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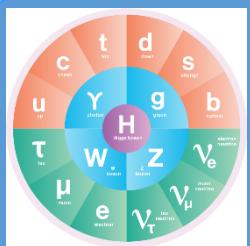
BSM searches with Charmonium at BESIII

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(On behalf of the BESIII collaboration)

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Beyond the Standard Model (BSM) new physics



BSM ?

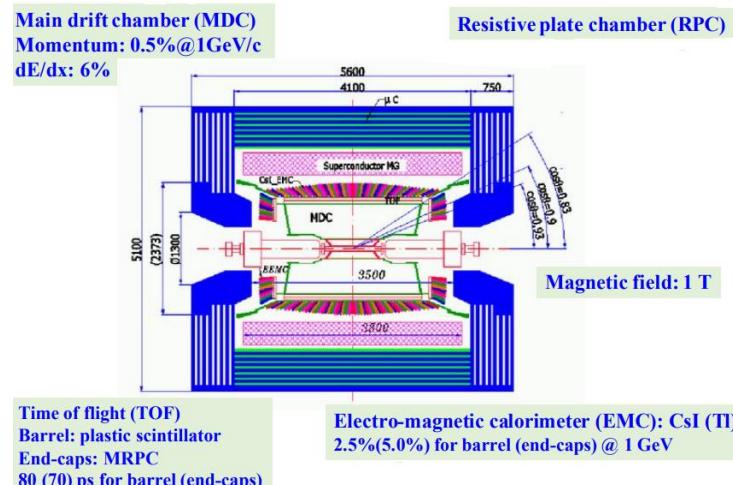
- Unification of forces...
- Anomalous physical observations...
- Neutrino mass and oscillation...
- Dark sectors...

High luminosity

- Huge on-resonance charmonium data samples
 - $\sim 1.3 \text{ B } J/\psi$ events
 - $\sim 0.5 \text{ B } \psi(3686)$ events
 - $\sim 2.9 \text{ fb}^{-1} \psi(3770)$ data

High precision

- Good detector performance



BSM Search with charmonium at BESIII

- Exotic particle

- ✓ Dark photon (γ')

- $J/\psi \rightarrow \eta'\gamma'$
 - $e^+e^- \rightarrow \gamma\gamma' @ \psi(3770)$



Preliminary
arXiv: 1705.04265,
accepted by PLB

- ✓ Light exotic particle (A^0)

- $\psi(3686) \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \gamma A^0$
 - $J/\psi \rightarrow \gamma A^0$

PRD 85,092012(2012)
PRD 93,052005(2016)

- FCNC process search

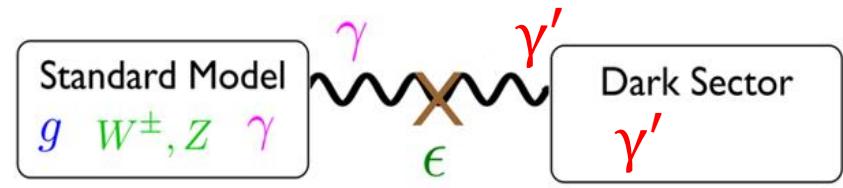
- J/ψ and $\psi(3686) \rightarrow D^0 e^+ e^- + c.c.$



arXiv:1710.02278

Dark photon

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



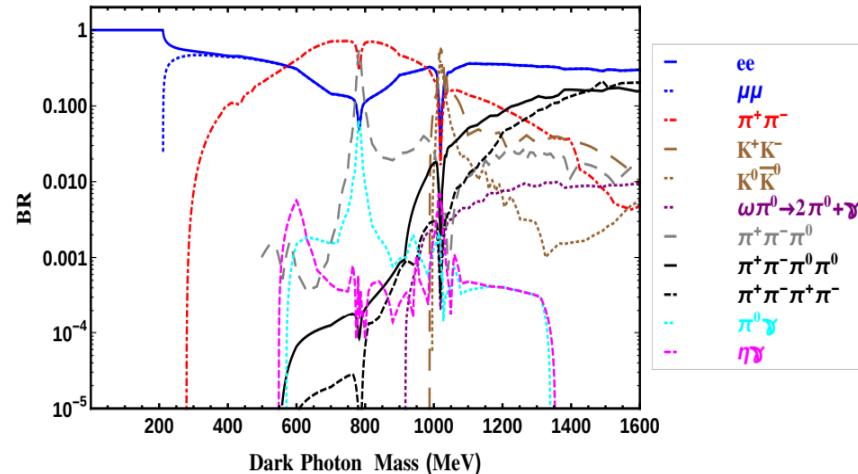
ordinary photon & γ' can mix

$$\Delta \mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} \quad \text{“Kinetic Mixing”}$$

- Dark photon, dubbed as γ' , A', U
- **Mixing strength: ϵ : 10^{-2} - 10^{-5} , Mass: O(MeV~GeV)** PRD 79,015014 (2009)

- Explain many astrophysical anomalies
PRD 79, 015014 (2009), arXiv:1008.4519
- Promising way:

$\checkmark \gamma' \rightarrow e^+e^-/\mu^+\mu^-$



JHEP 08, 050 (2015); 1412.1485

Dark photon search (I): $J/\psi \rightarrow \eta' \gamma'$

- $(1310 \pm 7.0) \times 10^6 J/\psi$ events

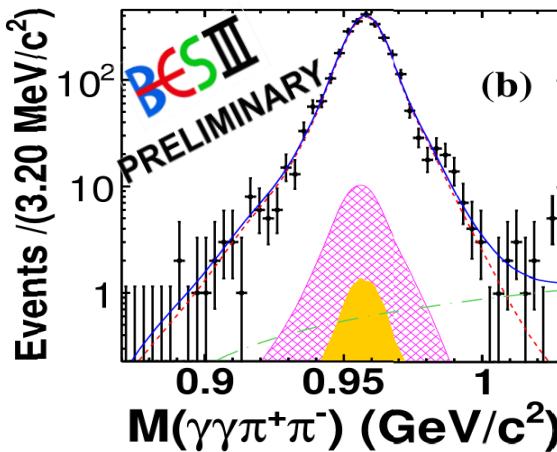
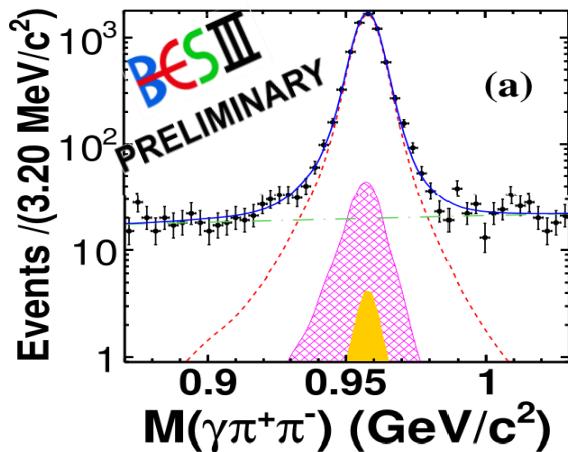
- Topology:

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

- $\eta' \rightarrow \gamma \pi^+ \pi^-$

- $\eta' \rightarrow \pi^+ \pi^- \eta (\gamma \gamma)$

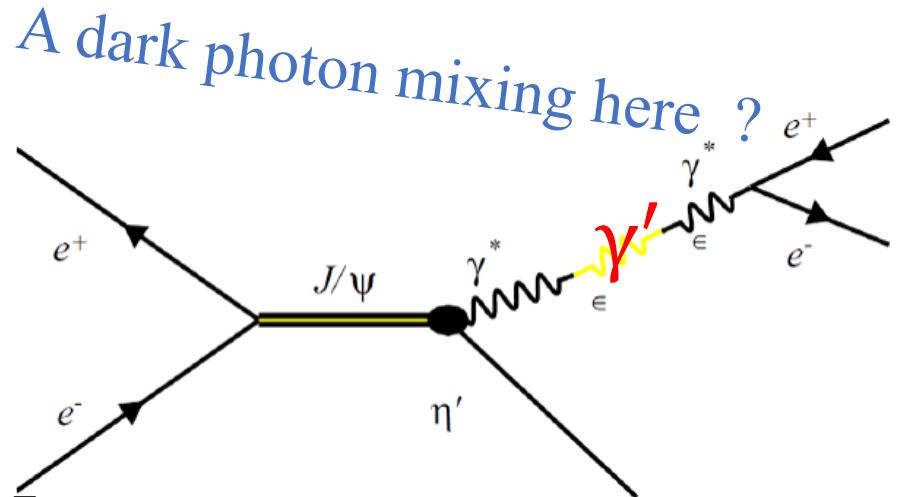
- Candidates selection: $J/\psi \rightarrow \eta' e^+ e^-$



- Update the branching fraction:

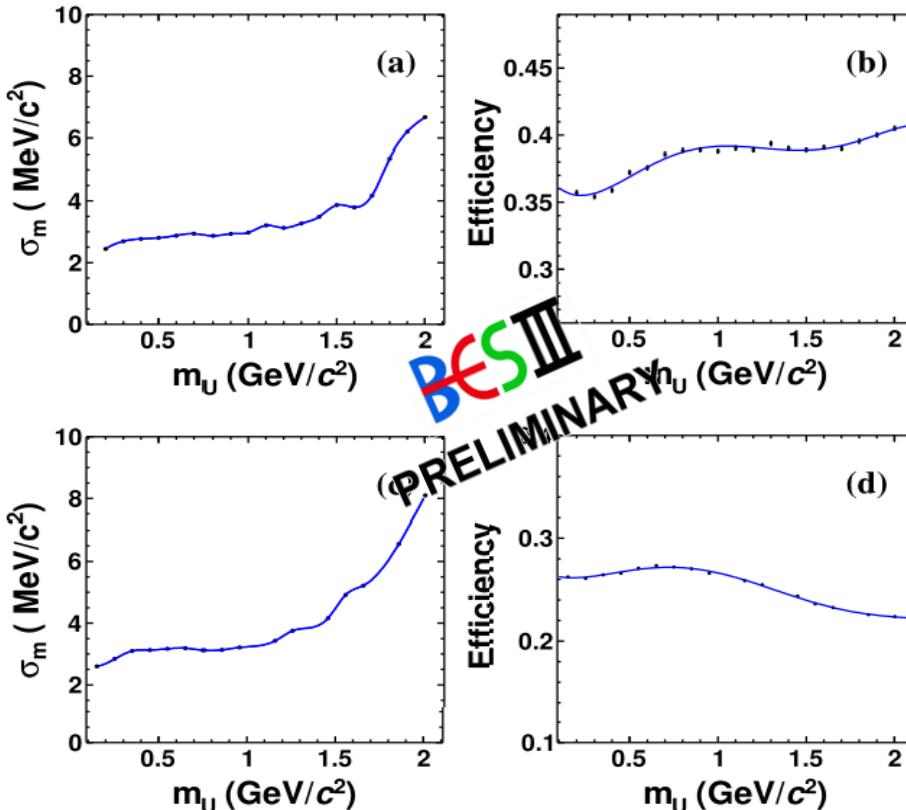
$$B(J/\psi \rightarrow \eta' e^+ e^-) = (5.83 \pm 0.07(stat) \pm 0.30(syst)) \times 10^{-5}$$

Consistent with previous measurement with improved uncertainty.



- η' signal
- Non-peaking background
- Peaking background:
 γ conversion/ $J/\psi \rightarrow \Phi\eta$

Dark photon search (I): $J/\psi \rightarrow \eta' \gamma'$



$\eta' \rightarrow \gamma\pi^+\pi^-$

- ◆ σ_m : 2 - 7 MeV
- ◆ Efficiency: 35 - 41 %

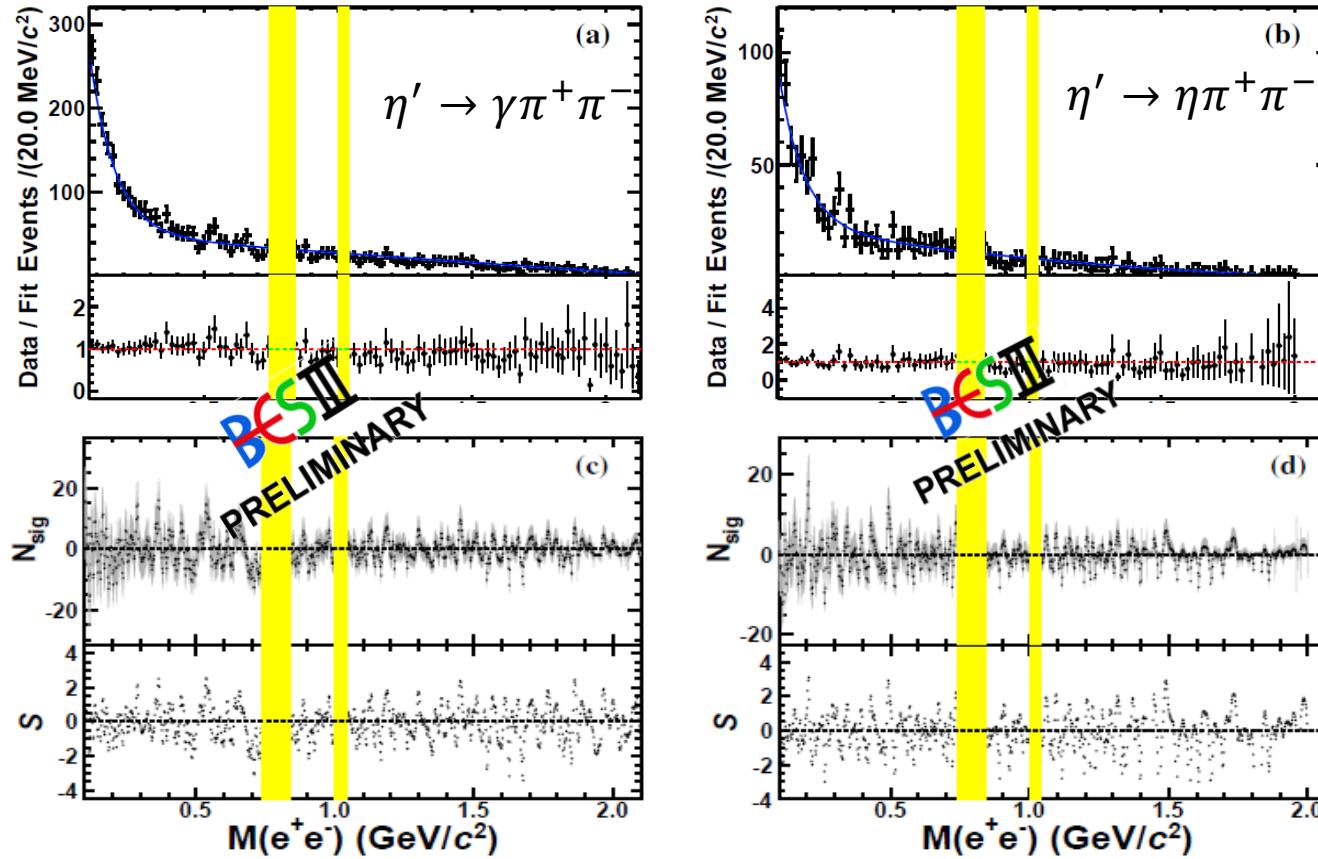
$\eta' \rightarrow \eta\pi^+\pi^-$

- ◆ σ_m : 2 - 8 MeV
- ◆ Efficiency: 22 - 28 %

- ◆ Signal Shape: A sum of two-crystal ball function

$$y = CB_1(x; \mu, \sigma_1, n1, \alpha_1) + f * CB_2(x; \mu, \sigma_2, n2, \alpha_2)$$
- ◆ The resolution σ_m of dark photon signal and selection efficiency depend on dark photon mass m_γ ,
- ◆ The efficiency and PDF parameters are interpolated between the known mass points.

Dark photon search (I): $J/\psi \rightarrow \eta' \gamma'$



- ◆ ω and ϕ are excluded due to low sensitivity and vector meson decay contamination

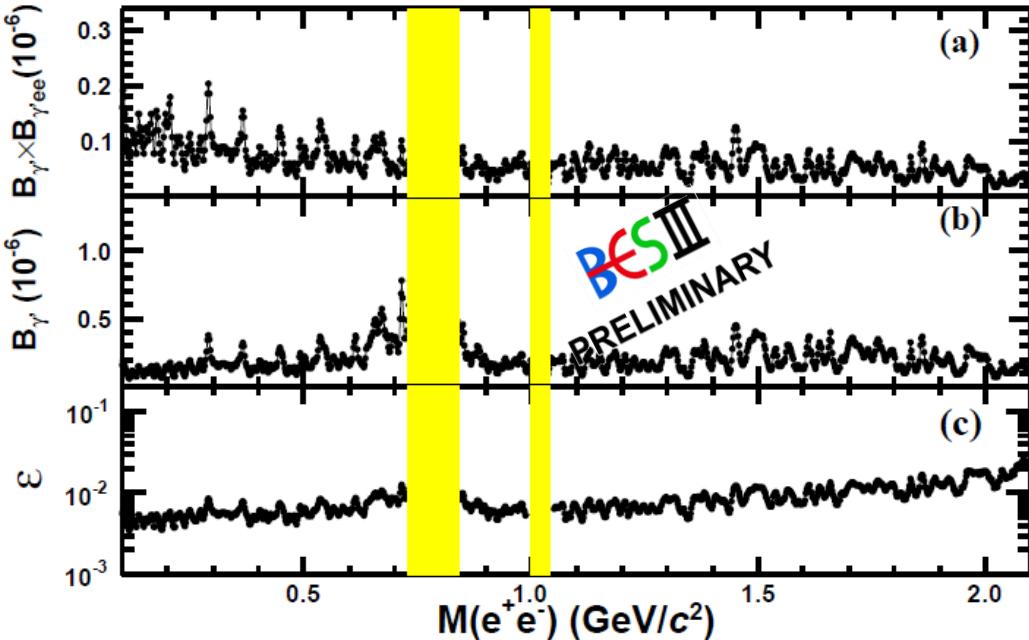
- ◆ $M(ee)$ continuum background description:

$$f(m_{e^+e^-}) = c_2 \cdot m_{e^+e^-}^2 + c_1 \cdot m_{e^+e^-} + c_0 + e^{c_3 \cdot m_{e^+e^-}}$$

- ◆ 100 MeV~ 2.1 GeV, Look for a narrow peak signal on $M(e+e-)$ by a step of 2 MeV.

- ◆ Significance $S = \text{sign}(N_{\text{sig}}) \sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})}$

Dark photon search (I): $J/\psi \rightarrow \eta'\gamma'$



$$1.8 \times 10^{-8} \sim 2.0 \times 10^{-7}$$

@90% C.L.

$$6.0 \times 10^{-8} \sim 7.8 \times 10^{-7}$$

@90% C.L.

$$3.4 \times 10^{-3} \sim 2.6 \times 10^{-2}$$

@90% C.L.

$$B_{\gamma'}: \mathcal{B}(J/\psi \rightarrow \eta'\gamma')$$

$$B_{\gamma ee}: \mathcal{B}(\gamma' \rightarrow e^+e^-)$$

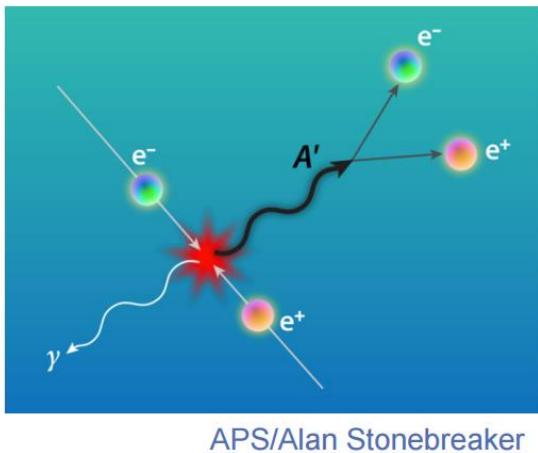
$$\frac{\mathcal{B}(J/\psi \rightarrow \eta'\gamma')}{\mathcal{B}(J/\psi \rightarrow \eta'\gamma)} = \varepsilon^2 |F(m_{\gamma'}^2)|^2 \frac{\lambda^{3/2}(m_{J/\psi}^2, m_{\eta'}^2, m_{\gamma'}^2)}{\lambda^{3/2}(m_{J/\psi}^2, m_{\eta'}^2, 0)}$$

JHEP 07(2009) 051

- Firstly search for γ' through charmonium decay $J/\psi \rightarrow \eta'\gamma'$, $\gamma' \rightarrow e^+e^-$.
- No significant dark photon signal is observed.
- Set upper limit on the branching fractions and mixing strength.

Dark photon search (II): $e^+e^- \rightarrow \gamma\gamma'$

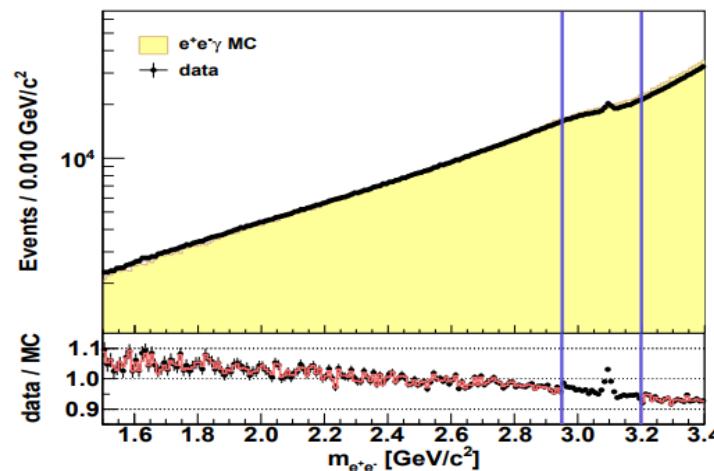
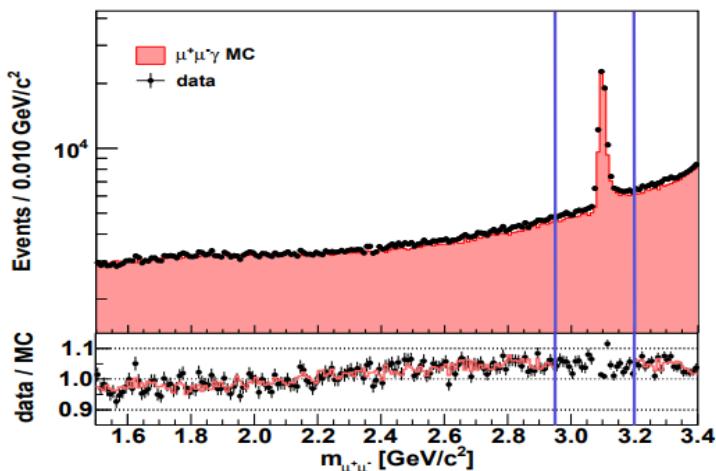
arXiv:1705.04265, accepted by PLB



- $2.9 \text{ fb}^{-1} \psi(3770)$ data
- **Initial State Radiation process:**

$$e^+e^- \rightarrow \gamma_{ISR}\gamma' \rightarrow \gamma_{ISR}\mu^+\mu^-$$

$$e^+e^- \rightarrow \gamma_{ISR}\gamma' \rightarrow \gamma_{ISR}e^+e^-$$



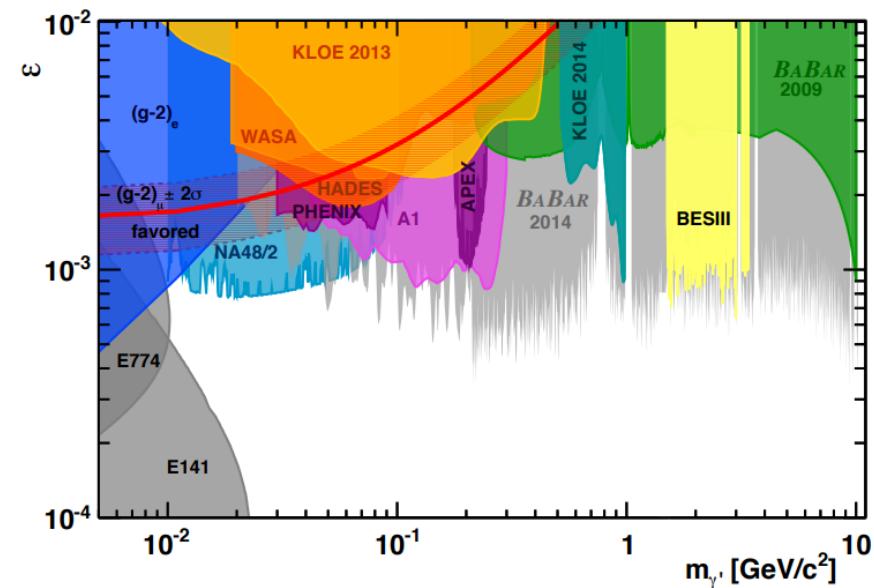
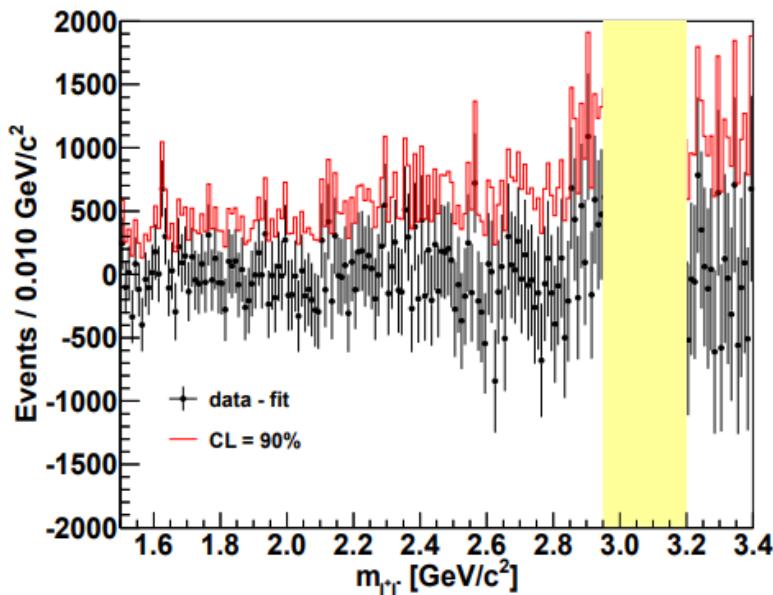
Cover mass region: $1.5 \text{ GeV}/c^2 \sim 3.4 \text{ GeV}/c^2$

- $<1.5 \text{ GeV}/c^2$: $\pi^+\pi^-$ background dominates
- $>3.4 \text{ GeV}/c^2$: hadronic $q\bar{q}$ -bar process

Dark photon search (II): $e^+e^- \rightarrow \gamma\gamma'$

arXiv:1705.04265, accepted by PLB

- Mass region 1.5~3.4 GeV
- No significant dark photon signal greater 3σ is found.



$$\frac{\sigma_i(e^+e^- \rightarrow \gamma'\gamma_{\text{ISR}} \rightarrow l^+l^-\gamma_{\text{ISR}})}{\sigma_i(e^+e^- \rightarrow \gamma^*\gamma_{\text{ISR}} \rightarrow l^+l^-\gamma_{\text{ISR}})} = \frac{3\pi}{2N_f^{l^+l^-}} \cdot \frac{\epsilon^2}{\alpha} \cdot \frac{m_{\gamma'}}{\delta_m^{l^+l^-}}$$

Phys. Rev. D 80 (2009) 075018

- ◆ Using an untagged ISR method
- ◆ Independent of radiator function
- ◆ The exclusion limit between $10^{-3} \sim 10^{-4}$ is compatible with Babar2014 and give slightly better results at some of the bins.

Light exotic particle search

- NMSSM Higgs boson family: 3 CP-even, 2 CP-odd, 2 charged
- The lightest CP-odd higgs boson (A^0) could have a mass smaller than twice the mass of c-quark.

➤ Coupling of fermions and the CP-odd Higgs A^0

$$L_{\text{int}}^{f\bar{f}} = -\cos\theta_A \tan\beta \frac{m_f}{v} A^0 \bar{d}(i\gamma_5)d, \quad d = d, s, b, e, \mu, \tau$$

$$L_{\text{int}}^{f\bar{f}} = -\cos\theta_A \cot\beta \frac{m_f}{v} A^0 \bar{u}(i\gamma_5)u, \quad u = u, c, t, v_e, v_\mu, v_\tau$$

$$\tan\beta = \frac{v_u}{v_d}$$

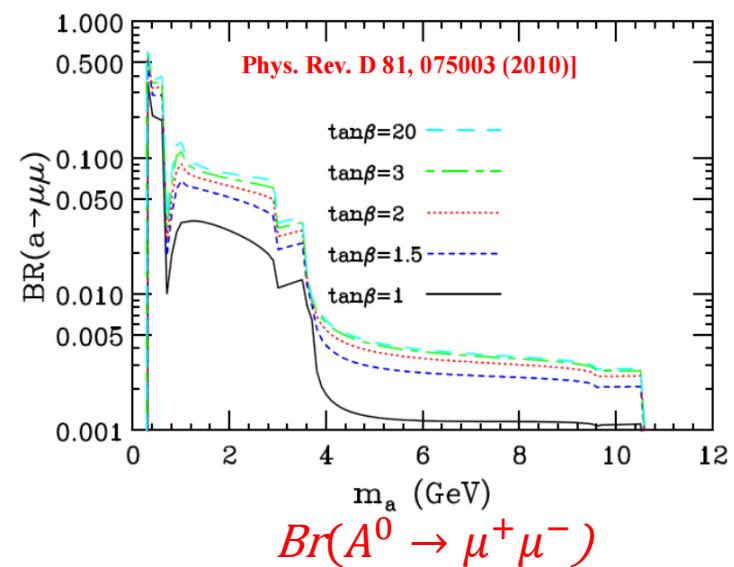
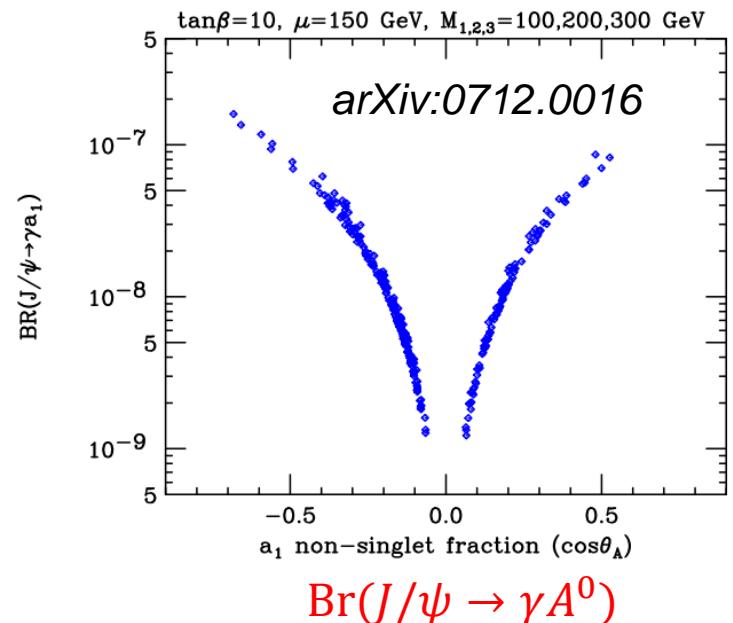
E. Fullana et. al,
Phys. Lett. B 653, 67 (2007)

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

Non-singlet Singlet

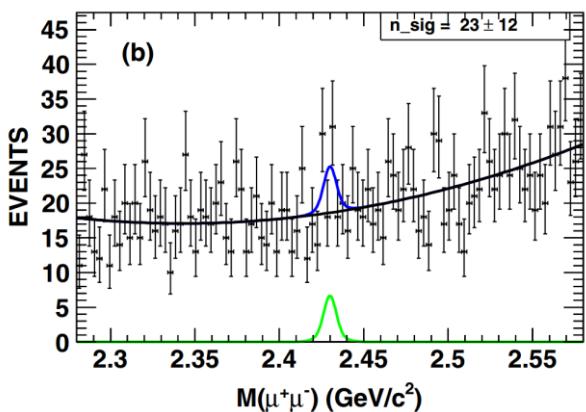
- Coupling of c-quark to the A^0 :BF~(10⁻⁷-10⁻⁹)

PRD 76, 051105 (2007)



Search(I): $J/\psi \rightarrow \gamma A^0$

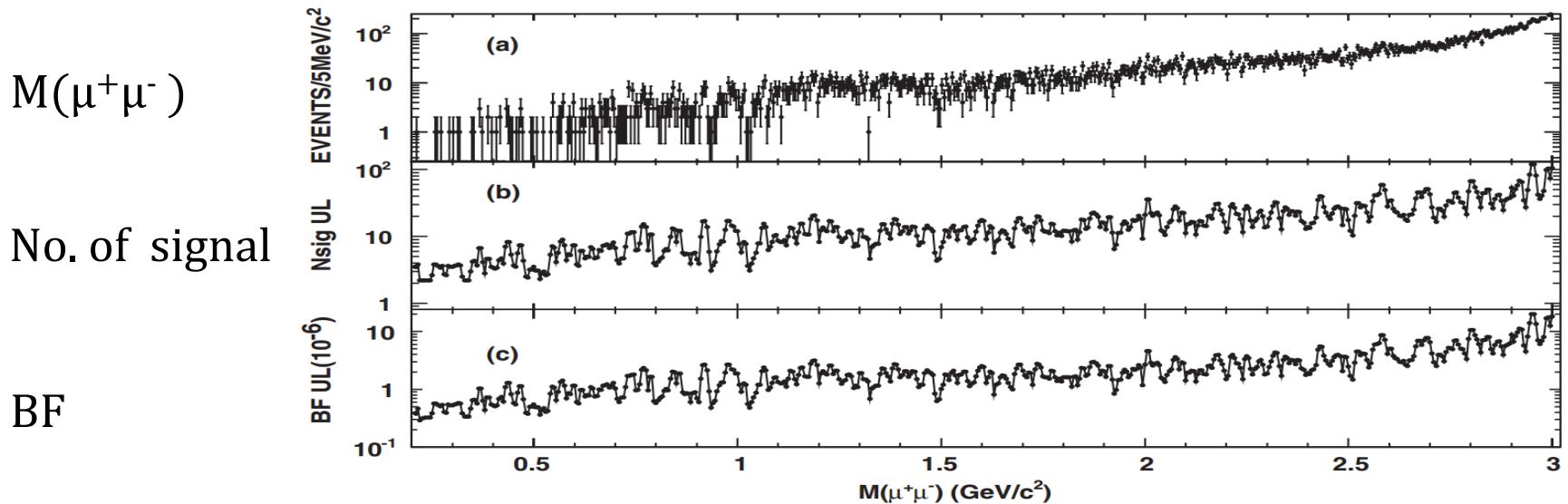
PRD 85,092012(2012)



- 106 million $\psi(3686)$ data
- Topology:

$$\psi(3686) \rightarrow \pi^+ \pi^- J/\psi, J/\psi \rightarrow \gamma A^0 (\mu^+ \mu^-)$$

$$\mathcal{B} < \frac{\text{Nsig(UL)}/\varepsilon}{N(\psi') \times \mathcal{B}(\psi' \rightarrow \pi^+ \pi^- J/\psi) \times (1 - \sigma)},$$



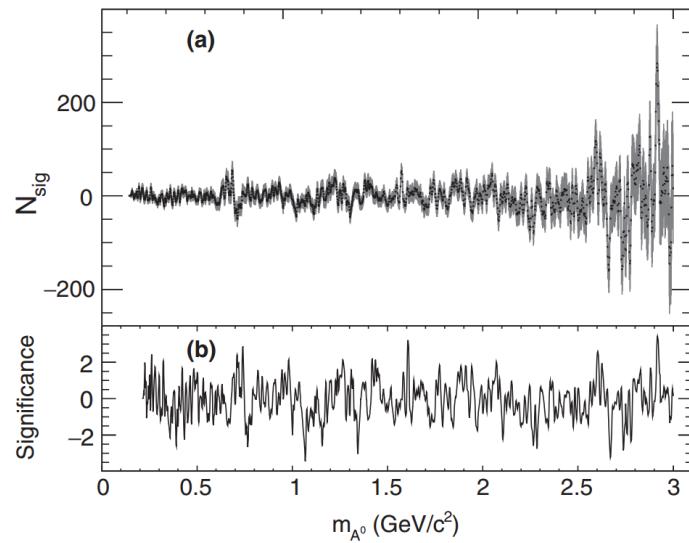
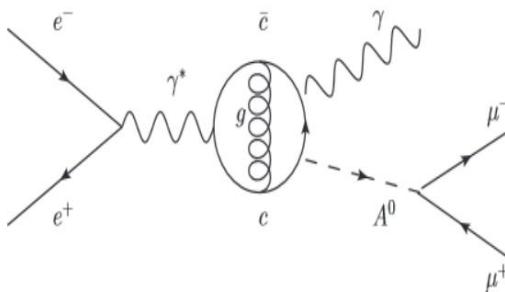
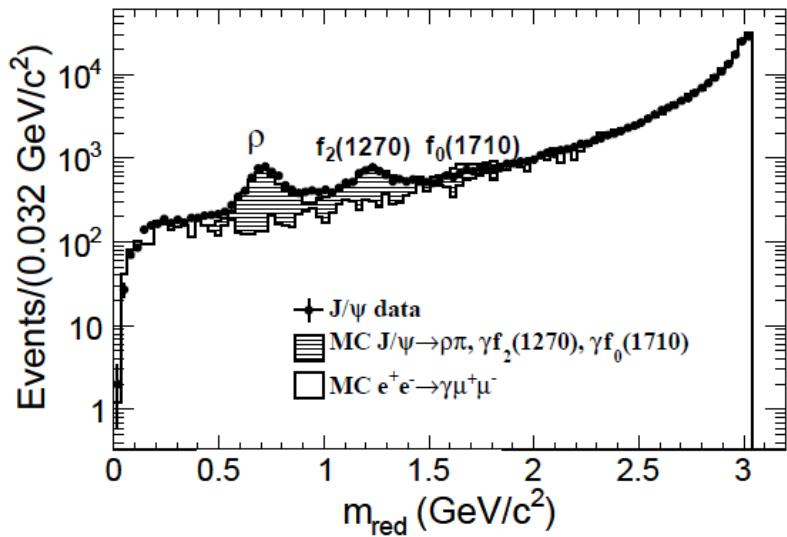
- No significant signals are observed.
- Upper limit for $B(J/\psi \rightarrow \gamma A^0) \times B(A^0 \rightarrow \mu^+ \mu^-)$ @ 90% C.L.

$4 \times 10^{-7} \sim 2.1 \times 10^{-5}$

Search (II): $J/\psi \rightarrow \gamma A^0$

PRD 93,052005(2016)

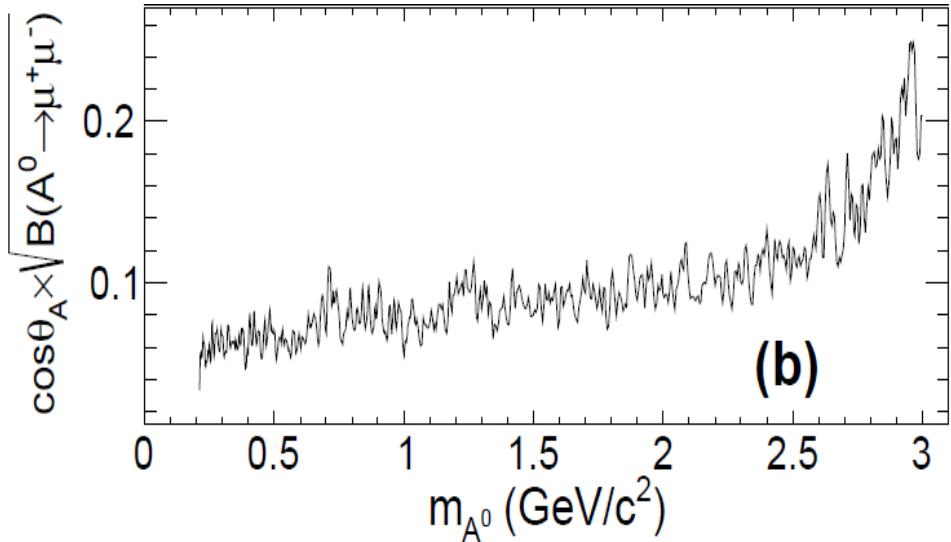
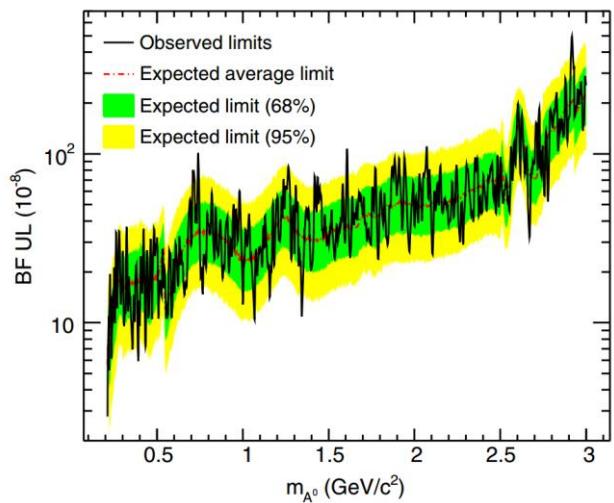
- 225 million J/ψ events
- Topology: $J/\psi \rightarrow \gamma A^0 (\mu^+ \mu^-)$
- $m_{\text{red}} = \sqrt{m_{\mu^+ \mu^-}^2 - 4m_\mu^2},$



- Range : $0.212 \sim 3.0 \text{ GeV}/c^2$
- Search for light exotic particle with a step of 1 MeV

Search (II): $J/\psi \rightarrow \gamma A^0$

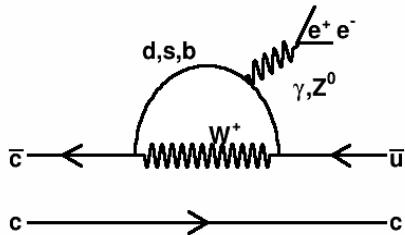
PRD 93,052005(2016)



- Upper limit on $B(J/\psi \rightarrow \gamma A^0) \times B(A^0 \rightarrow \mu^+ \mu^-)$
 $2.8 \times 10^{-8} - 4.95 \times 10^{-6}$
 A factor of five times better than previous [2012, $\psi(3686)$]
- Combined with Babar result, A^0 is constrained to be mostly a singlet particle

J/ψ and $\psi(3686) \rightarrow D^0 e^+ e^- + c.c.$

- Flavor-changing neutral currents (FCNC): $c \rightarrow u$



loop level in SM

SM
 $10^{-10} \sim 10^{-13}$

Z. Phys. C 62, 271 (1994), Eur. Phys. J. C 54, 107 (2008)

- New physics models: Enhanced by **two or three** orders of magnitude

PLB 345, 483 (1995), PLB119, 136 (1982), PRD 15, 1858 (1977)

- Present experimental result of by BESII *PLB 639, 418 (2006)*

$B(J/\psi \rightarrow \overline{D^0} e^+ e^- + c.c.) < 1.1 \times 10^{-5}$

- Study non-perturbative QCD effects and their underlying dynamics; a probe to search for new physics beyond the SM

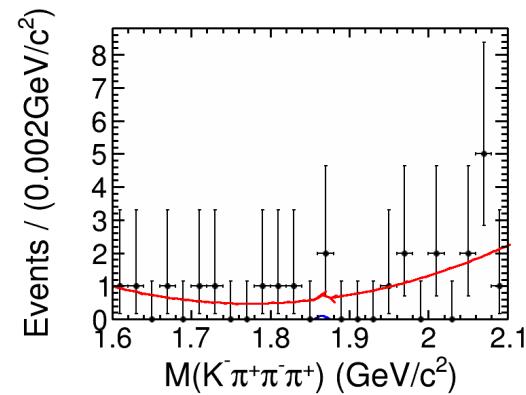
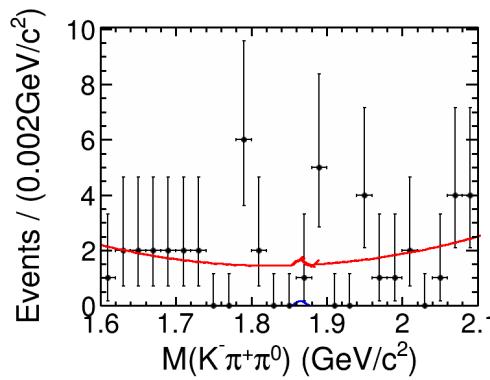
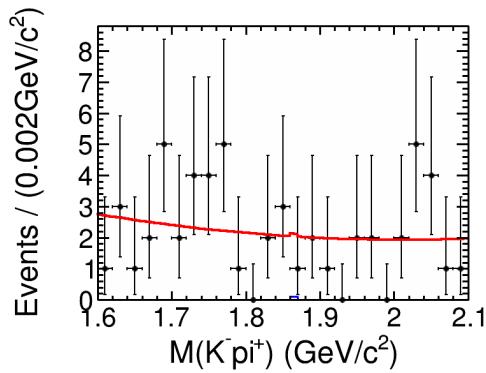
HEP&NP, 25, 461 (2001), PRD 60, 014011 (1999).

J/ψ and $\psi(3686) \rightarrow D^0 e^+ e^- + c.c.$

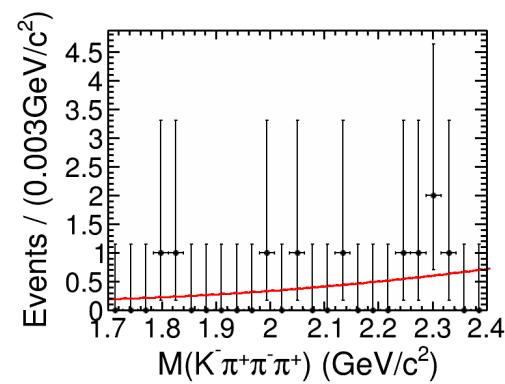
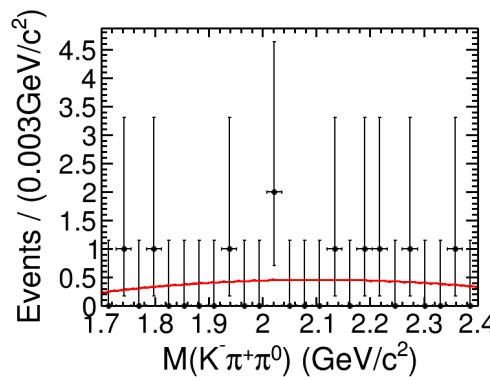
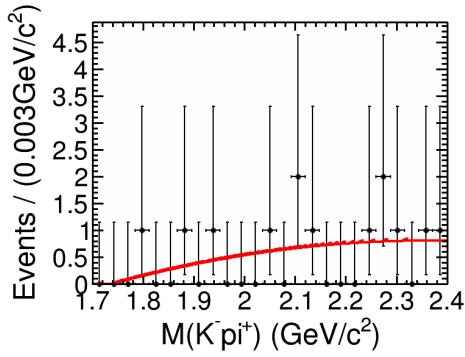
- 1.31 billion J/ψ and 448.1 million $\psi(3686)$ events
- Three channels: $D^0 \rightarrow K^- \pi^+$, $K^- \pi^+ \pi^0$, $K^- \pi^+ \pi^+ \pi^-$
- Low background, simultaneous fit for three channels.
- No significant D^0 signals are observed

arXiv: 1710.02278

J/ψ



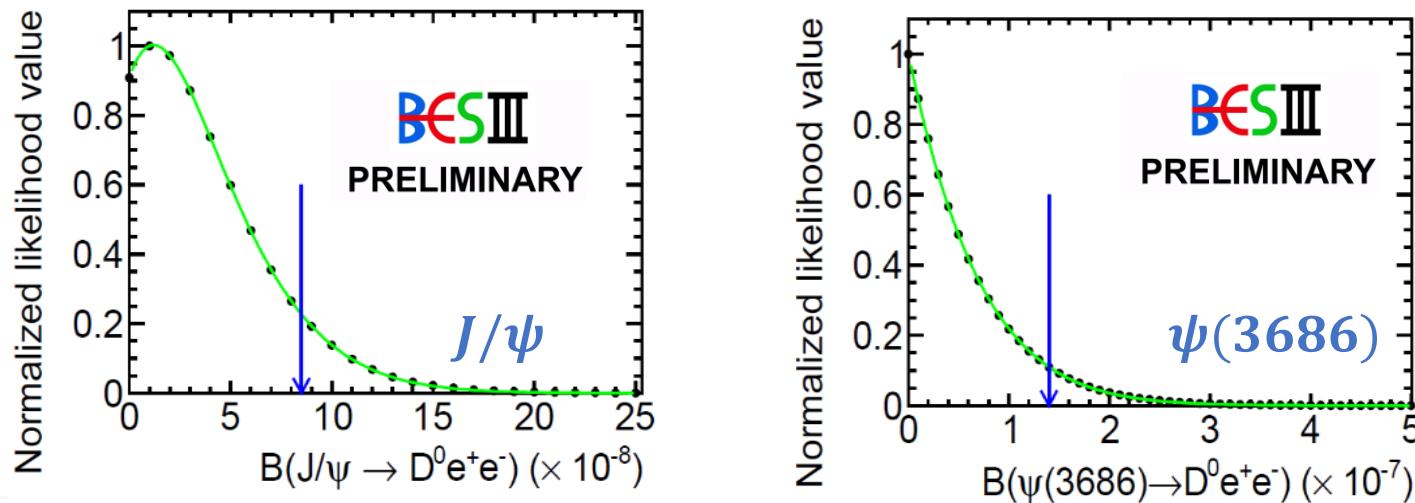
$\psi(3686)$



J/ψ and $\psi(3686) \rightarrow D^0 e^+ e^- + c.c.$

- Overall Likelihood: the product of likelihoods of three channels
- Set upper limit @ 90% C.L. using a Bayesian method

arXiv: 1710.02278



| | $B(J/\psi \rightarrow D^0 e^+ e^- + c.c.)$ | $B(\psi(3686) \rightarrow D^0 e^+ e^- + c.c.)$ |
|---------------------------|---|--|
| BESII | $< 1.1 \times 10^{-5}$ | -- |
| BESIII (This work) | $< 8.5 \times 10^{-8}$ | $< 1.4 \times 10^{-7}$ |

- No significant FCNC signals are observed.
- The upper limit result
 - J/ψ : Improved by about two orders in magnitude
 - $\psi(3686)$: Firstly set

Summary

- With huge charmonium data samples and good detector performance, BESIII is an ideal place to search for BSM new physics at high precision.
- BESIII has performed searches for BSM new physics with charmonium data, no significant new physics signals are observed and a series of upper limits are set, helpful for constraining the BSM model parameters.
 - Dark photon
 - $J/\psi \rightarrow \eta'\gamma'$ UL on BFs and ε
 - $e^+e^- \rightarrow \gamma\gamma' @ \psi(3770)$ UL on ε
 - Light exotic particle
 - $\psi(3686) \rightarrow \pi^+\pi^-J/\psi, J/\psi \rightarrow \gamma A^0$ UL on BFs
 - $J/\psi \rightarrow \gamma A^0$ UL on BFs and constrain A^0
 - FCNC
 - J/ψ and $\psi(3686) \rightarrow D^0 e^+e^- + c.c.$ UL on BFs
- With the plan to take more charmonium data in the future, BESIII is promising to study more new physics topics with higher precision.

Thanks !