi \to \eta'\gamma', \gamma' \to e^+e^-$ $\quad \eta' \to \gamma/\eta\,\pi^+\pi^-$
  - $J/\psi \to \eta\gamma', \gamma' \to e^+e^-$ $\quad \eta \to \gamma\gamma$ or $\pi^+\pi^-\pi^0$
- Look for a narrow peaking structure in the $m_{e^+e^-}$ on top of background







Dark photon search (2)

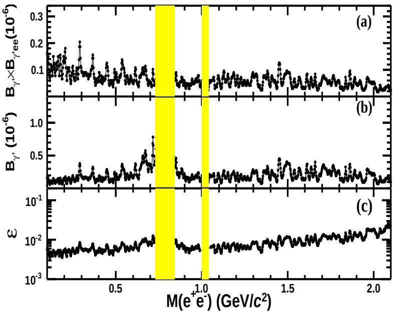
$J/\psi \to \eta'/\eta\gamma', \gamma' \to e^+e^-$

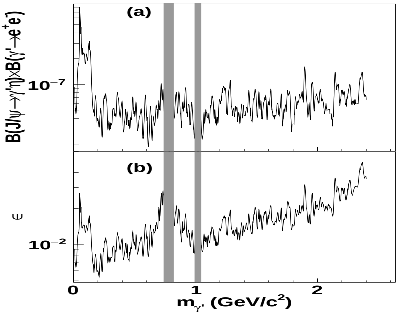
BESIII Preliminary (2018)

$1310.6 \times 10^6 \ J/\psi$

- No obvious peaking structures are observed
- Fit $m_{e^+e^-}$ of data to obtain signal yields (ω, ϕ regions excluded)
- Combined results of 90% C.L. limits on BF and ε

	$\mathcal{B}(\psi \to P\gamma')\mathcal{B}(\gamma' \to e^+e^-)$	$\mathcal{B}(\psi \to P\gamma')$	ε
$P = \eta'$	$< 1.8\times10^{-8} - 2.0\times10^{-7}$	$< 6.0\times10^{-8} - 7.8\times10^{-7}$	$3.4\times10^{-3} - 2.6\times10^{-2}$
$P = \eta$	$< 1.9\times10^{-8} - 9.1\times10^{-7}$		$10^{-3} - 10^{-2}$





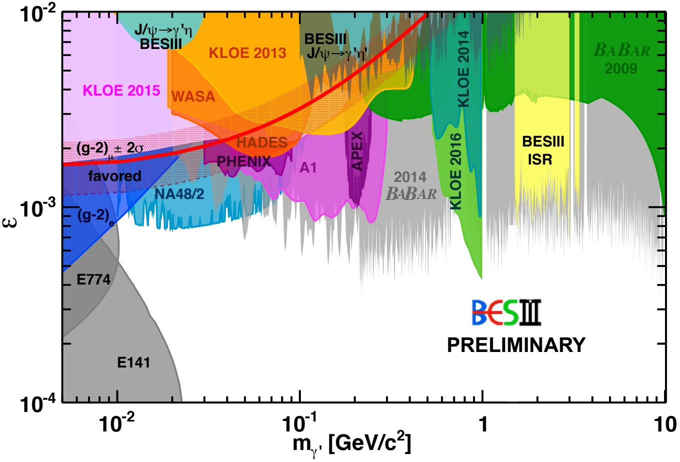
Dark photon search (2)

$J/\psi \to \eta'/\eta\gamma', \gamma' \to e^+e^-$

BESIII Preliminary (2018)

$1310.6 \times 10^6 \ J/\psi$

- Constraints on ε (also shown are those from other experiments)



Outline

Invisible decay

- Quarkonium states $(q\bar{q})$ can annihilate into $\nu\bar{\nu}$ via virtual Z^0 boson

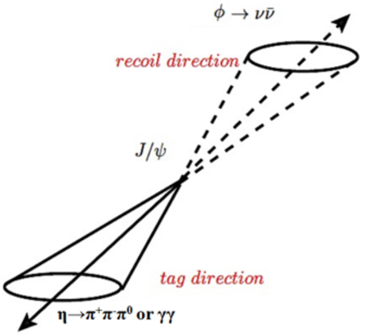
$$\mathcal{B}(\omega \to \nu\bar{\nu}) = 8.4 \times 10^{-14}, \qquad \mathcal{B}(\phi \to \nu\bar{\nu}) = 5.8 \times 10^{-12}$$

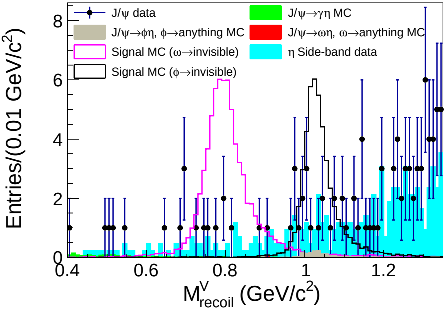
- If a singlet scalar, pseudoscalar or vector (portal) is present, and mediates the SM-DM interaction, it can mediate invisible decay of quarkonium states
- $\mathcal{B}$ of invisible decay might be enhanced in the presence of light DM particles

mode	s-wave	p-wave
$\mathrm{BR}(\Upsilon(1S) \to \chi\chi)$	4.2×10^{-4}	1.8×10^{-3}
$\mathrm{BR}(\Upsilon(1S) \to \nu\bar{\nu})$	9.9×10^{-6}	
$\mathrm{BR}(J/\Psi \to \chi\chi)$	2.5×10^{-5}	1.0×10^{-4}
$\mathrm{BR}(J/\Psi \to \nu\bar{\nu})$	2.7×10^{-8}	
$\mathrm{BR}(\eta \to \chi\chi)$	3.4×10^{-5}	1.4×10^{-4}
$\mathrm{BR}(\eta' \to \chi\chi)$	3.7×10^{-7}	1.5×10^{-6}
$\mathrm{BR}(\eta_c \to \chi\chi)$	1.3×10^{-7}	5.3×10^{-7}
$\mathrm{BR}(\chi_{c0}(1P) \to \chi\chi)$	2.7×10^{-8}	1.2×10^{-7}
$\mathrm{BR}(\phi \to \chi\chi)$	1.9×10^{-8}	7.8×10^{-8}
$\mathrm{BR}(\omega \to \chi\chi)$	7.2×10^{-8}	3.0×10^{-8}

B. McElrath, eConf C070805, 19, (2007)

- First search for $J/\psi \to \eta\,\omega/\phi, \omega/\phi \to$ invisible, $\eta \to \pi^+\pi^-\pi^0$
- Define recoiling mass against η: $M^V_{\text{recoil}} \equiv \sqrt{(E_{\text{CM}} - E_{3\pi})^2 - \vec{p}^{\,2}_{3\pi}}$





Invisible decay search

$J/\psi \to \eta\omega/\phi, \omega/\phi \to$ invisible

Accepted by PRD, arXiv:1805.05613

$1310.6 \times 10^6\ J/\psi$

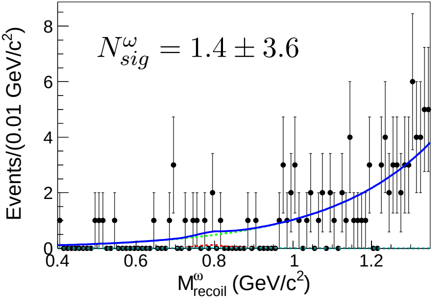
- Fit M^V_{recoil} to obtain signal yield
- No obvious signals observed, set 90% C.L. UL's

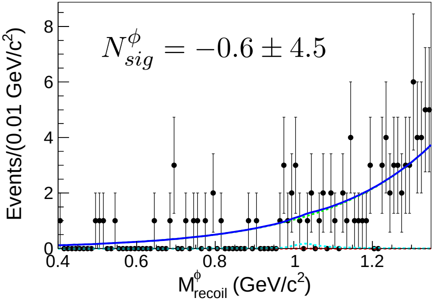
$$\frac{\mathcal{B}(\omega \to \text{invisible})}{\mathcal{B}(\omega \to \pi^+\pi^-\pi^0)} < 8.1 \times 10^{-5}$$

$$\mathcal{B}(\omega \to \text{invisible}) < 7.3 \times 10^{-5}$$

$$\frac{\mathcal{B}(\phi \to \text{invisible})}{\mathcal{B}(\phi \to K^+K^-)} < 3.4 \times 10^{-4}$$

$$\mathcal{B}(\phi \to \text{invisible}) < 1.7 \times 10^{-4}$$



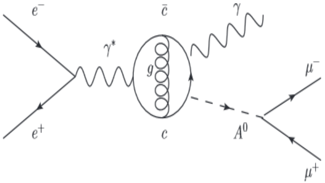


Outline

NMSSM and light Higgs boson

- The NMSSM has a rich Higgs sector: 2 charged, 3 neutral CP-even, 2 neutral CP-odd. The lightest CP-odd Higgs is denoted as A^0 or a_1
- If $m_{A^0} < 2m_c$, it is possible for J/ψ (and Υ) to decay into γA^0

$$\mathcal{B}(\Upsilon \to \gamma A^0) \propto \cos\theta_A \tan\beta$$
$$\mathcal{B}(J/\psi \to \gamma A^0) \propto \cos\theta_A \cot\beta$$



$$A^0 = \cos\theta_A A_{\text{MSSM}} + \sin\theta_A A_{\text{S}}$$

$\cos\theta_A$: parameterizes how singlet-like the A^0 is

$\tan\beta = \frac{v_u}{v_d}$: ratio of the VEV's of the up and down types of the Higgs doublets

- $\mathcal{B}(J/\psi \to \gamma A^0)$ in NMSSM: $\sim 10^{-7} - 10^{-9}$ PRD **76**, 051105 (2007)
- A^0 can decay into DM (neutralinos) or SM particles, such as $\mu^+\mu^-$

Ligh Higgs boson search

$J/\psi \to \gamma A^0, A^0 \to \mu^+\mu^-$

Phys. Rev. D **93**, 052005 (2016)

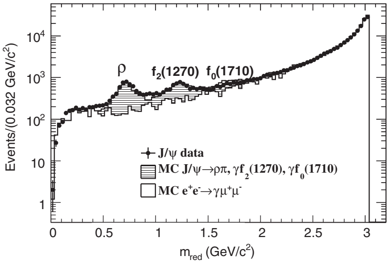
$225 \times 10^6 \; J/\psi$

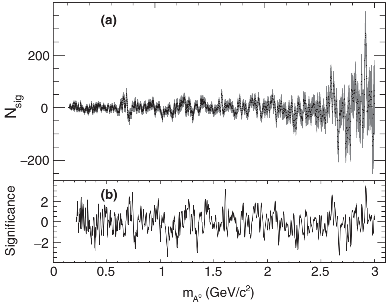
- $J/\psi \to \gamma A^0, A^0 \to \mu^+\mu^-$
- Define reduced dimuon mass

$$m_{\text{red}} = \sqrt{m^2_{\mu^+\mu^-} - 4m^2_\mu}$$

- Fit m_{red} to determine signal yields N_{sig} as a function of m_{A^0} in the range of

$$m_{A^0} \in [0.212, 3.0]\,\text{GeV}/c^2$$





Ligh Higgs boson search

$J/\psi \to \gamma A^0, A^0 \to \mu^+\mu^-$

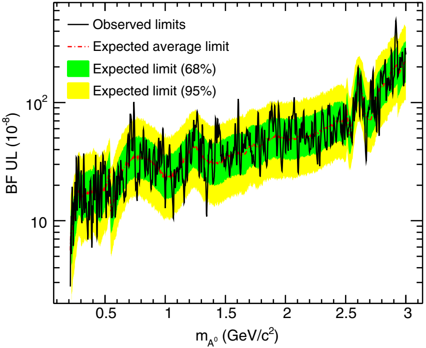
Phys. Rev. D **93**, 052005 (2016)

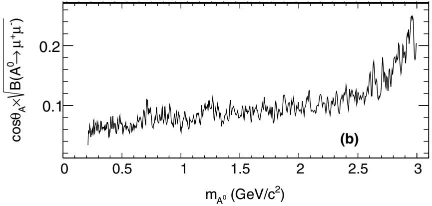
$225 \times 10^6\ J/\psi$

- No evidence of A^0 is found at any mass points
- UL's on the production BF @ 90% C.L.

$$\mathcal{B}(J/\psi \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-) < 2.8 \times 10^{-8} - 4.95 \times 10^{-6}$$

A factor of five times better than BESIII 2012 results PRD **85**, 092012 (2012)



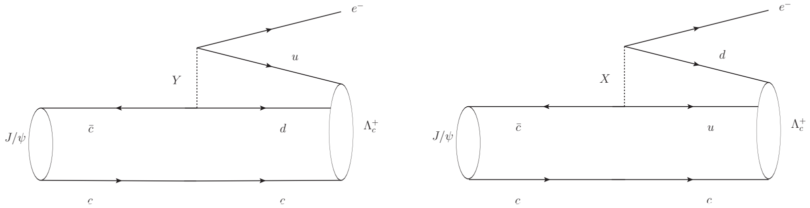


Combined with the BaBar result, A^0 is constrained to be mostly singlet

Outline

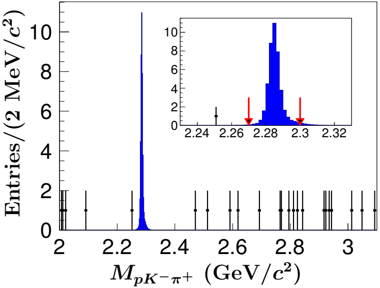
BNV and LNV processes

- Many SM extensions and Grand Unified Theories such as superstring models and SUSY predict proton decays. In this case, baryon number is violated while the difference $\Delta(B-L)$ is conserved
- In the assumption of the heavy bosons $X(4/3e)$ and $Y(1/3e)$, there exists BNV processes via $\bar{c}Yd$ or $\bar{c}Xu$ couplings, e.g. $J/\psi \to \Lambda_c^+ e^-$



- Any detection of BNV and/or LNV decay indicates the existence of new physics

- First search for $J/\psi \to \Lambda_c^+ e^- + \text{c.c.}$, $\Lambda_c^+ \to pK^-\pi^+$
- Examine $M_{pK^-\pi^+}$ distribution
- No events are observed in the signal window



- Upper limit @ 90% C.L. on the BF

$$\mathcal{B}(J/\psi \to \Lambda_c^+ e^-) < 6.9 \times 10^{-8}$$

More than two orders of magnitude more strict than CLEO's measurement in the analogous process $D^0 \to \bar{p}e^+ + \text{c.c.}$

P. Rubin et al., PRD **79**, 097101 (2009)

Outline

Summary and prospects

- Clean and large e^+e^- data samples taken near threshold at BESIII are well suited to indirect searches for new physics
- Many recent results on exotic phenomena and forbidden decays
  - ✔ Dark photon with ISR: $e^+e^- \to \gamma_{\text{ISR}}\gamma', \gamma' \to e^+e^-$
    $J/\psi \to \eta/\eta'\,\gamma', \gamma' \to e^+e^-$
  - ✔ Invisible decay of light quarkonium: $J/\psi \to \eta\,\omega/\phi, \omega/\phi \to$ invisible
  - ✔ Light CP-odd Higgs boson: $J/\psi \to \gamma A^0, A^0 \to \mu^+\mu^-$
  - ✔ Baryon and lepton number violation process: $J/\psi \to \Lambda_c^+ e^- + \text{c.c.}$
- Also at ICHEP2018
  - ✔ Search for FCNC's at BESIII, Dayong Wang, PKU, July 7
- More to come, especially with newly acquired J/ψ data sample