Dark photon and muon-philic particle at BESIII

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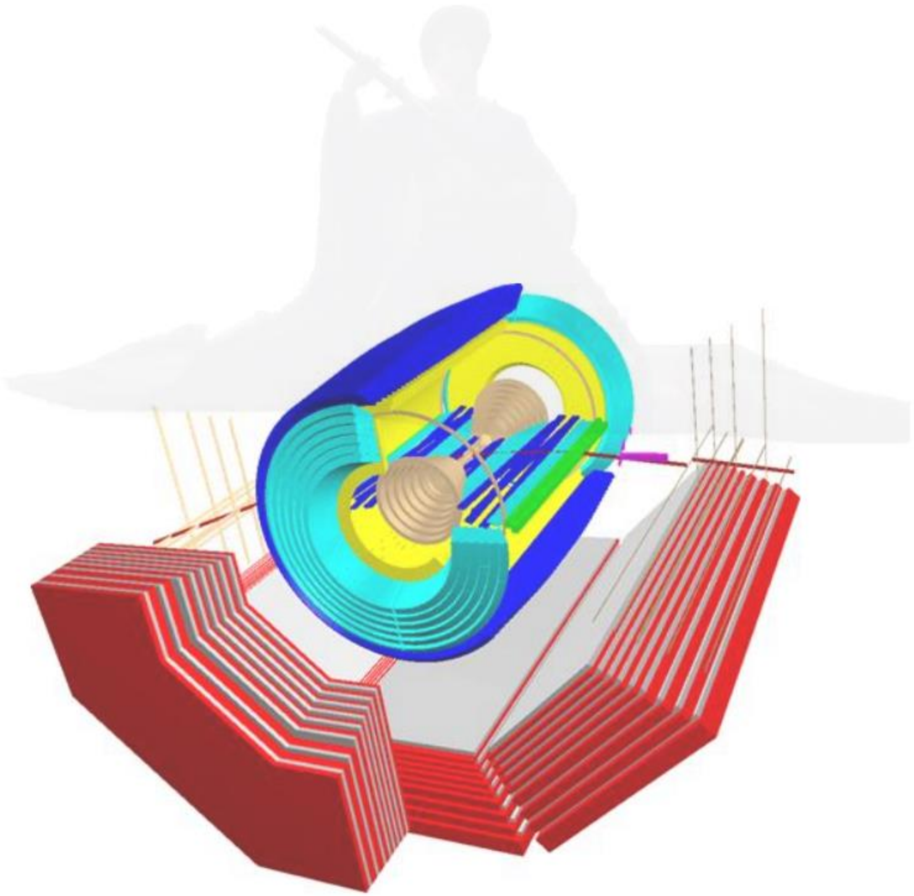
OUTLINE

- **Introduction**
- Massive dark photon
- Massless dark photon
- Muon-philic particle
- Summary

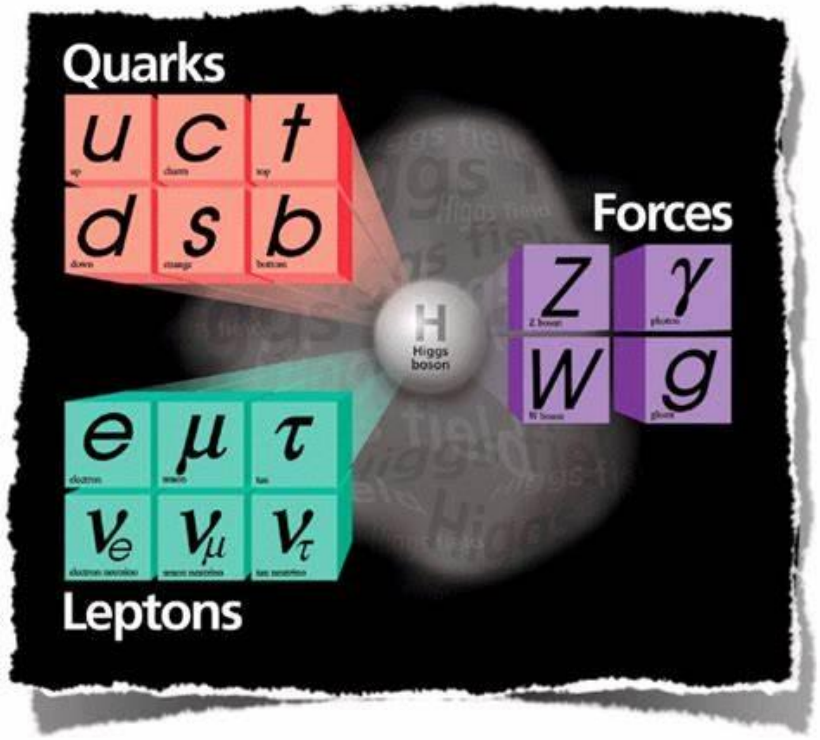


SM and dark sector

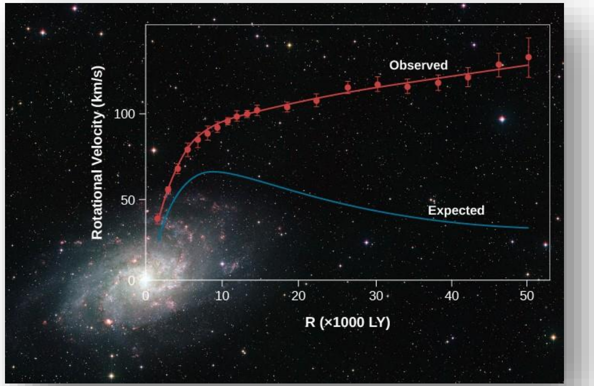
Standard model (SM):

$\boldsymbol{SU(3)_C \times SU(2)_L \times U(1)_Y}$

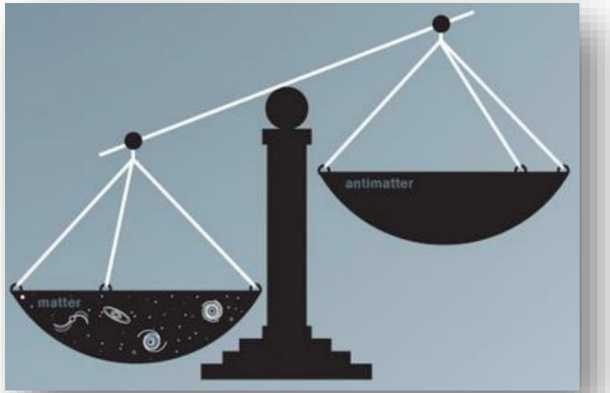
- Successful!
- But also some **puzzles**



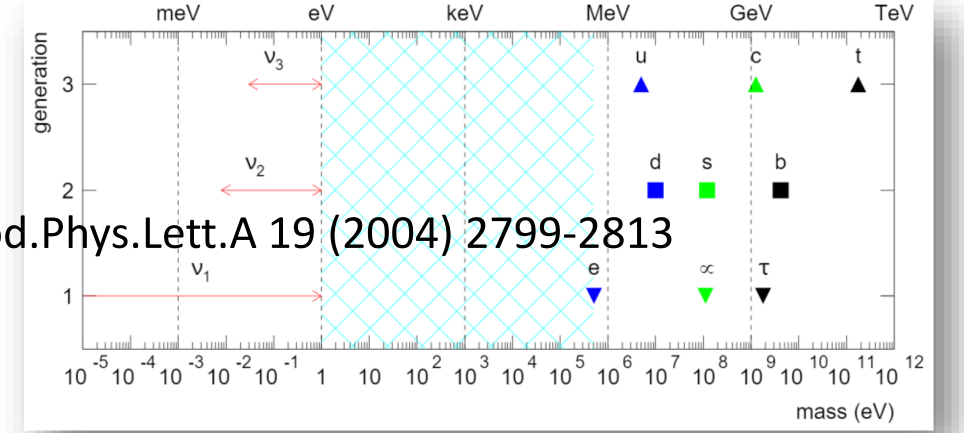
- Dark matter



- Matter and anti-matter asymmetry

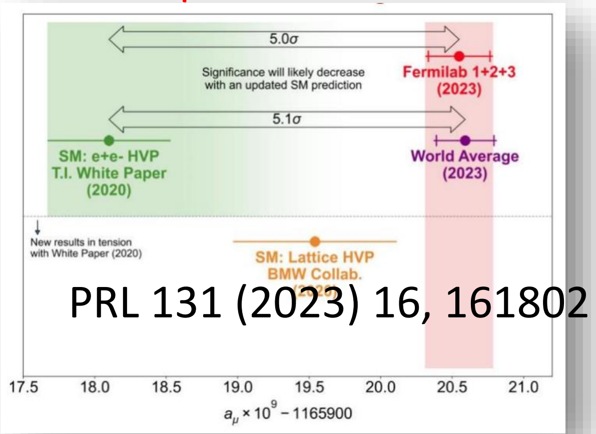


- Fermion mass hierarchy



Mod.Phys.Lett.A 19 (2004) 2799-2813

- $g_\mu - 2$ anomaly

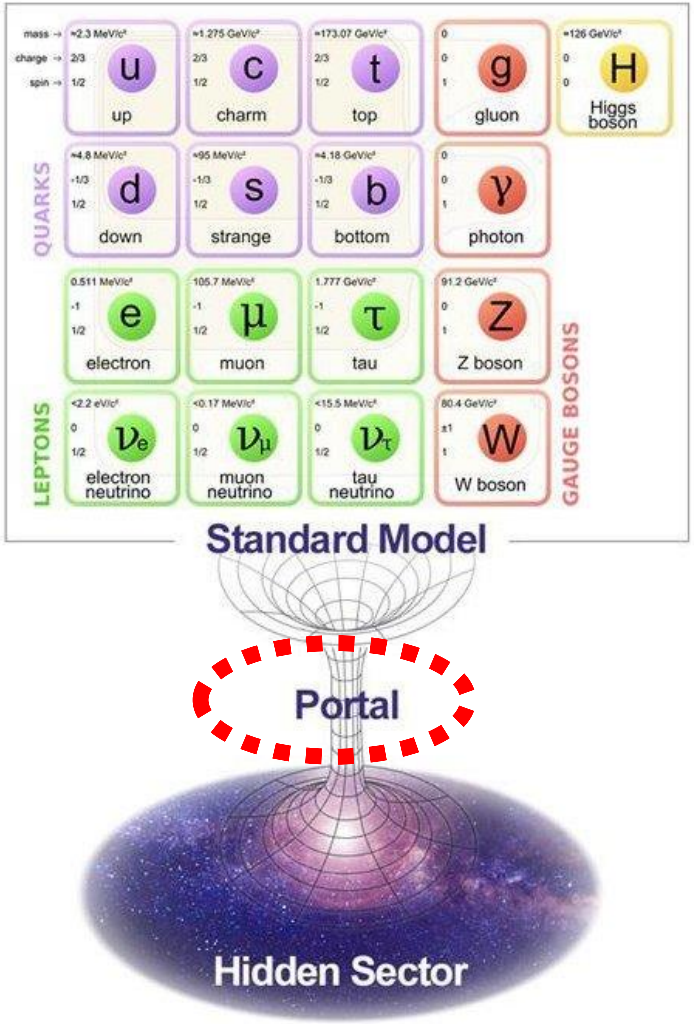


PRL 131 (2023) 16, 161802

- More…

We believe there are something new beyond the SM: dark sector

Portal to connect the dark sector



- Some **"portal"** may connect the SM matter and the dark sector matter

This talk

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

Xiaoxuan's talk

These portal-particles can also **resolve some puzzles** in the SM: fermion mass hierarchy, $g_\mu - 2$ anomaly…

The dark photon

SM photon

Dark photon

(Symmetry broken spontaneously, massive kind)

Kinetic mixing: $\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$

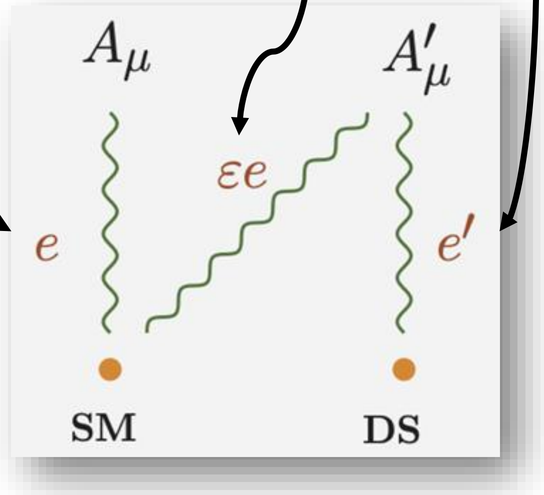
$A^{\mu} \to A^{\mu} + \epsilon A'^{\mu}$

ϵ: mixing strength

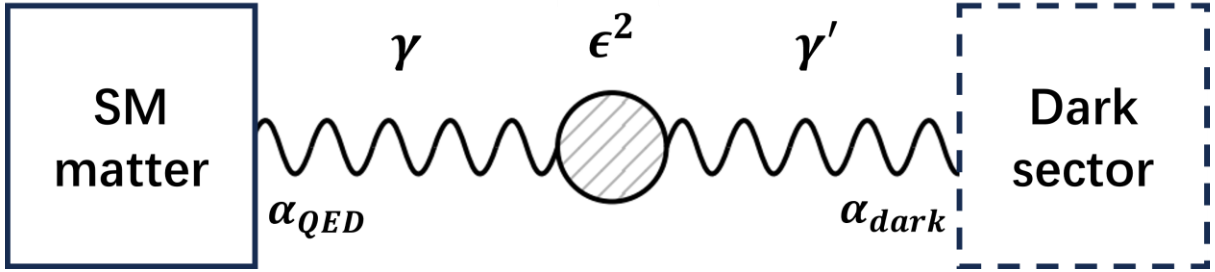
PLB 166, 196 (1986)

$(J^{\mu} = \bar{\psi}\gamma^{\mu}\psi)$

$$\mathcal{L} = eJ_{\mu}A^{\mu} + e\epsilon J_{\mu}A'^{\mu} + e'J'_{\mu}A'^{\mu}$$



arXiv:2005.01515

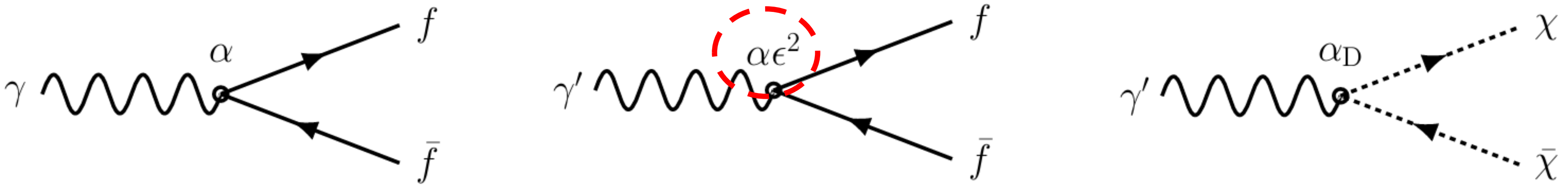


A portal to connect the SM matter and the dark sector

The coupling and production of the dark photon

$$\mathcal{L} = eJ_\mu A^\mu + e\epsilon J_\mu A'^\mu + e'J'_\mu A'^\mu$$

The coupling of the dark photon

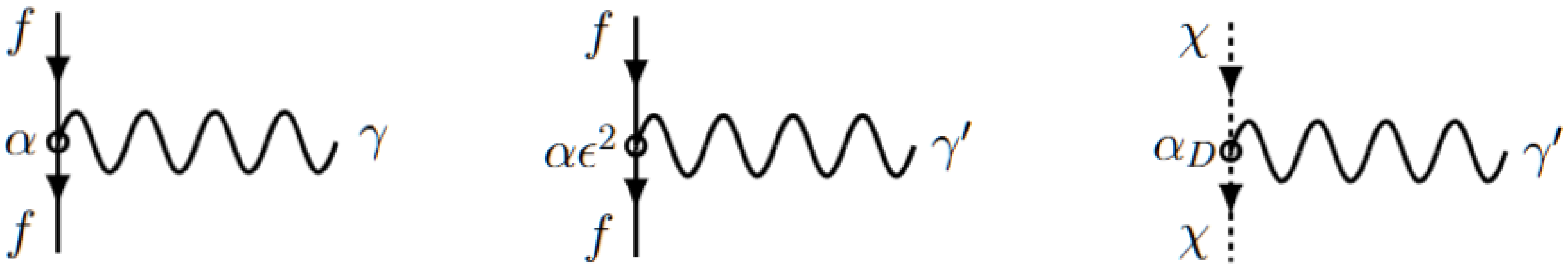


Similar couplings with SM photon but with ϵ^2 times coupling strength

$$\alpha_D = \frac{e'^2}{4\pi}$$

dark photon couples to dark fermion

The production of the dark photon

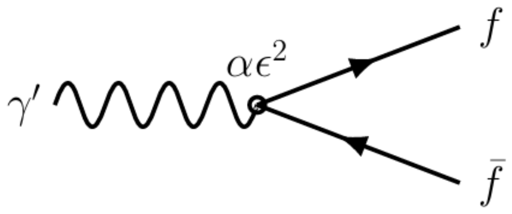


Dark photon produced in dark fermion radiation

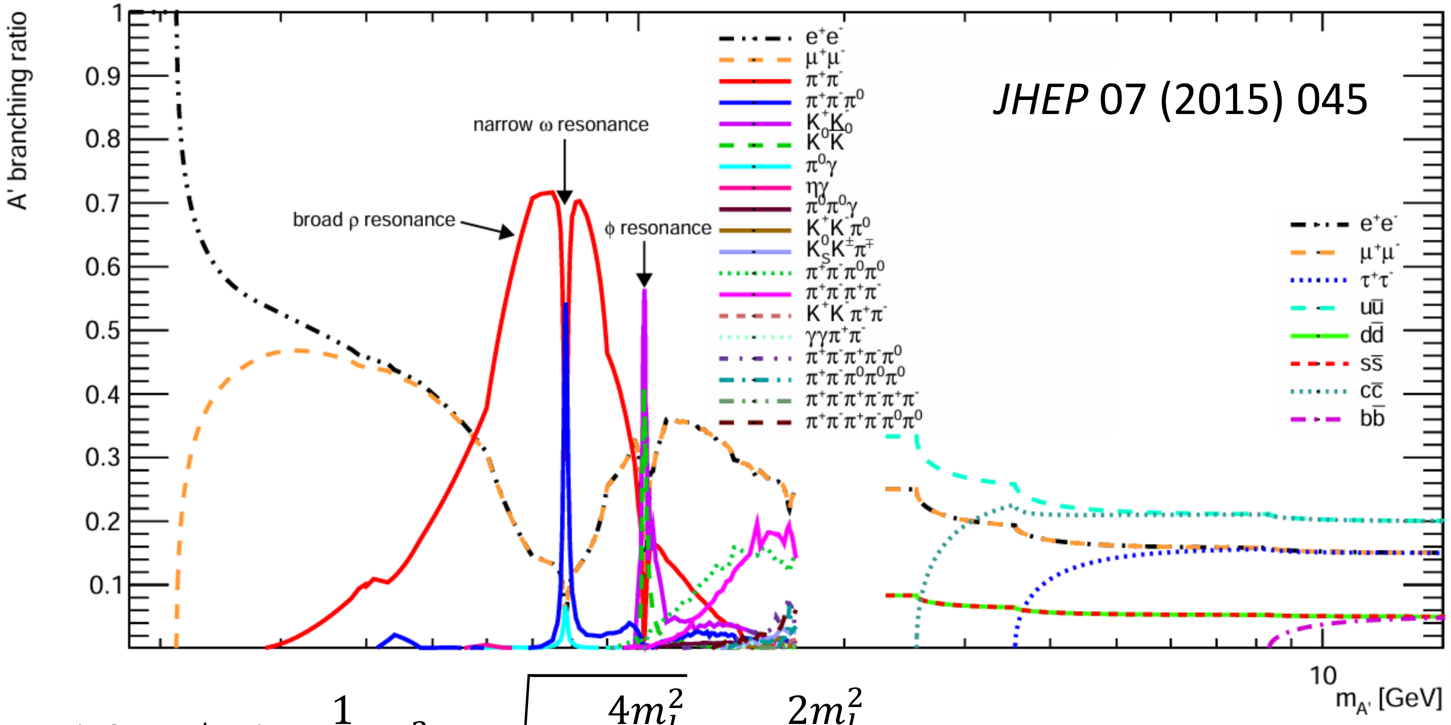
Dark photon can be produced in any process by replacing SM photon

The decay of the dark photon

Type I
Visible



- $\boldsymbol{m_\chi > \frac{m_{\gamma'}}{2}}$
- $m_{\gamma'} > 1\ MeV$

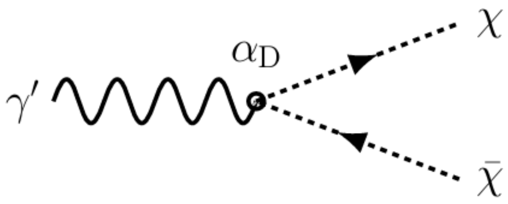


$$\Gamma(\gamma' \to l^+l^-) = \frac{1}{3}\alpha\epsilon^2 m_{\gamma'}\sqrt{1-\frac{4m_l^2}{m_{\gamma'}^2}}\left(1+\frac{2m_l^2}{m_{\gamma'}^2}\right)$$

$$\Gamma(\gamma' \to \text{hadrons}) = \Gamma(\gamma' \to \mu^+\mu^-)R(s = m_{\gamma'}^2)$$

Usually Detecting lepton final state

Type II
Invisible



- $\boldsymbol{m_\chi < \frac{m_{\gamma'}}{2}}$
- $\boldsymbol{\alpha_D \gg \alpha\epsilon^2}$

$$\Gamma(\gamma' \to \chi\bar{\chi}) = \frac{1}{3}\alpha_D m_{\gamma'}\sqrt{1-\frac{4m_\chi^2}{m_{\gamma'}^2}}\left(1+\frac{2m_\chi^2}{m_{\gamma'}^2}\right)$$

$$\mathcal{B}(\gamma' \to \chi\bar{\chi}) \sim 100\%$$

Missing energy,
Missing mass …

Why we need the dark photon

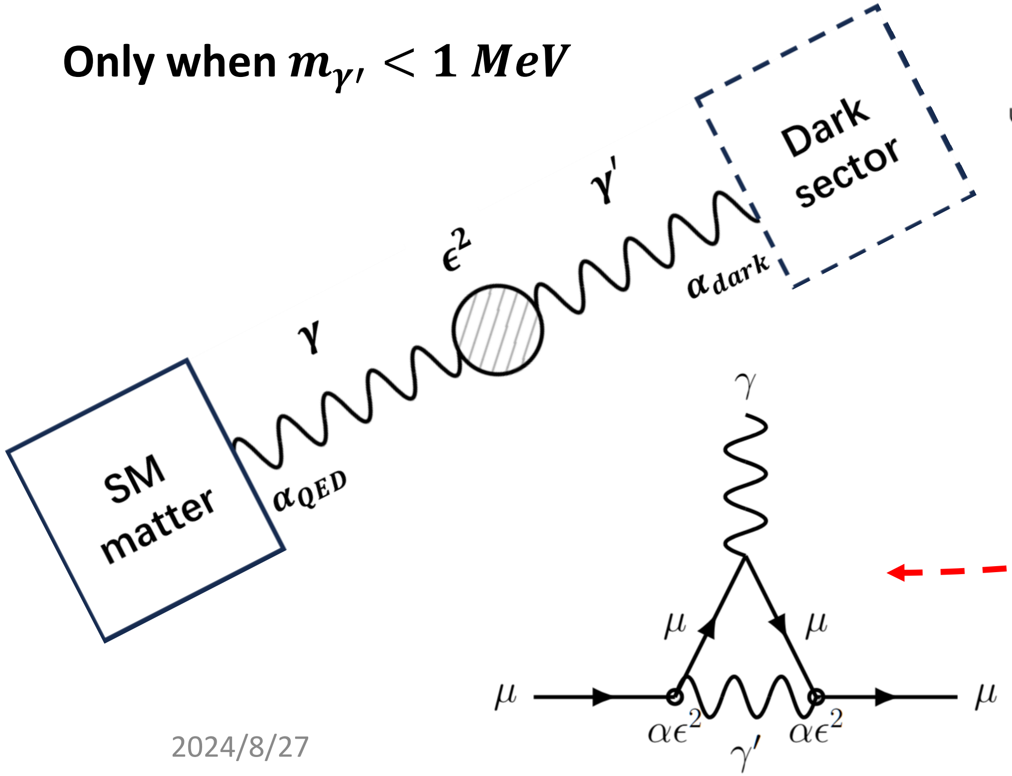
Dark matter candidate

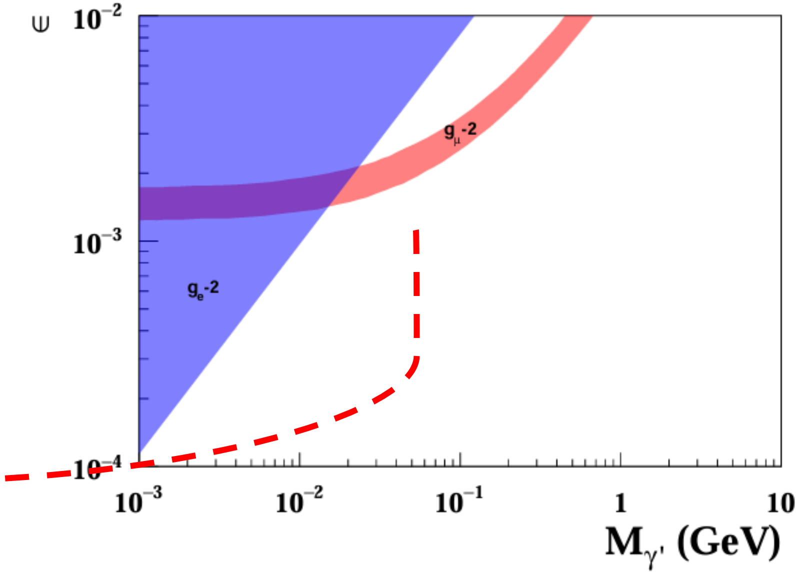
Portal to the dark sector

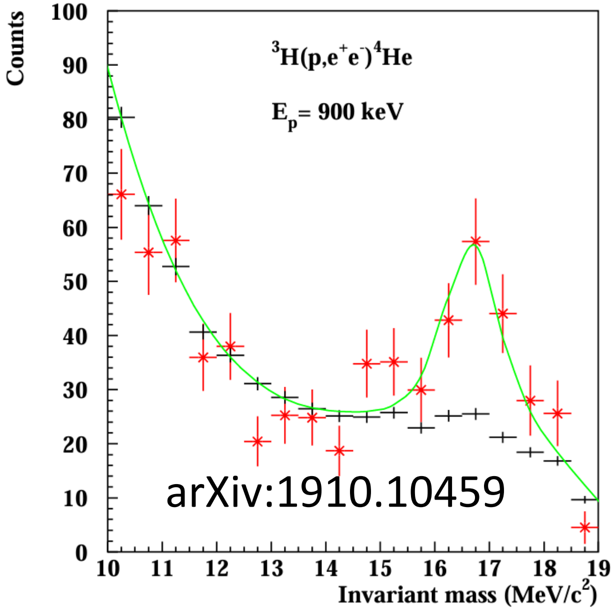
Resolve the $g_\mu - 2$ anomaly

$X17$ candidate

Only when $m_{\gamma'} < 1\ MeV$

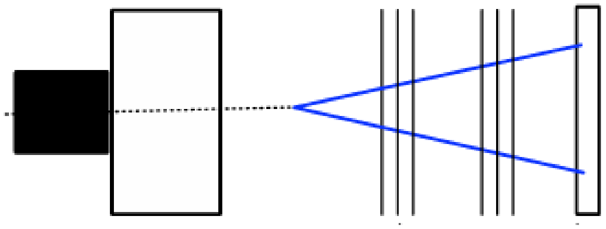


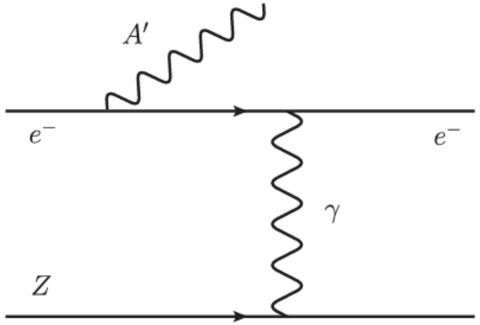




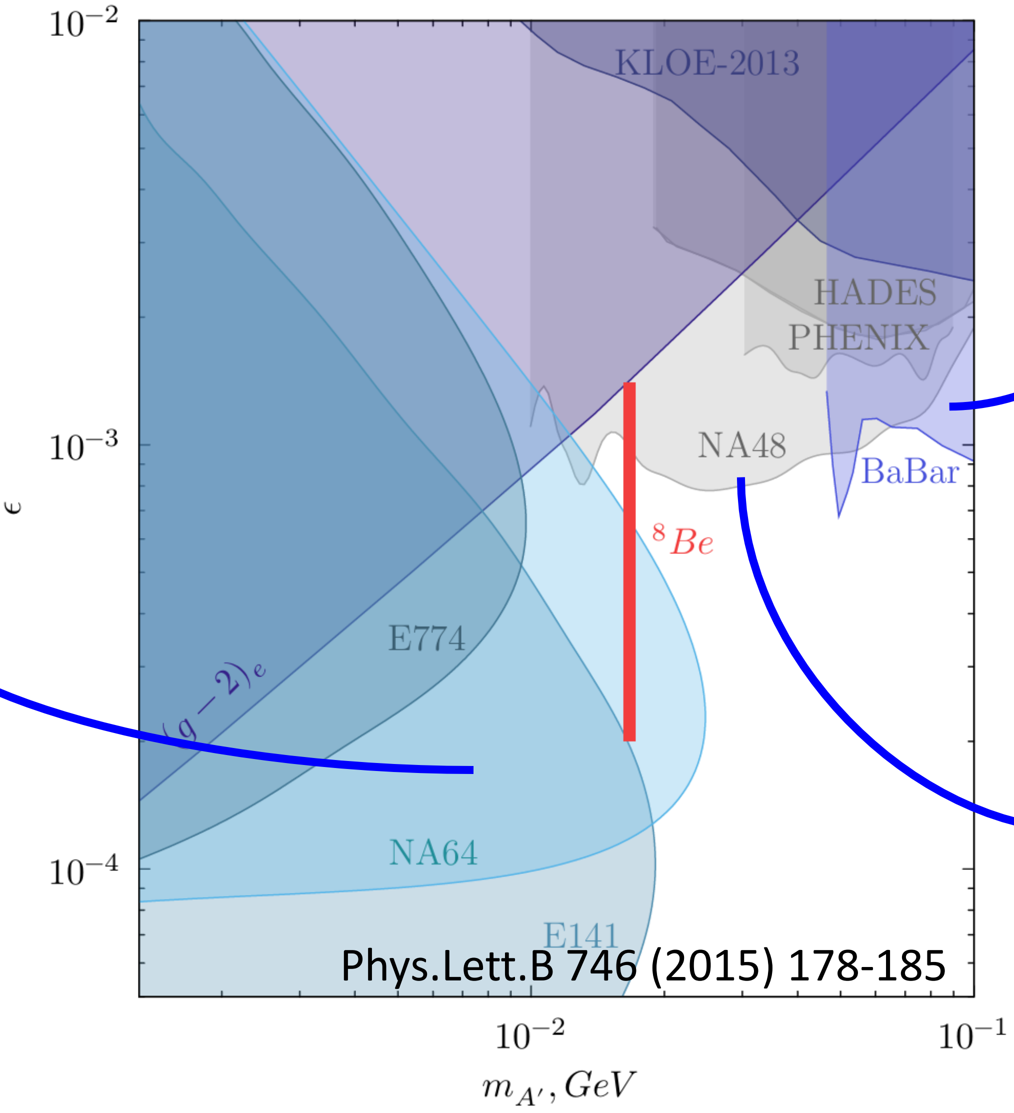
The experimental method of the dark photon

- **Beam-dump**



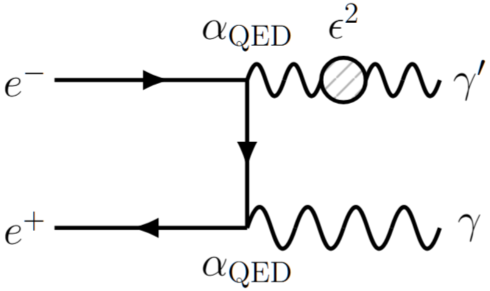


eg. NA64, E774, E141



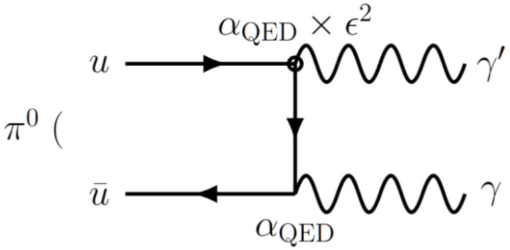
Phys.Lett.B 746 (2015) 178-185

- **Annihilation**



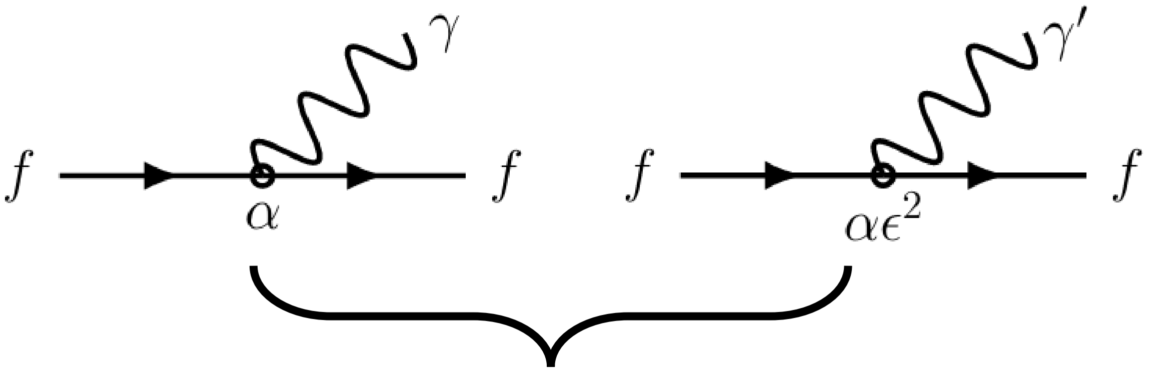
eg. BaBar, BESIII

- **Meson decay**



eg. NA48, BESIII

The (massive) dark photon at BESIII



Dark photon can be produced in any process by replacing SM photon

$$\mathcal{P}(\blacksquare \to \blacksquare\gamma') \sim \epsilon^2 \times \mathcal{P}(\blacksquare \to \blacksquare\gamma)$$

SM Process	Branching fraction
$J/\psi \to \gamma\eta'$	0.53%
$J/\psi \to \gamma\eta$	0.11%
$J/\psi \to \gamma\eta_c$	1.41%
$\psi(2S) \to \gamma\chi_{cJ}$	$\sim 10\%$
$\chi_{c1} \to \gamma J/\psi$	34.3%
$\chi_{c2} \to \gamma J/\psi$	19.5%

Less statistic

$\boldsymbol{e^+e^- \to \gamma\gamma'}$
$\boldsymbol{J/\psi \to \gamma'\eta'}$
$\boldsymbol{J/\psi \to \gamma'\eta}$

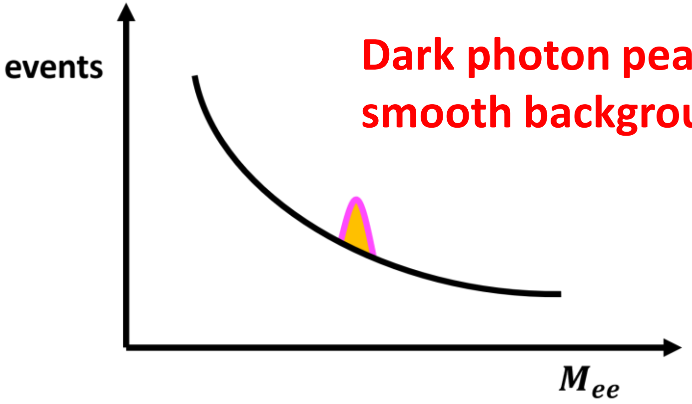
(massive) dark photon at this talk

- Data samples at BESIII
  - 10^{10} J/ψ
  - 2.7×10^9 $\psi(2S)$
  - $20\ fb^{-1}$ @ 3.773 GeV
  - $> 20 fb^{-1}$ @ $>$ 4 GeV
  - …

Massless dark photon, muon-philic particle?
Discuss later…

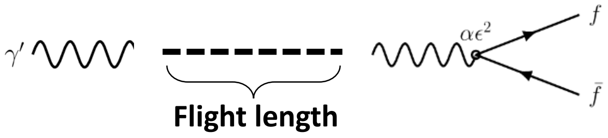
How do we detect the dark photon

Visible dark photon

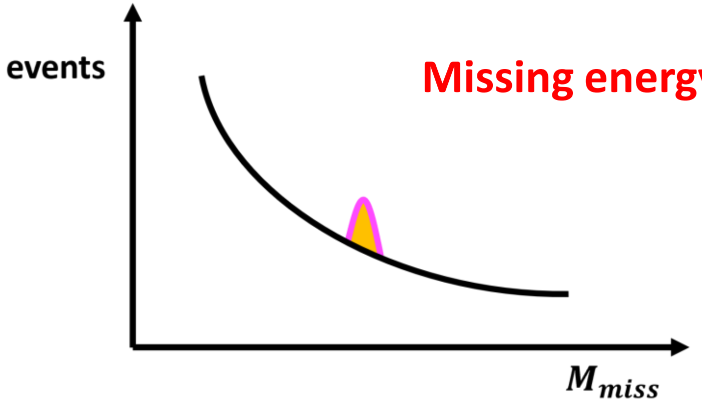


Dark photon peak at the smooth background

- $m_{\gamma'} = 1\ GeV, \epsilon < 10^{-3} \rightarrow \Gamma_{ee} \lesssim 2 \times 10^{-3} eV$ → **Width could be ignored**
- $m_{\gamma'} = 1\ GeV, P_{\gamma'} = 1\ GeV \rightarrow L_{\gamma'} \sim \frac{8\times10^{-12}}{3\epsilon^2}\ cm$ $\epsilon \sim 10^{-3}$ →**Decay length could be ignored**



Invisible dark photon



Missing energy

- $m_{\gamma'} = 1\ GeV, m_{\chi} \ll m_{\gamma'}, \alpha_D = 0.1 \rightarrow \Gamma \sim 33\ MeV$
- $m_{\gamma'} = 1\ GeV, m_{\chi} \ll m_{\gamma'}, \alpha_D = 0.01 \rightarrow \Gamma \sim 3\ MeV$
- **Width can be ignored only when $\boldsymbol{\alpha_D \lesssim 0.01}$**

Our target: observe the dark photon or constraint the mixing strength ϵ
BUT Summary: no significant signal is found

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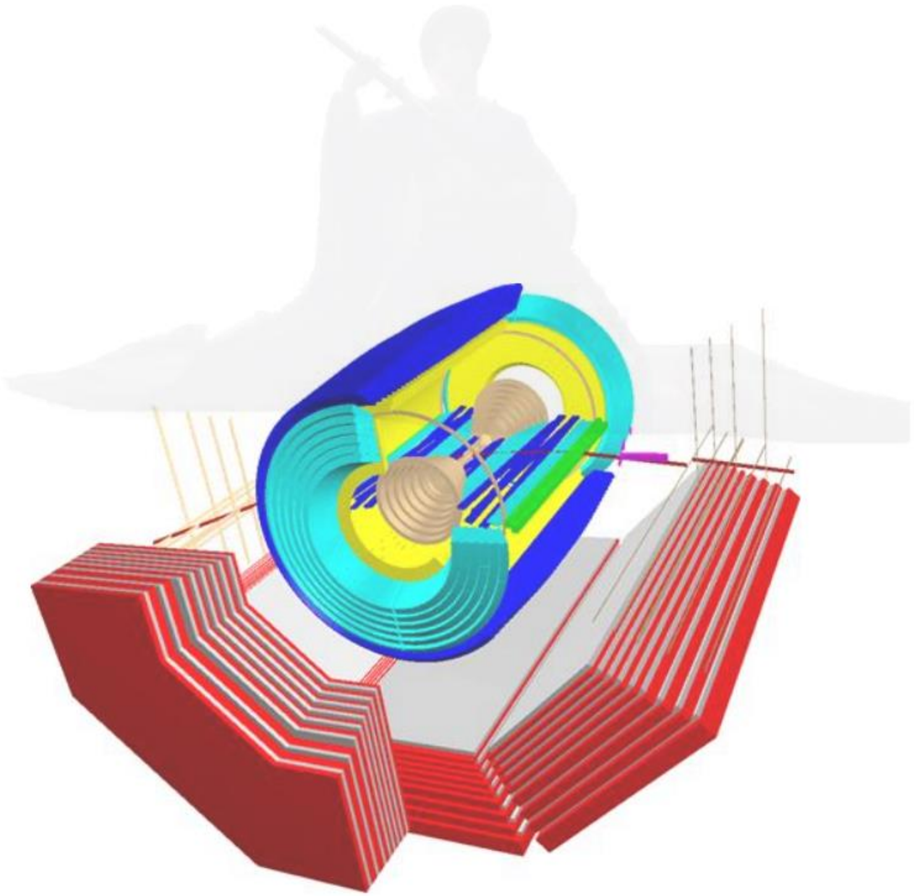
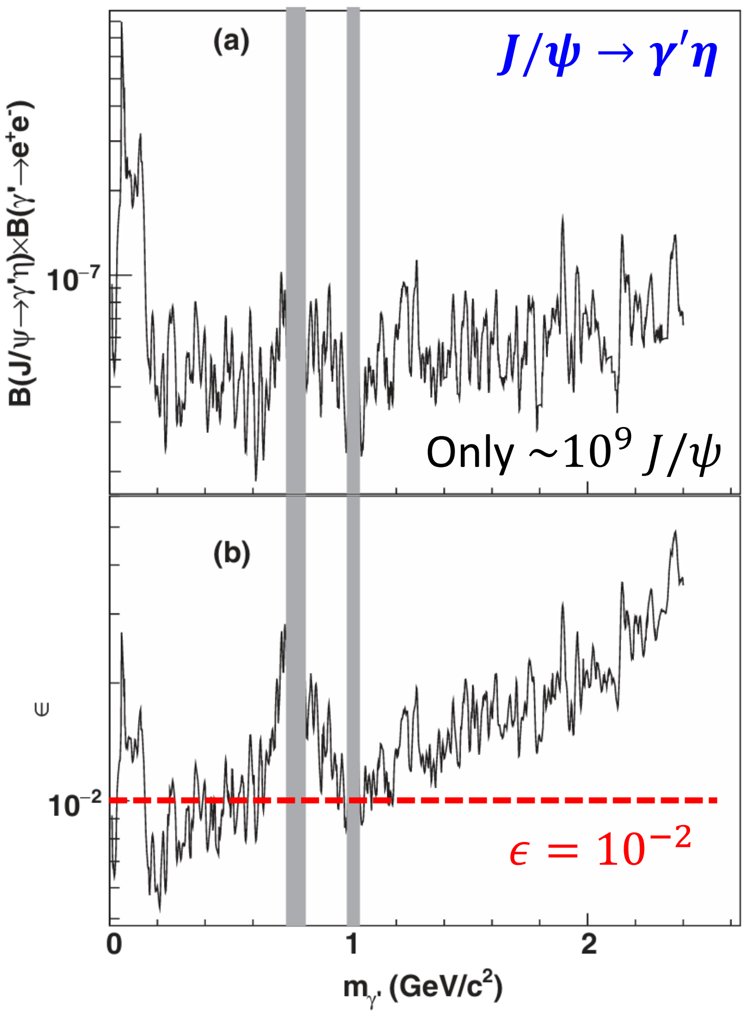
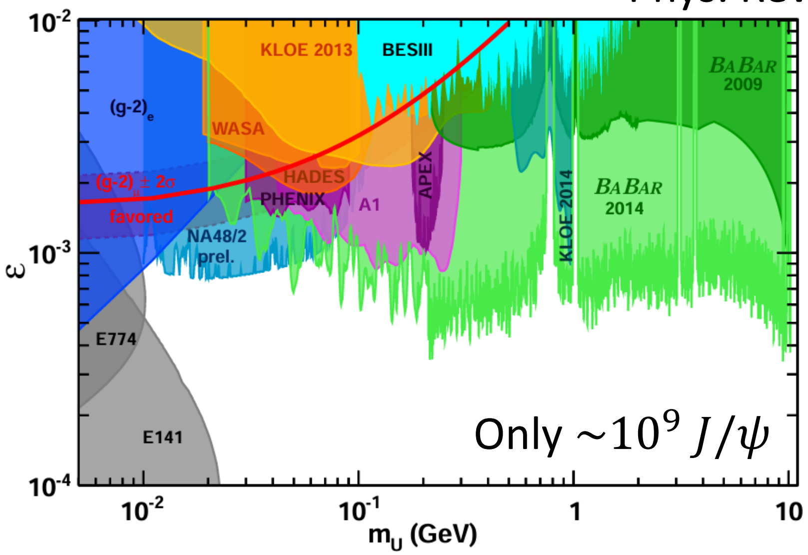


Mixing strength from $J/\psi \to \gamma' \eta^{(\prime)}, \gamma' \to e^+e^-$

Phys. Rev. D 99, 012006 (2019)



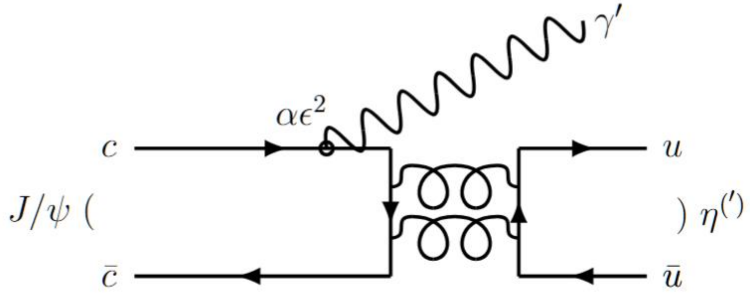
Phys. Rev. D 99, 012013 (2019)



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

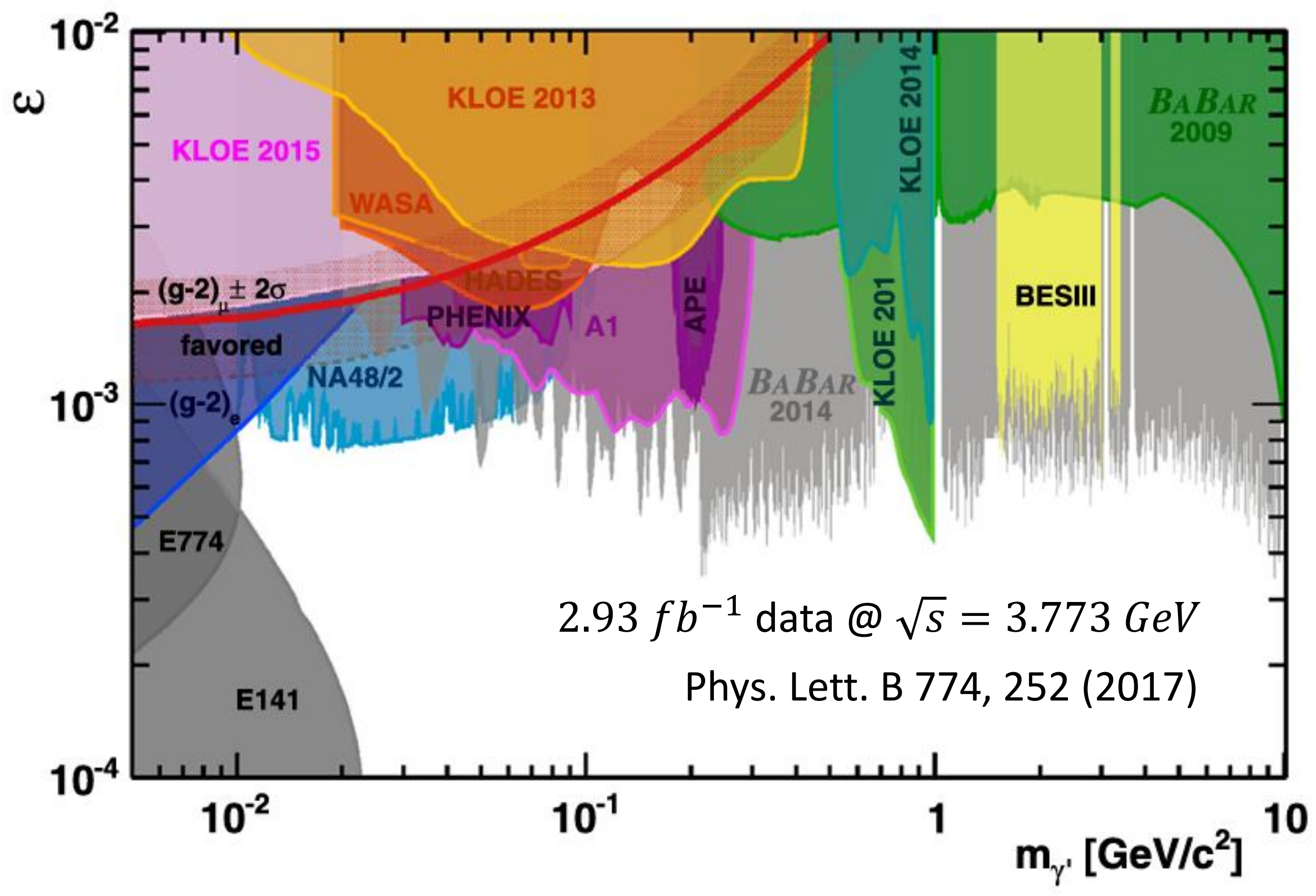
SM Process	BF
$J/\psi \to \gamma\eta'$	0.53%
$J/\psi \to \gamma\eta$	0.11%

η' has better sensitivity



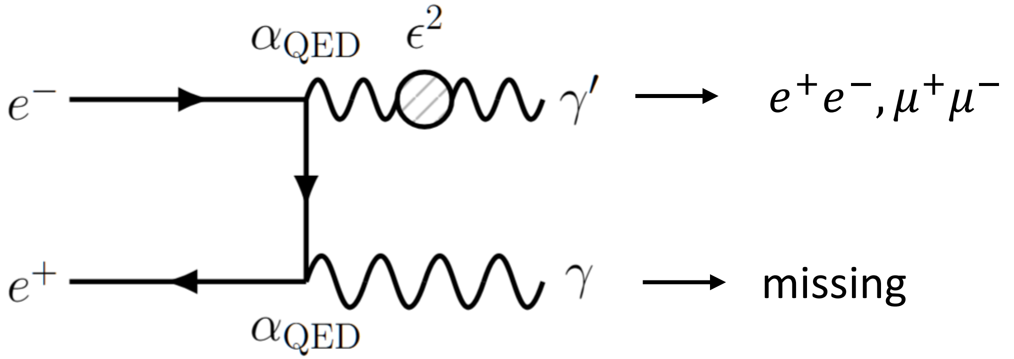
- Only using $\sim 10^9\ J/\psi$ events, but now we have $10^{10} J/\psi$ events
- **What about using the full data? Will discuss later…**

Mixing strength from $e^+e^- \to \gamma\gamma',\ \gamma' \to l^+l^-$



$2.93\ fb^{-1}$ data @ $\sqrt{s} = 3.773\ GeV$

Phys. Lett. B 774, 252 (2017)



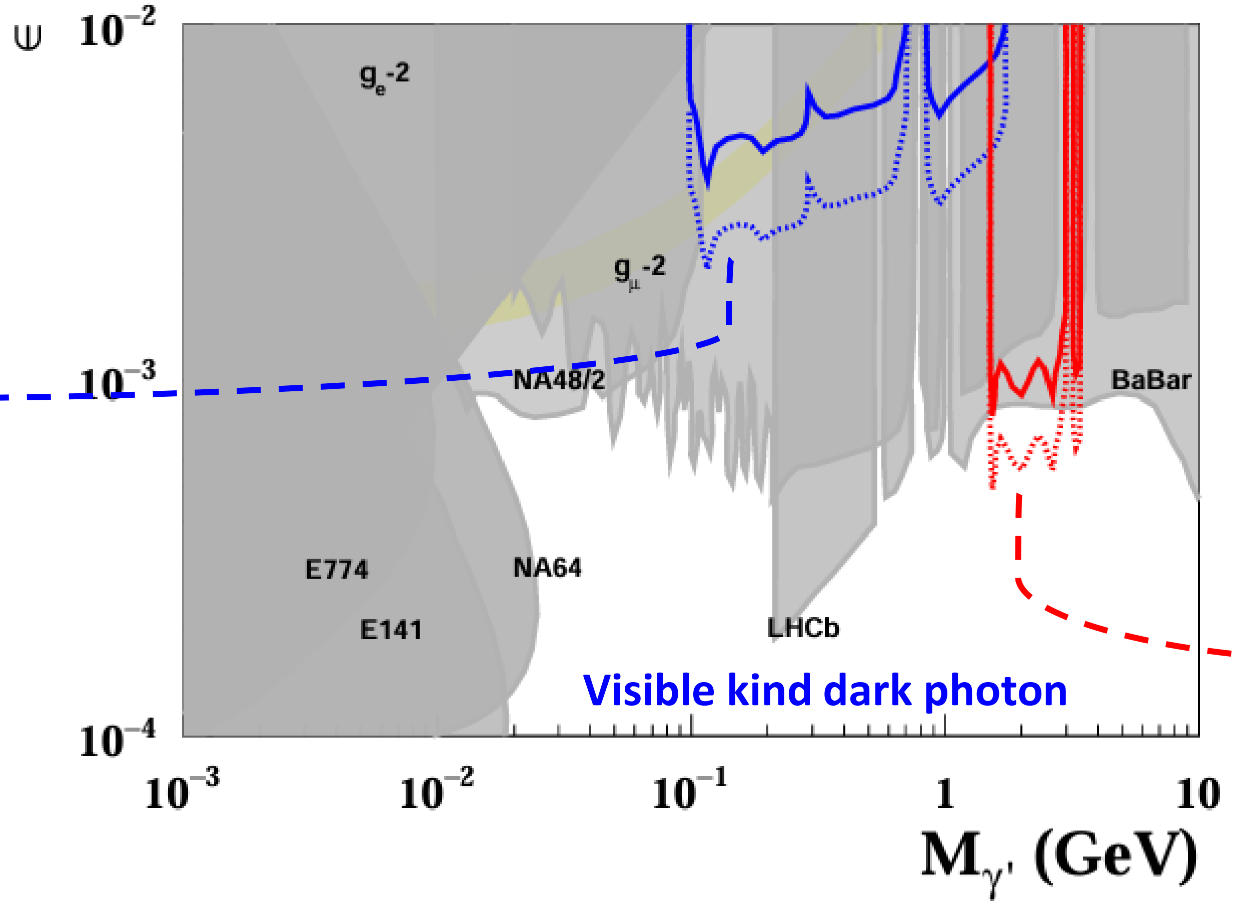
Only using $2.93\ fb^{-1}$ data,
Now $20\ fb^{-1}$ data are collected

- ☐ **BESIII: $2.93 fb^{-1}$**
- ☐ **BaBar: $514 fb^{-1}$**

The future of visible dark photon at BESIII

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

J/ψ:
$10^9 \to 10^{10}$



$e^+e^- \to \gamma\gamma', \gamma' \to e^+e^-$

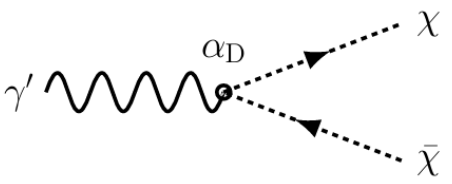
$\mathcal{L}(fb^{-1})$:
$2.93 \to 20$

Expected to explore new parameter region

- Some more possible improvements:
- Missing some particles in the reconstruction
- Remove some PID
- Add $\eta \to \pi^+\pi^-\pi^0$ in $\eta' \to \pi^+\pi^-\eta$
- …

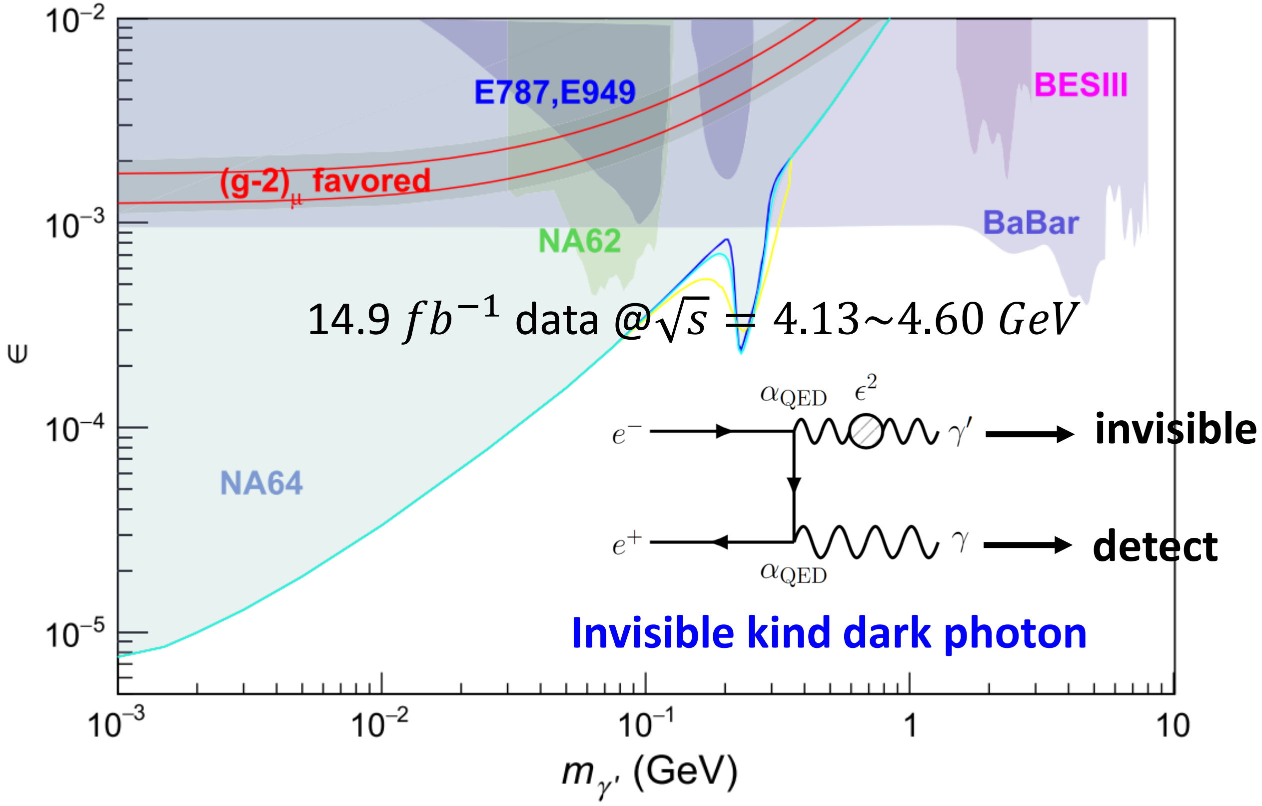
$N_{sig} \sim \epsilon^2 \to$ **data statistic 10000** $\uparrow$, $\mathcal{B}$ **sensitivity 100** $\uparrow$, ϵ **sensitivity 10** $\uparrow$

Mixing strength from $e^+e^- \to \gamma\gamma', \gamma'$ invisibly



- $m_\chi < \frac{m_{\gamma'}}{2}$
- $\alpha_D \gg \alpha\epsilon^2$

$\to \mathcal{B}(\gamma' \to \chi\bar{\chi}) \sim 100\%$



Phys.Lett.B 839 (2023) 137785

The future?

- ☐ **$(20 - 2.93)\ fb^{-1}$ data @3.773 GeV**
  - Lower mass region
  - Limit improvement with the statistic
  - $\epsilon \sim \sqrt{s}$, improved by $\frac{4.2\ GeV}{3.773\ GeV} < 1.113$
- ☐ **New method: gamma conversion to tag γ**
  - Better solution, lower background
  - Wider mass range
  - But only $\sim \frac{1}{100}$ statistic
- ☐ **$J/\psi \to \gamma'\eta'$ with 10^{10} J/ψ, invisible γ'**
  - Lower mass region
  - $\epsilon \sim 10^{-3}$ level

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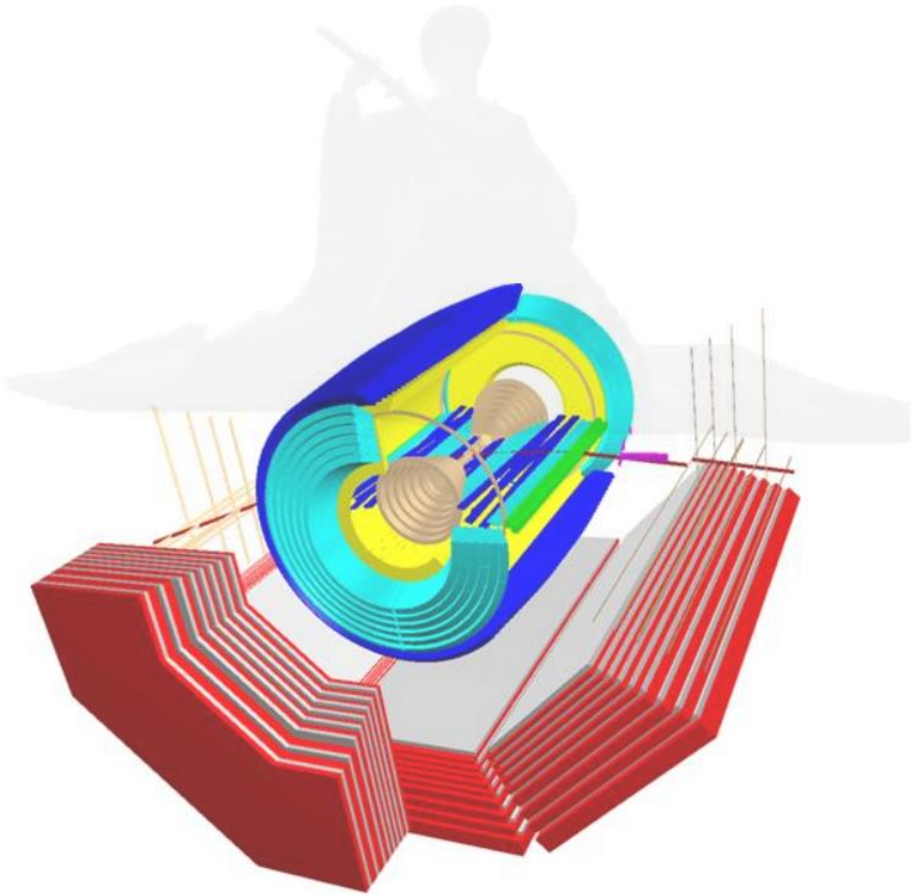


Massless dark photon

Massive dark photon

Symmetry broken spontaneously

Kinetic mixing: $\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$

ϵ**: mixing strength**

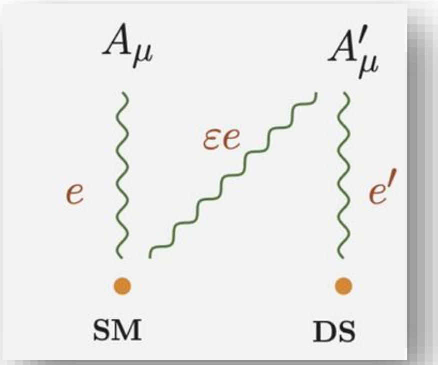
Massless dark photon

Symmetry remains unbroken

PRL 94, 151802 (2005)

$$A^\mu \to A^\mu + \epsilon A'^\mu$$
$$\mathcal{L} = eJ_\mu A^\mu + \underline{e\epsilon J_\mu A'^\mu} + e'J'_\mu A'^\mu$$

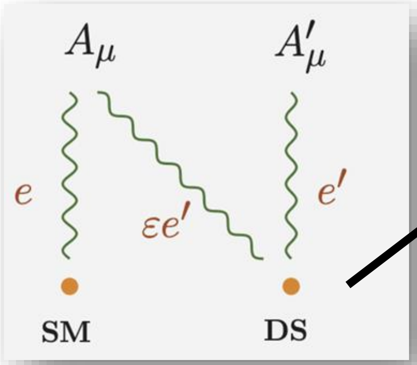
- **Dark photon couples to the SM matter**



$$A'^\mu \to A'^\mu + \epsilon A^\mu$$
$$\mathcal{L} = eJ_\mu A^\mu + \underline{e'\epsilon J'_\mu A^\mu} + e'J'_\mu A'^\mu$$

- **SM photon couples to the dark sector particles**

Massless dark photon has no interaction with the SM matter in the dimension-4 operator



(Milli-charged particles)

arXiv:2005.01515

The interaction of the massless dark photon

Dimension-six operator

PRL 94, 151802 (2005)

$$\mathcal{L}_{NP} = \frac{1}{\Lambda_{NP}^2}\left(C^U_{jk}\bar{q}_j\sigma^{\mu\nu}u_k\widetilde{H} + C^D_{jk}\bar{q}_j\sigma^{\mu\nu}d_k H + C^L_{jk}\bar{l}_j\sigma^{\mu\nu}e_k H + h.c.\right)\bar{F}_{\mu\nu}$$

Up type quarks coupling

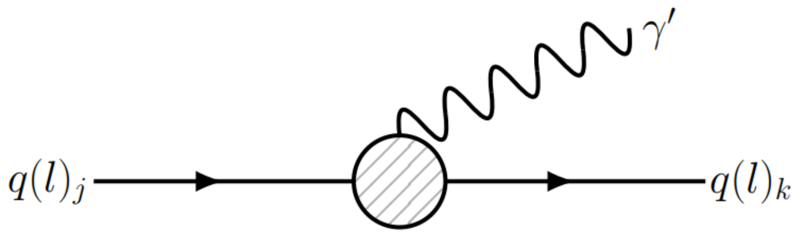
Down type quarks coupling

Charged leptons coupling

Massless dark photon

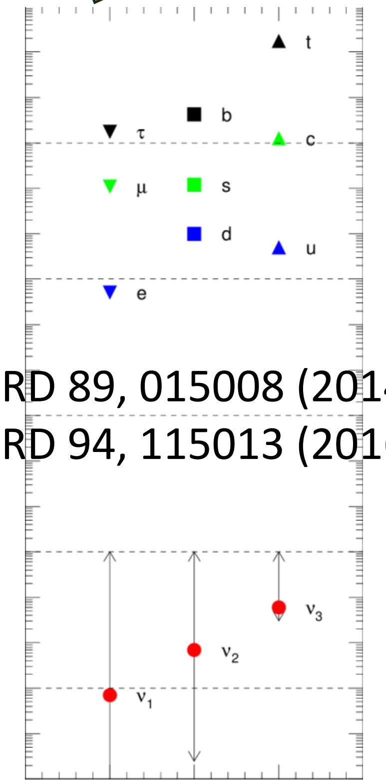
- ✓ **Λ_{NP}: effective heavy mass (NP energy scale)**
- ✓ $C^U_{jk}, C^D_{jk}, C^L_{jk}$: dimensionless coefficients about dimension-six operators, independent
- ✓ Both Λ_{NP} and $C^U_{jk}, C^D_{jk}, C^L_{jk}$ depend on NP, **$C^U_{jk}, C^D_{jk}, C^L_{jk}$ are not necessarily related to another**

- ✓ q_j, l_j: left-handed quark / lepton doublet
- ✓ d_k, u_k, e_k: right-handed down/up type quark / charged lepton
- ✓ $\bar{F}_{\mu\nu}$: dark photon's field-strength tensor



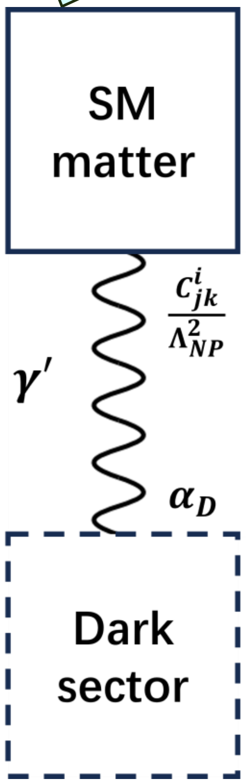
Why we need the massless dark photon

Resolve the Fermion mass hierarchy

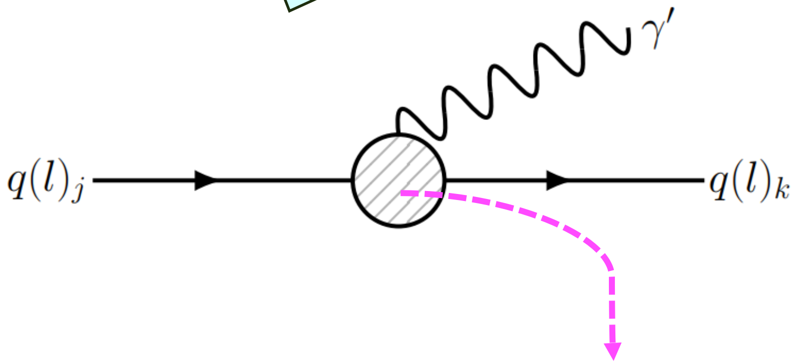


PRD 89, 015008 (2014)
PRD 94, 115013 (2016)

Portal to the dark sector

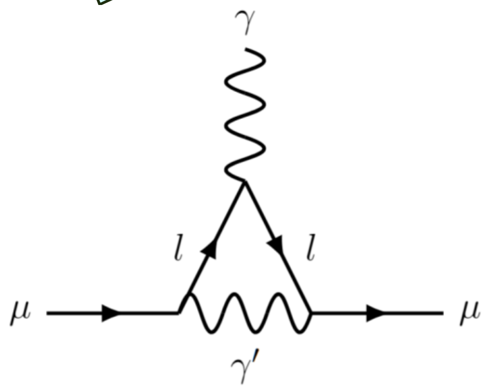


Probe the new physics energy scale



- In effective field theory, not care the details in the effective coupling (model independent)
  PRL 94, 151802 (2005)
- But in the effective coupling, it could include some heavy dark sector particles in the NP energy scale (model dependent)

Resolve the $g_\mu - 2$ anomaly



- In principle, it can contribute to $g_\mu - 2$
- But no theory calculation until now

FCNC process with massless dark photon

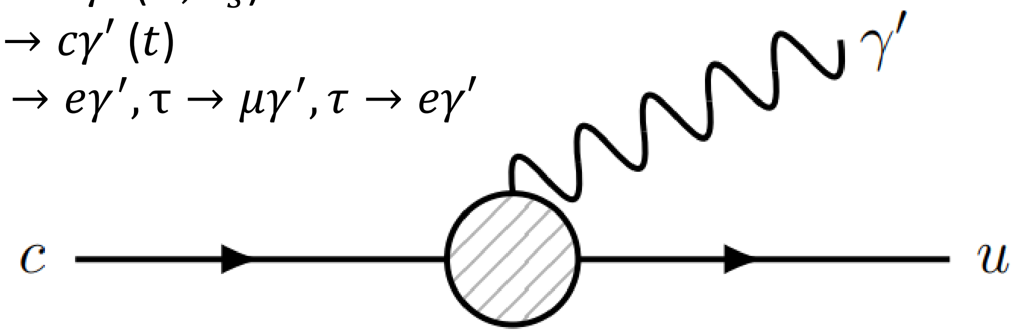
PRL 94, 151802 (2005)

$$\mathcal{L}_{NP} = \frac{1}{\Lambda_{NP}^2}\big(\underbrace{C^U_{jk}\bar{q}_j\sigma^{\mu\nu}u_k\widetilde{H}}_{\text{Up type quarks coupling}} + \underbrace{C^D_{jk}\bar{q}_j\sigma^{\mu\nu}d_kH}_{\text{Down type quarks coupling}} + \underbrace{C^L_{jk}\bar{l}_j\sigma^{\mu\nu}e_kH}_{\text{Charged leptons coupling}} + h.c.\big)\underbrace{\bar{F}_{\mu\nu}}_{\text{Massless dark photon}}$$

FCNC of charm

FCNC process beyond the SM

- $c \to u\gamma'$ (Λ_c, D, D_s)
- $s - d\gamma$ $(K, \Lambda, \Sigma^+, \Xi^0)$
- $b \to s\gamma'$ (B, B_s)
- $t \to c\gamma'$ (t)
- $\mu \to e\gamma', \tau \to \mu\gamma', \tau \to e\gamma'$



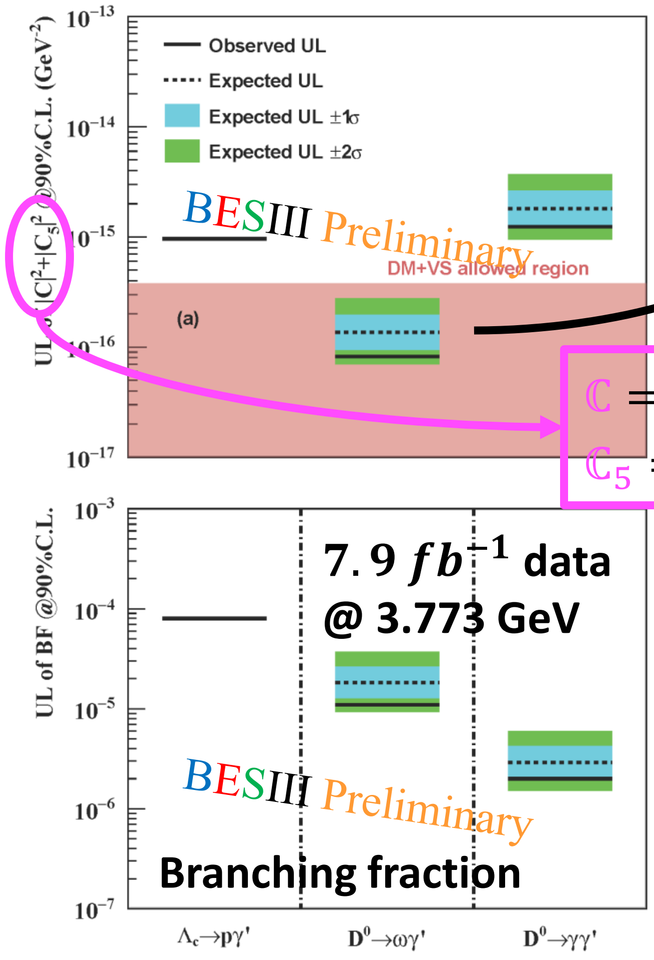
➢ $\mathcal{L}_{uc\gamma'} = \bar{u}(\mathbb{C} + \gamma_5\mathbb{C}_5)\sigma^{\mu\nu}c\bar{F}_{\mu\nu} + h.c.$

- $\mathbb{C} = \Lambda_{NP}^{-2}\left(C^U_{12} + C^{U*}_{21}\right)v/\sqrt{8}$ PRD 102, 115029 (2020)
- $\mathbb{C}_5 = \Lambda_{NP}^{-2}\left(C^U_{12} - C^{U*}_{21}\right)v/\sqrt{8}$
- v: Higgs vacuum expectation value
- $\boldsymbol{\Lambda_{NP}}$: effective heavy mass**(NP energy scale)**

Candidate channels at BESIII:
$\boldsymbol{\Lambda_c \to p\gamma', D \to \omega\gamma', D \to \gamma\gamma',}$
$D \to \rho\gamma'$ **…**

This talk

Upper limit of $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$



$7.9\ fb^{-1}$ data
@ 3.773 GeV

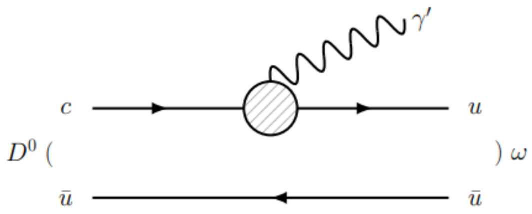
Branching fraction

Reaching into the dark matter (DM) and vacuum stability (VS) allowed region for the first time

Dimensionless coefficient

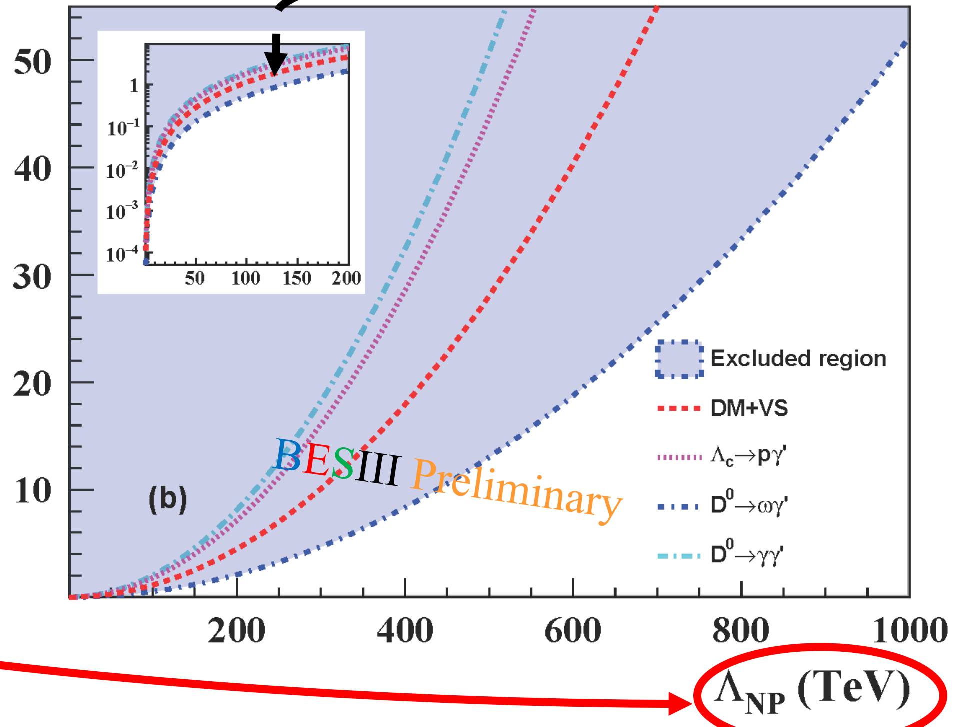
$|C^U_{12}|$

$$\mathbb{C} = \Lambda_{NP}^{-2}(C^U_{12} + C^{U*}_{21})v/\sqrt{8}$$
$$\mathbb{C}_5 = \Lambda_{NP}^{-2}(C^U_{12} - C^{U*}_{21})v/\sqrt{8}$$



the most stringent constraint on Λ_{NP} associated with $cu\gamma'$ coupling

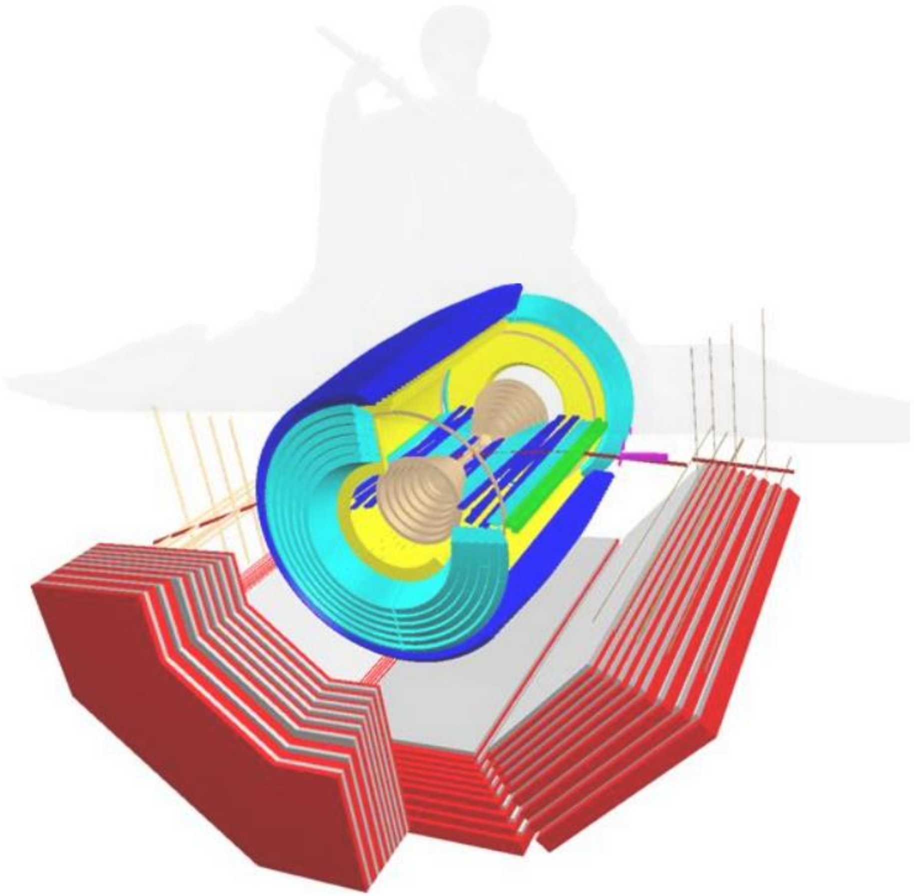
If assuming $|C^U_{12}| = 1$
$\to \Lambda_{NP} > 138\ TeV$



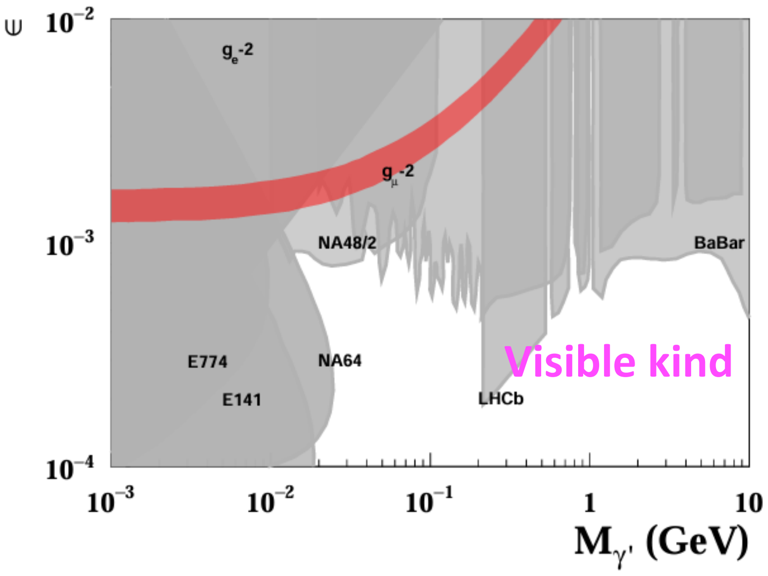
New physics scale

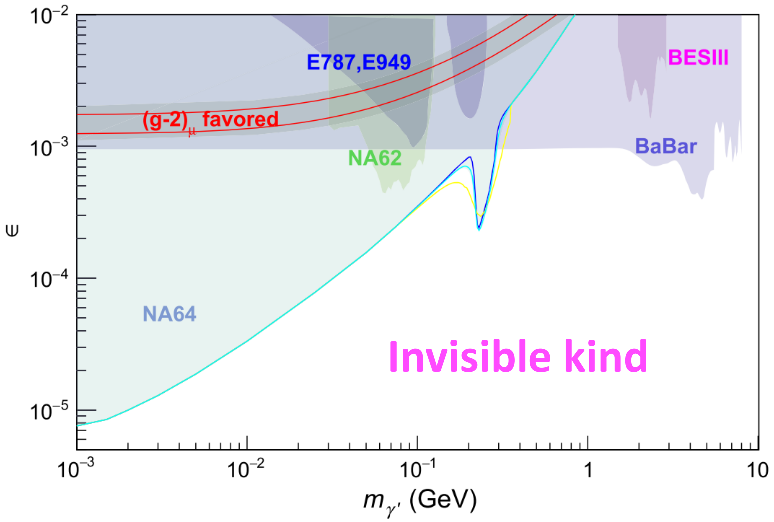
OUTLINE

- Introduction
- Massive dark photon
- Massless dark photon
- **Muon-philic particle**
- Summary



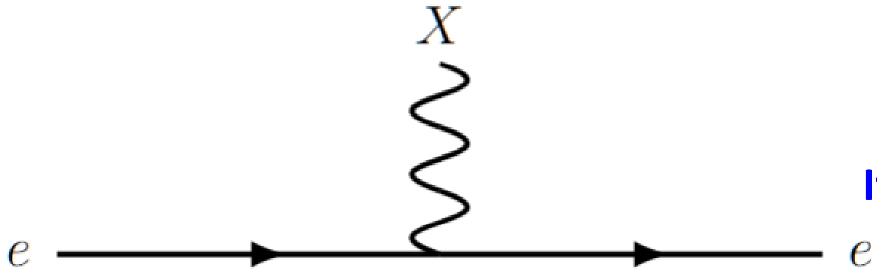
Why we need the muon-philic particle

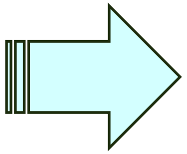




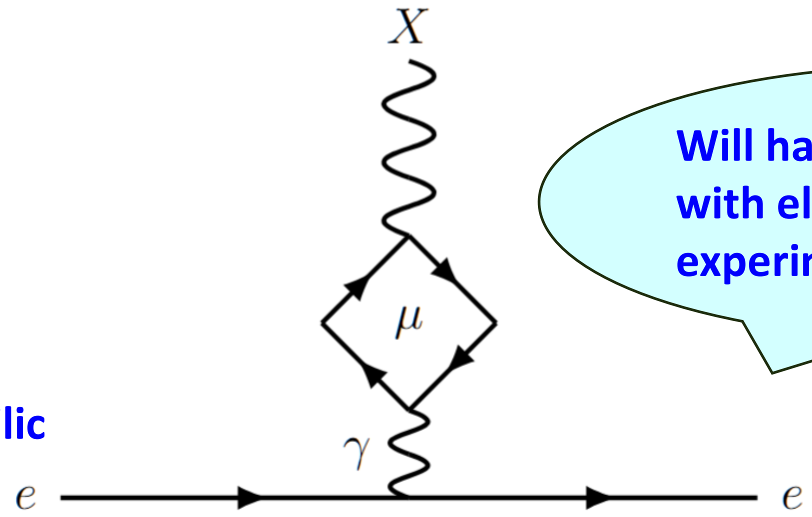
The space of dark photon for $g_\mu - 2$ has been excluded

But most of the experiments are based on electron coupling or light quark coupling





If only muon-philic



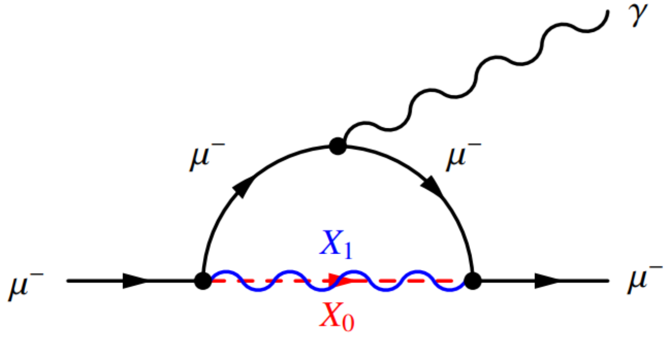
Will have worse constraint with electron-coupling experiment

Muon-philic scalar or vector particle $X_{0,1}$

- Similar to the previous dark photon, an extra $U(1)$ group is added as minimal extension to the SM

$$\mathcal{L}_\mu^{\text{scalar}} = -g_0\, X_0\, \overline{\mu}\, \mu,$$
$$\mathcal{L}_\mu^{\text{vector}} = -g_1\, X_{1\alpha}\, \overline{\mu}\, \gamma^\alpha\, \mu.$$

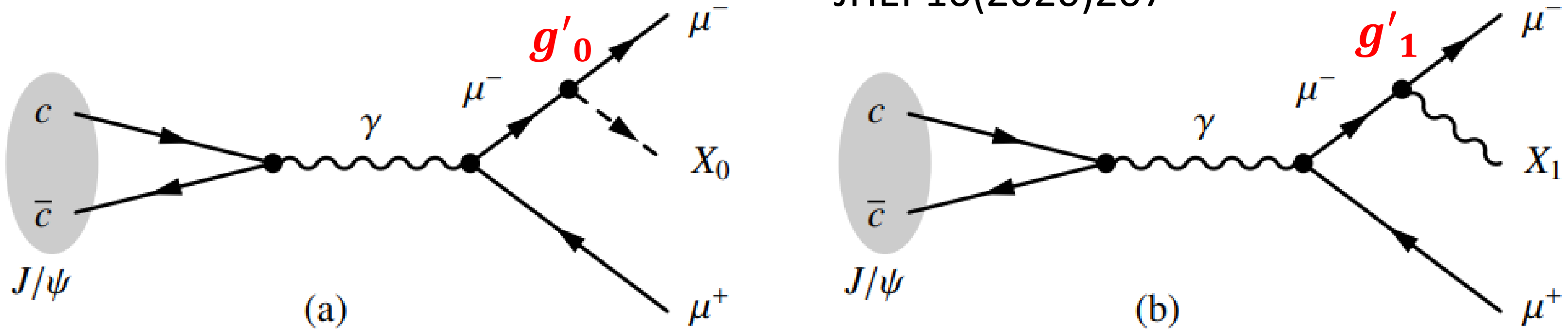
- **$U(1)_{L\mu-L\tau}$ model**: A new massive scalar boson X_0 or vector boson X_1 **only couples to the second and third generations** of leptons $(\mu, \nu_\mu, \tau, \nu_\tau)$ with the **coupling strength $g'_{0,1}$**



explain $(g-2)_\mu$ anomaly

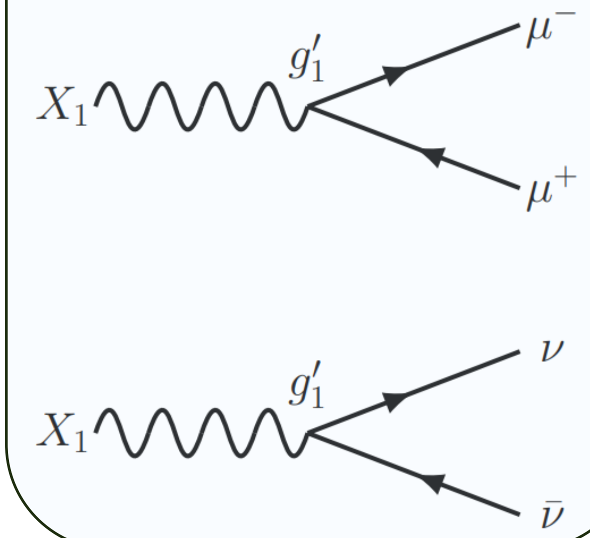
> **Can be accessible via $J/\psi \to \mu^+\mu^- X_{0,1}$ at BESIII**

JHEP10(2020)207

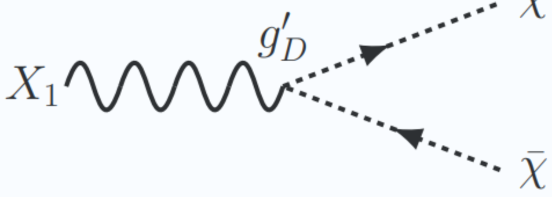


Three cases of muon-philic particles

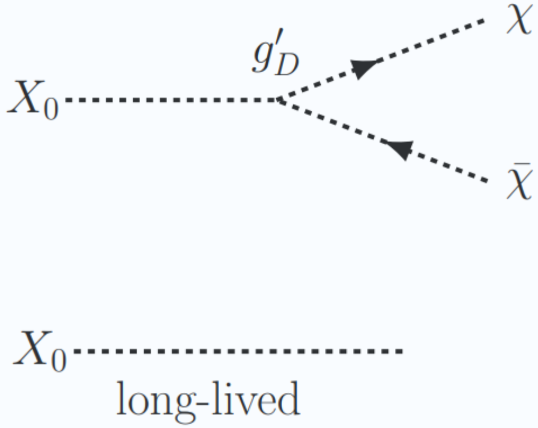
"vanilla" $L_\mu - L_\tau$ model



"invisible" $L_\mu - L_\tau$ model



"scalar" $U(1)$ model



- Large mass of dark matter kind:
  $$m_\chi > m_{X_1}/2$$
- $\mathcal{B}(X_1 \to \upsilon\bar{\upsilon}) = 33\% - 100\%$ with different m_{X_1}

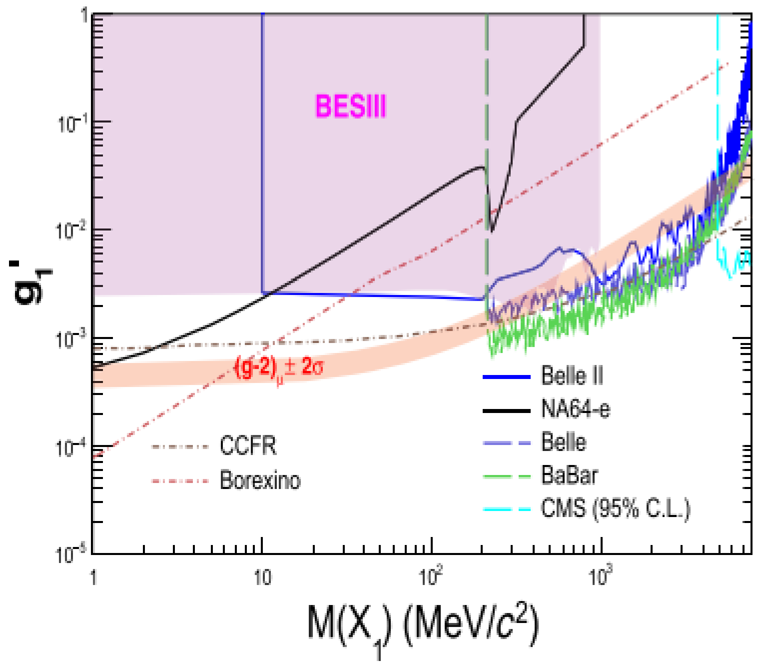
- Light dark matter kind:
  $$m_\chi < m_{X_1}/2$$
- $g'_D \gg g'_1$
- $\mathcal{B}(X_1 \to \chi\bar{\chi}) \sim 100\%$

- Assuming the X_0 is long-lived or only decay to invisible final states

Search for muonphilic scalar X_0 or vector X_1 via $J/\psi \to \mu^+\mu^- X_{0,1}$ with $X_{0,1}$ invisible

Coupling constraint from $J/\psi \to \mu^+\mu^- X$

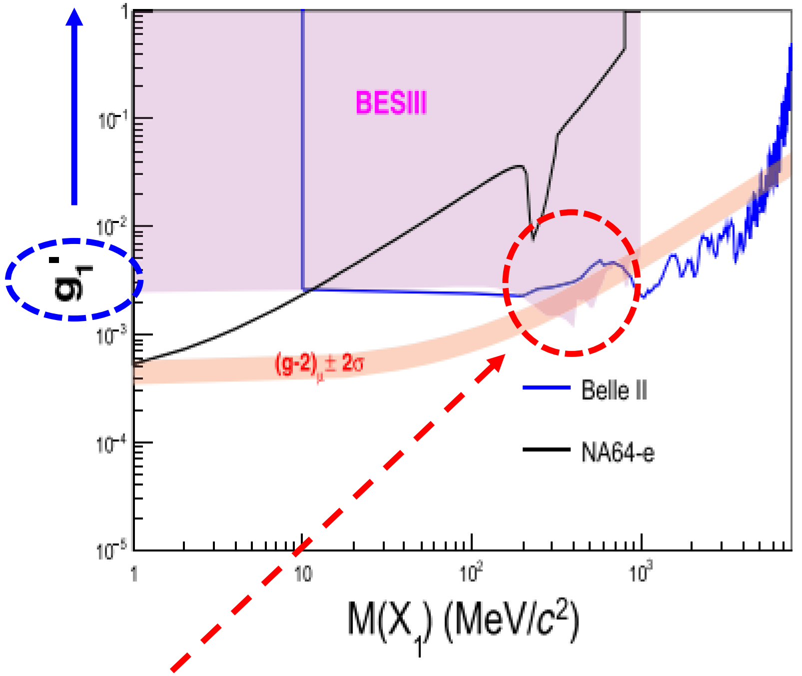
“vanilla” $L_\mu - L_\tau$ model



BarBar, CMS, Belle: $X_1 \to \mu^+\mu^-$
Belle II, BESIII: $X_1 \to \upsilon\bar{\upsilon}$
(Taking $\mathcal{B}(X_1 \to \upsilon\bar{\upsilon})$ into account)

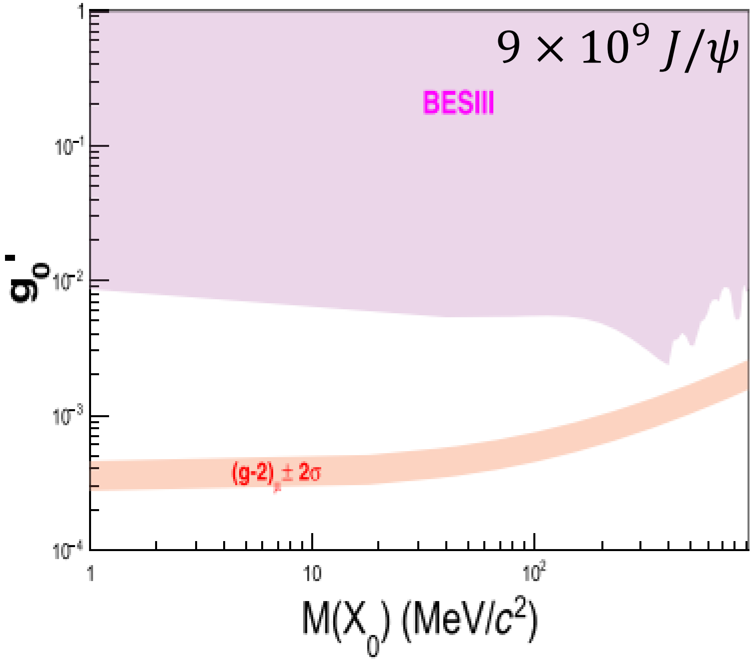
“invisible” $L_\mu - L_\tau$ model

$g'_1 = e\epsilon$, $e \approx 0.3$



Better sensitivity in the range 200-860 MeV/c^2

“scalar” $U(1)$ model

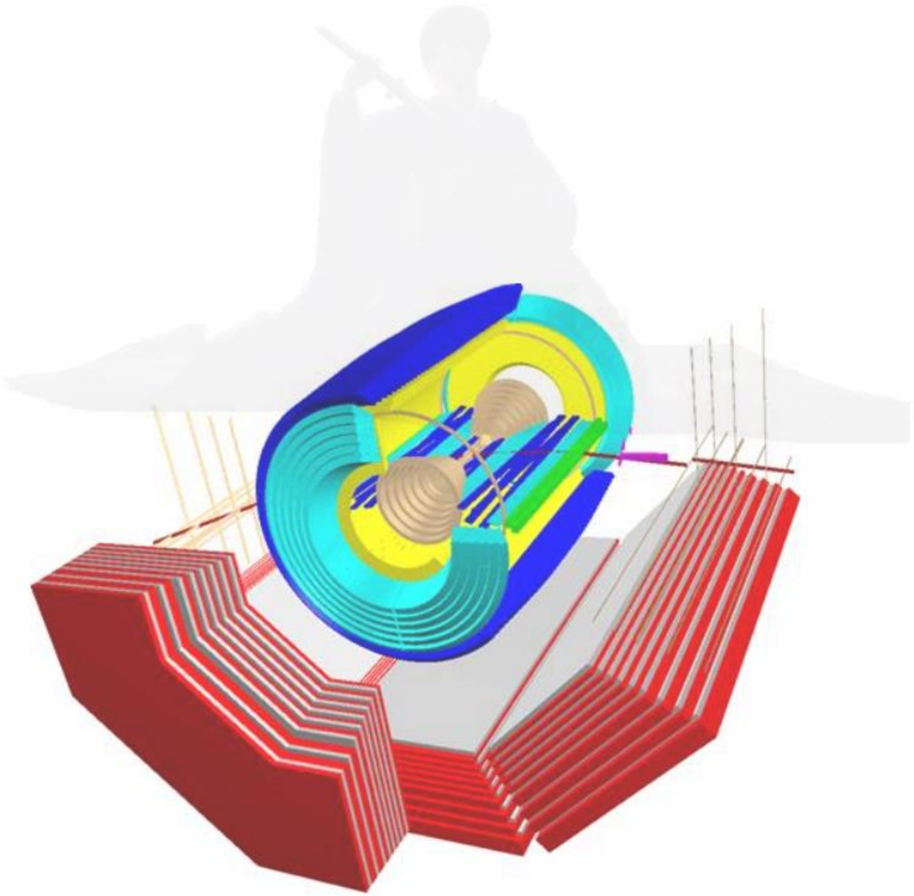


First constraint for the “scalar” invisible X_0 case
Belle II can also give the constraint

PHYS. REV. D 109, L031102 (2024)

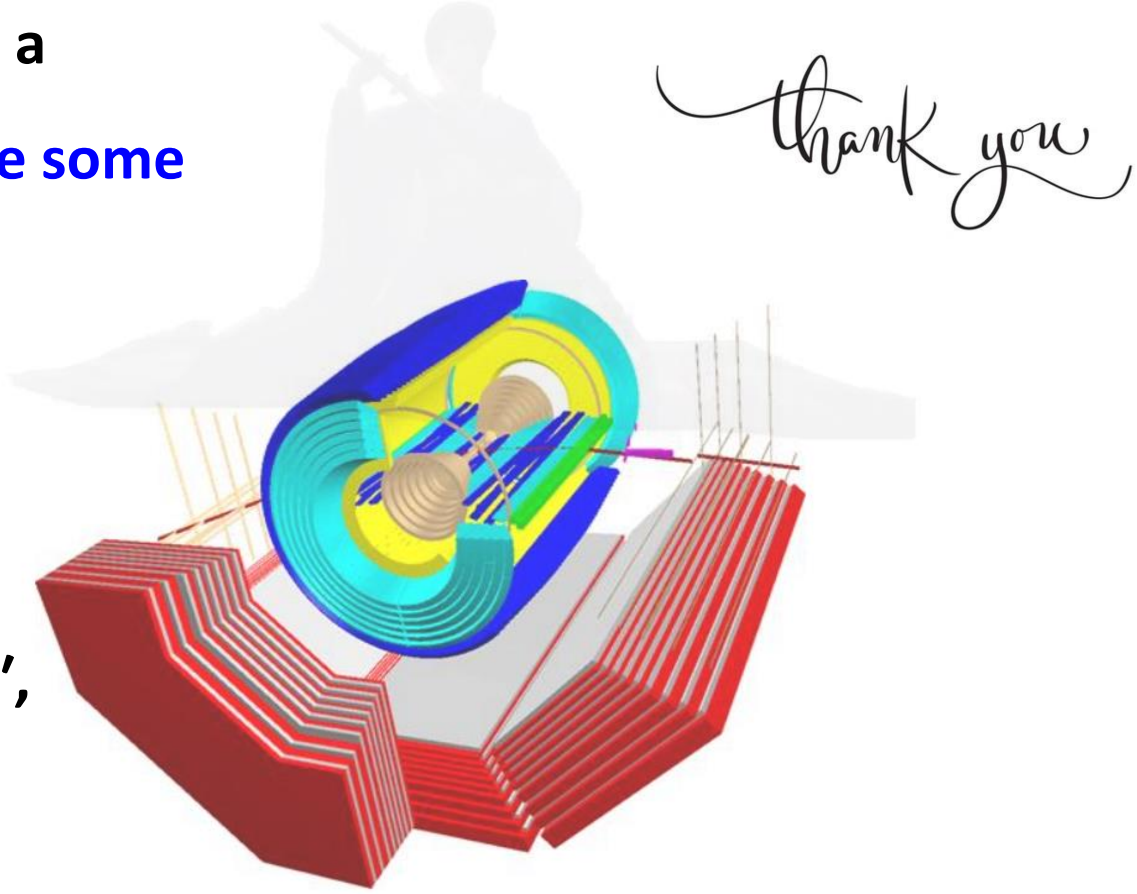
OUTLINE

- Introduction
- Visible dark photon
- Invisible dark photon
- Massless dark photon
- Muon-philic particle
- **Summary**



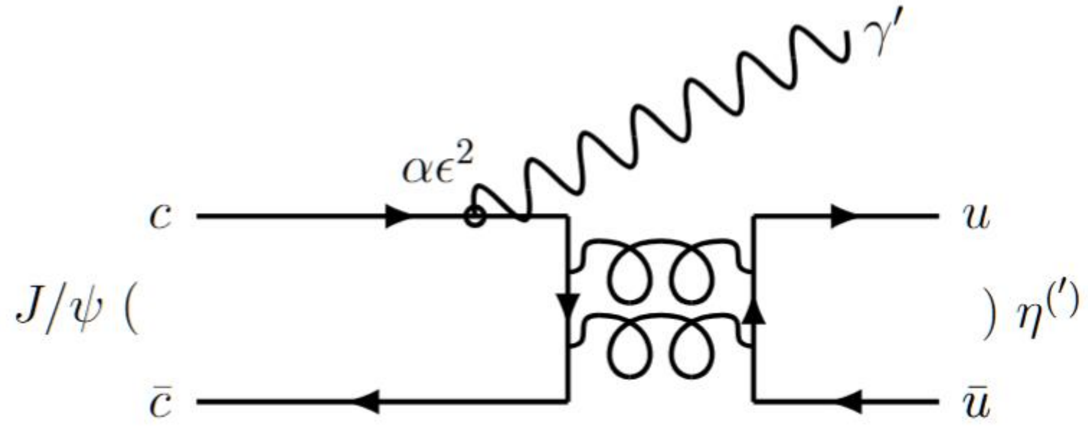
Summary

- Dark photon / muon-philic particle provides a portal to **connect the dark sector** and **resolve some puzzles** beyond the SM
- Unfortunately, **no evidence** is found
- BESIII has collected $10^{10}\ J/\psi$, $2.7 \times 10^9\ \psi'$, $20\ \mathrm{fb}^{-1}$ @ 3.77 GeV data ($D\bar{D}$) and more…
- **More & better** results are coming soon



The future of Dark Sector is Bright !

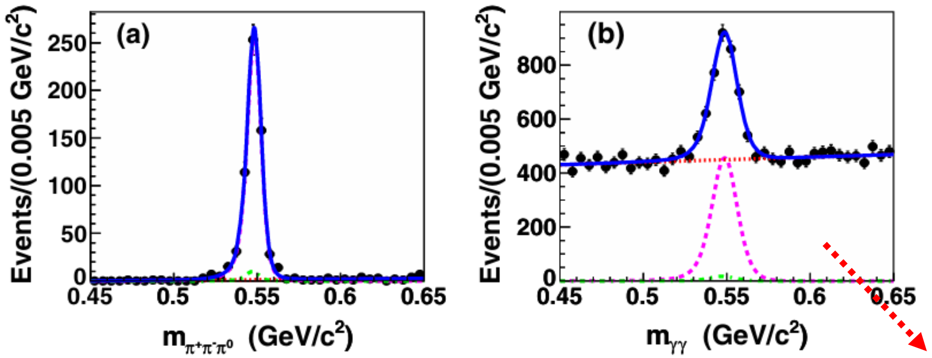
$J/\psi \to \gamma' \eta^{(\prime)}, \gamma' \to e^+e^-$



- [ ] Reconstruction of η:
  - $\eta \to \gamma\gamma$ (39.36%)
  - $\eta \to \pi^+\pi^-\pi^0$ (23.02%)
- [ ] Reconstruction of η'
  - $\eta' \to \pi^+\pi^-\gamma$ (29.5%)
  - $\eta' \to \pi^+\pi^-\eta$ (42.5%),$\eta \to \gamma\gamma$ (39.36%)
- [ ] Reconstruction of γ'
  - $\gamma' \to e^+e^-$ (10%~100%)

Phys. Rev. D 99, 012006 (2019)

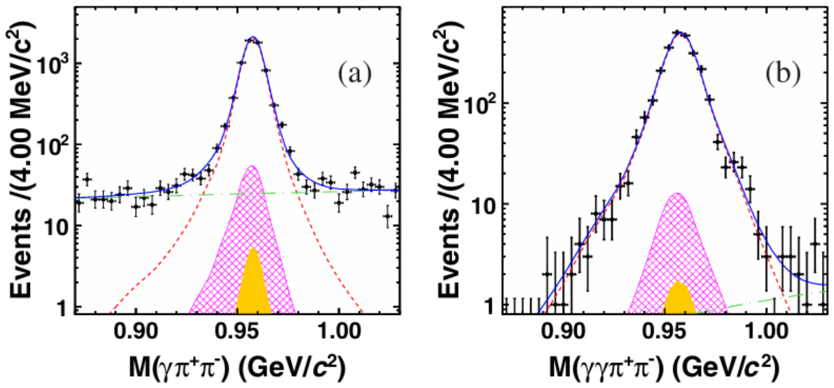
Only $\sim 10^9$ J/ψ



High QED background

Reconstruction of η in ηe^+e^-

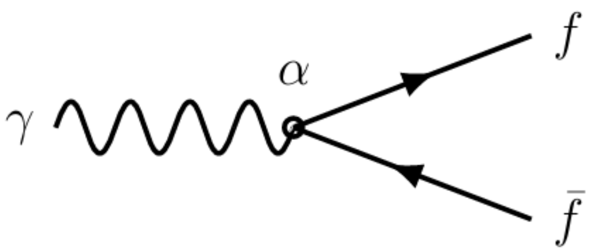
Phys. Rev. D 99, 012013 (2019)



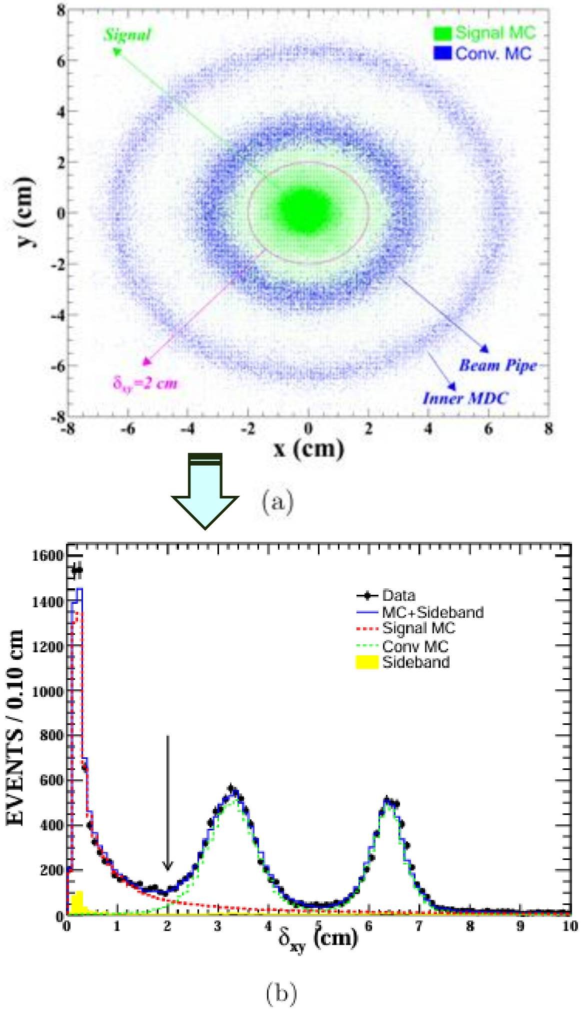
Reconstruction of η' in $\eta' e^+e^-$

Main background of $J/\psi \to \gamma' \eta^{(\prime)}, \gamma' \to e^+ e^-$

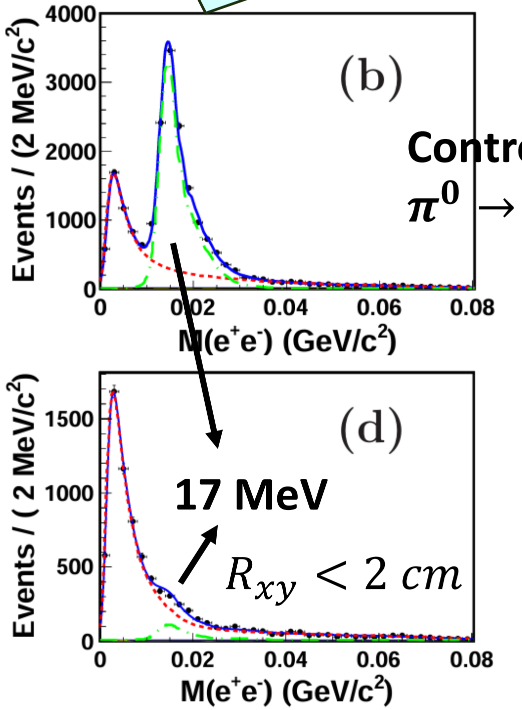
Background I:
$J/\psi \to \gamma^* \eta^{(\prime)} \to e^+ e^- \eta^{(\prime)}$



- **Usually can not be removed**
- **Peak around zero but long tail**
- **Main background: $\gamma^* \to e^+ e^-$**



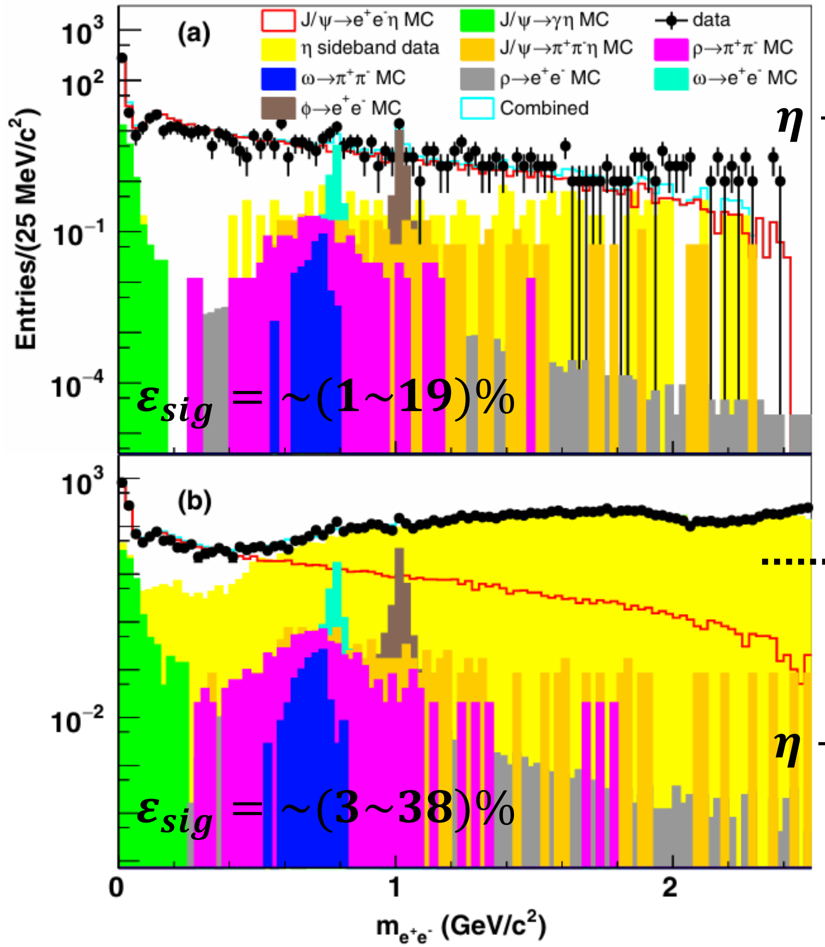
Background II:
gamma conversion



Control sample
$\pi^0 \to \gamma e^+ e^-$

Phys.Rev.D 89 (2014) 9, 092008

M_{ee} spectrum of $J/\psi \to \gamma'\eta^{(\prime)}, \gamma' \to e^+e^-$



$\eta \to \pi^+\pi^-\pi^0$

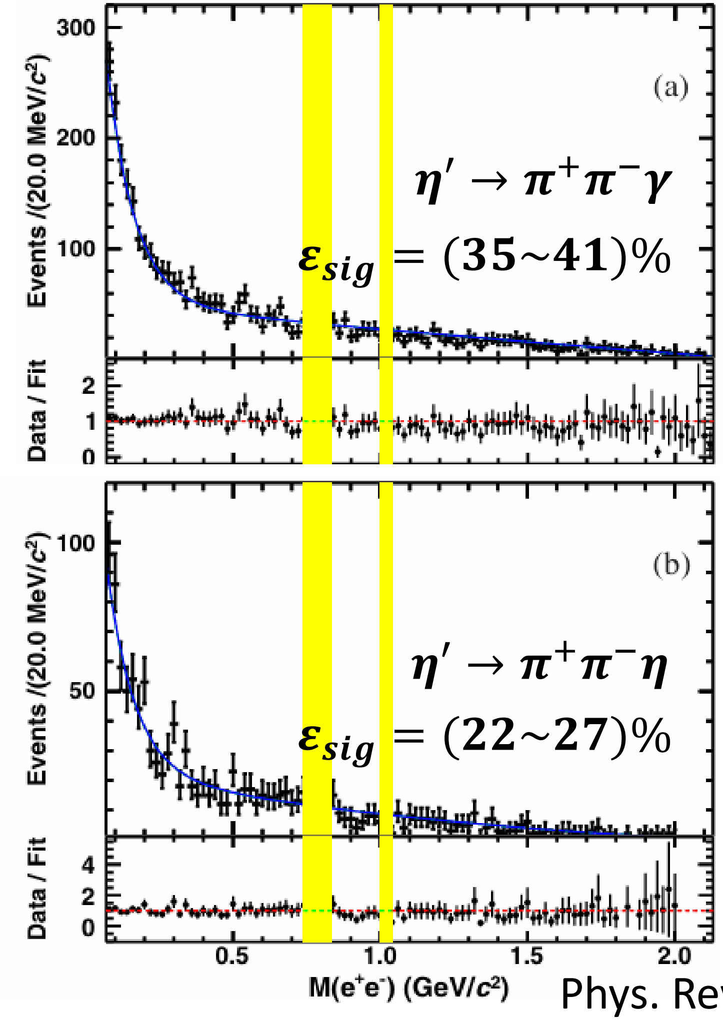
$\varepsilon_{sig} = \sim(1\sim19)\%$

High QED background

$\eta \to \gamma\gamma$

$\varepsilon_{sig} = \sim(3\sim38)\%$

Phys. Rev. D 99, 012006 (2019)



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

$\varepsilon_{sig} = (35\sim41)\%$

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

$\varepsilon_{sig} = (22\sim27)\%$

$\omega \to e^+e^-$ and $\phi \to e^+e^-$ peak would be removed in the fit

Phys. Rev. D 99, 012013 (2019)

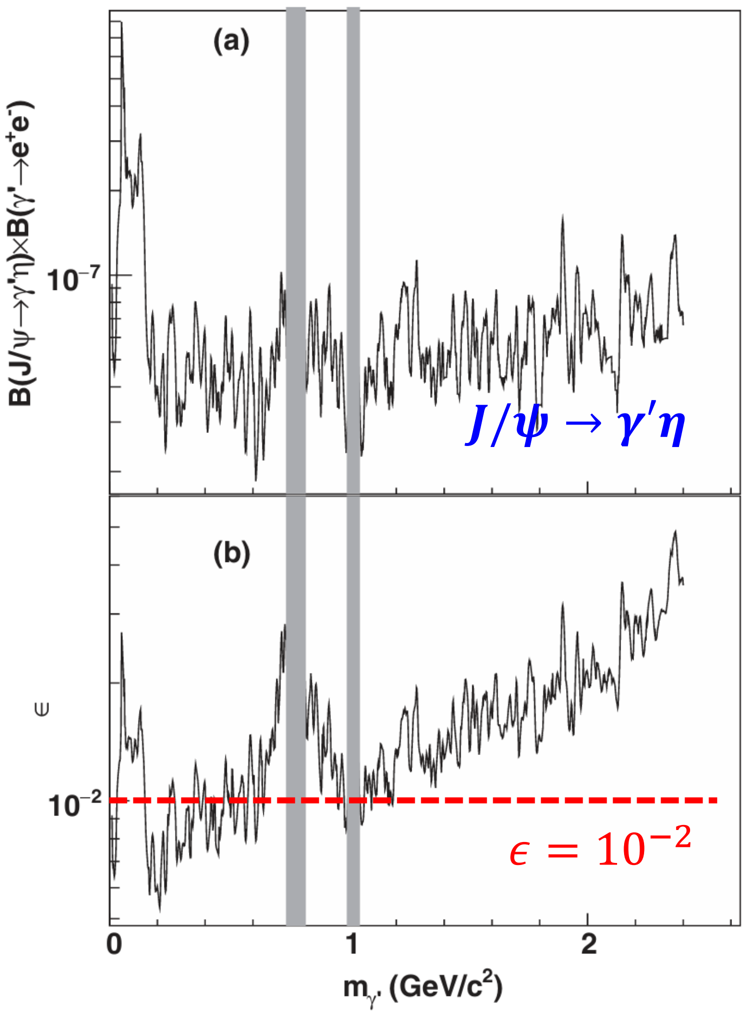
Only $\sim 10^9$ J/ψ

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

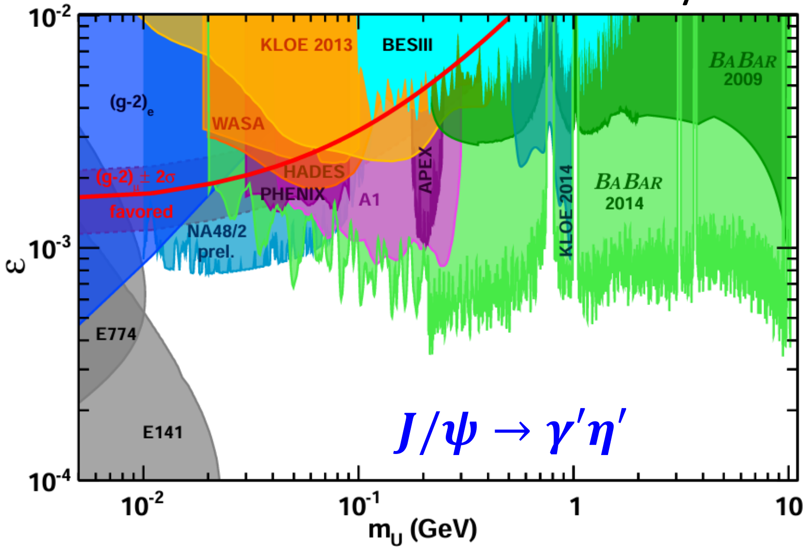
$J/\psi \to \gamma'\eta'$

Mixing strength from $J/\psi \to \gamma'\eta^{(\prime)}, \gamma' \to e^+e^-$

Phys. Rev. D 99, 012006 (2019)



Phys. Rev. D 99, 012013 (2019)



SM Process	BF
$J/\psi \to \gamma\eta'$	0.53%
$J/\psi \to \gamma\eta$	0.11%

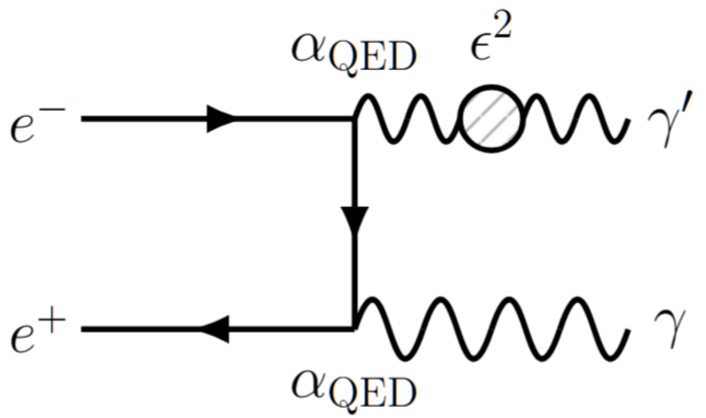
η' has better sensitivity

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

- $|F(q^2)| = 1/(1 - q^2/\Lambda^2)$, Λ is effective pole mass
- $\lambda^{3/2}(m_1^2, m_2^2, m_3^2) = (1 + \frac{m_3^2}{m_1^2 - m_2^2})^2 - \frac{4m_1^2 m_3^2}{(m_1^2 - m_2^2)^2}$

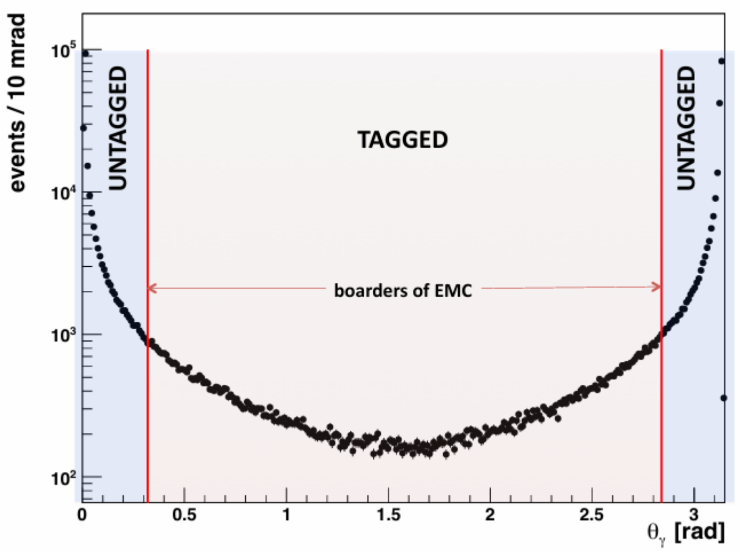
- **Only using $\sim 10^9$ J/ψ events, but now we have $10^{10} J/\psi$ events**
- **What about using the full data? Will discuss later…**

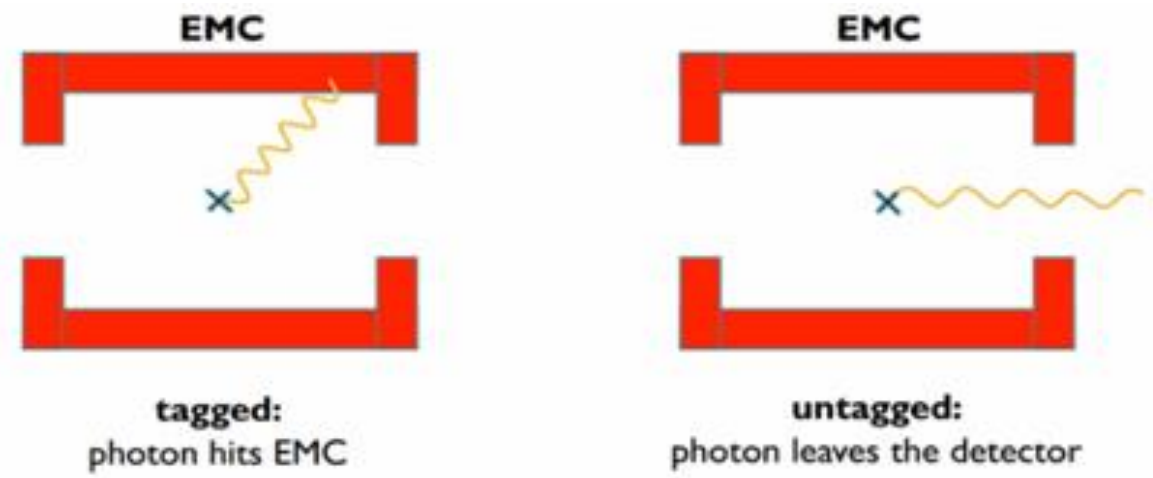
$e^+e^- \to \gamma\gamma', \gamma' \to l^+l^-$



- Data: $2.93\ fb^{-1}$ data taken at $\sqrt{s} = 3.773\ GeV$
- $\gamma' \to e^+e^-$ and $\gamma' \to \mu^+\mu^-$
- Untagged photon method (high efficiency)

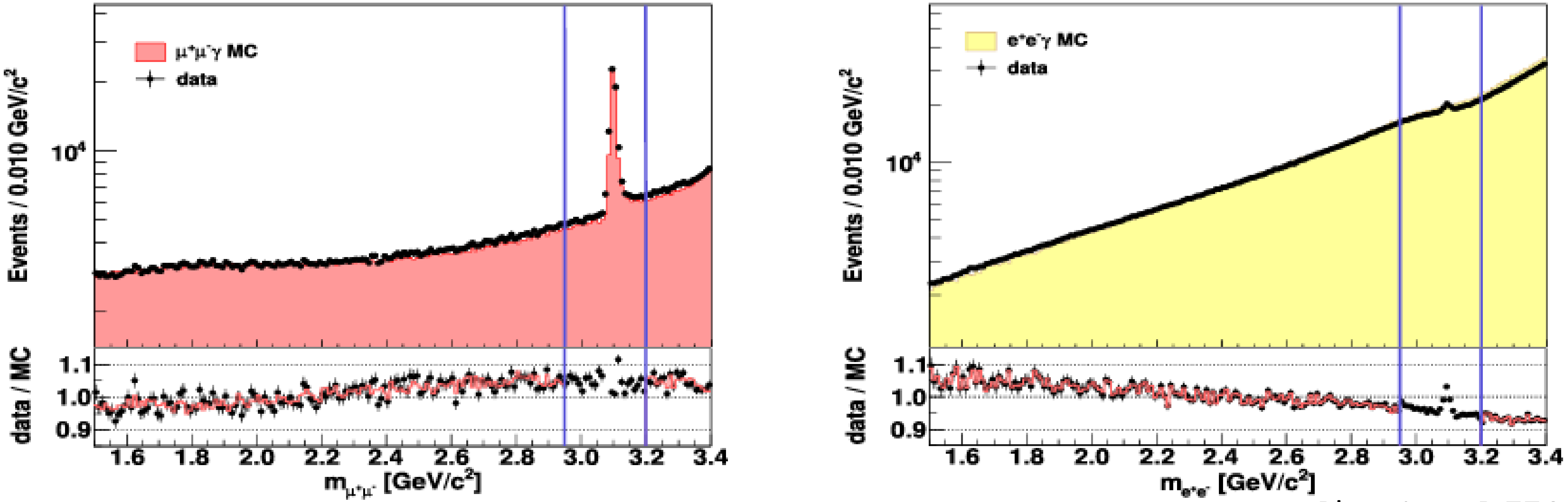
Phys. Lett. B 774, 252 (2017)





Main background: $\gamma^* \to e^+e^-$

M_{ee} spectrum of $e^+e^- \to \gamma\gamma', \ \gamma' \to l^+l^-$

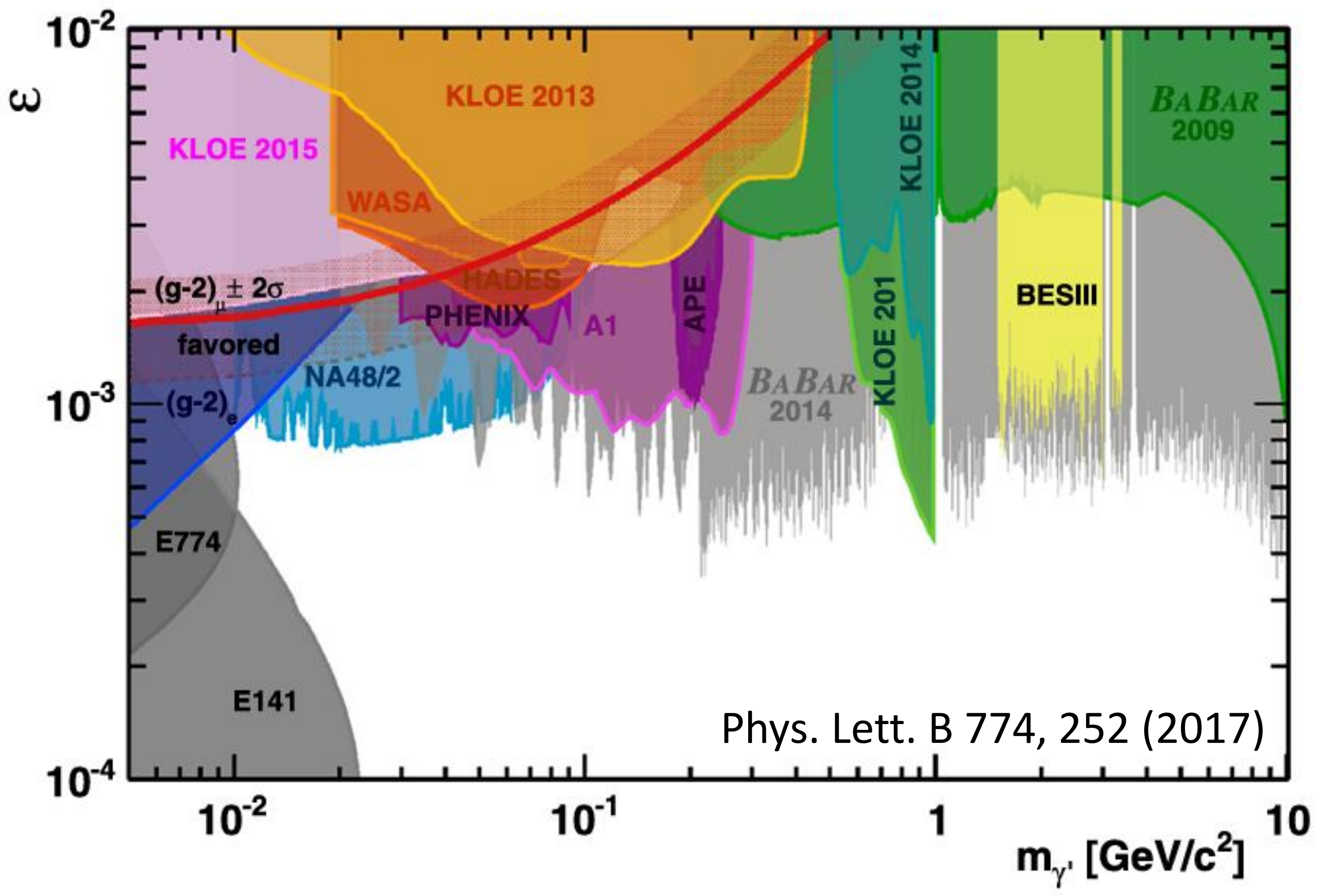


Phys. Lett. B 774, 252 (2017)

- Below 1.5 GeV, $\pi^+\pi^-\gamma$ cross section with muon misidentification dominate the $m_{\mu\mu}$ spectrum
- Above 3.4 GeV, larger hadronic $q\bar{q}$ process background
- $J/\psi \to l^+l^-$ peaks are removed in the fit

$2.93\ fb^{-1}$ data

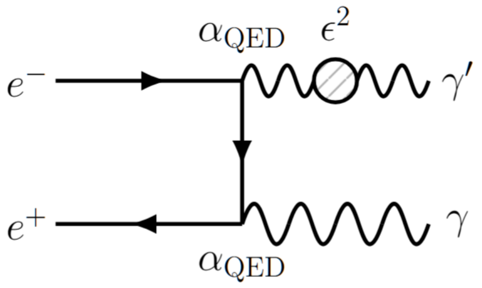
Mixing strength from $e^+e^- \to \gamma\gamma',\ \gamma' \to l^+l^-$



Only using $2.93\ fb^{-1}$ data, Now $20\ fb^{-1}$ data are collected

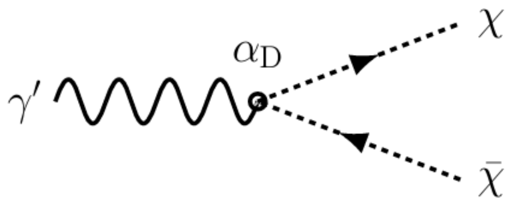
$$\frac{\sigma_i(e^+e^- \to \gamma\gamma' \to \gamma l^+l^-)}{\sigma_i(e^+e^- \to \gamma\gamma^* \to \gamma l^+l^-)} = \frac{N_i^{up}(e^+e^- \to \gamma\gamma' \to \gamma l^+l^-)}{N_i^{B}(e^+e^- \to \gamma\gamma^* \to \gamma l^+l^-)} = \frac{3\pi \cdot \epsilon^2 \cdot m_{\gamma'}}{2\alpha\delta_m^{l^+l^-}} \cdot \mathcal{B}(\gamma' \to l^+l^-) \cdot \varepsilon_{sig}$$

- $\delta_m^{l^+l^-}$: mass bin width, 10 MeV
- ε_{sig}: signal efficiency in the corresponding $\delta_m^{l^+l^-}$ bin



- ☐ **BESIII: $2.93 fb^{-1}$**
- ☐ **BaBar: $514 fb^{-1}$**

Invisible dark photon from $e^+e^- \to \gamma\gamma'$



- $m_\chi < \frac{m_{\gamma'}}{2}$
- $\alpha_D \gg \alpha\epsilon^2$

$\to \mathcal{B}(\gamma' \to \chi\bar{\chi}) \sim 100\%$

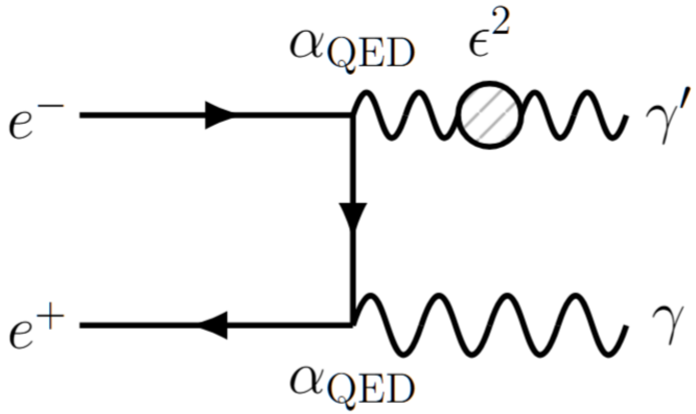
$$\Gamma(\gamma' \to \chi\bar{\chi}) = \frac{1}{3}\alpha_D m_{\gamma'}\sqrt{1-\frac{4m_\chi^2}{m_{\gamma'}^2}}\left(1+\frac{2m_\chi^2}{m_{\gamma'}^2}\right)$$

$m_{\gamma'} = 1\ GeV, m_\chi \ll m_{\gamma'}, \alpha_D = 0.1 \to \Gamma \sim 33\ MeV$

$m_{\gamma'} = 1\ GeV, m_\chi \ll m_{\gamma'}, \alpha_D = 0.01 \to \Gamma \sim 3\ MeV$

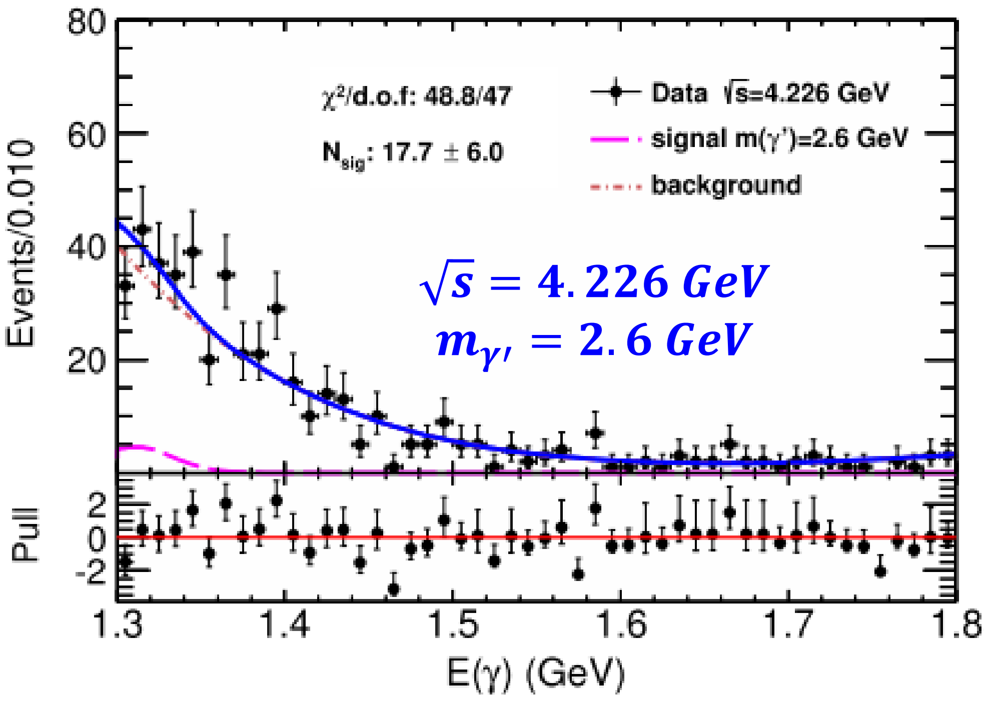
Width can be ignored only when $\alpha_D \lesssim 0.01$

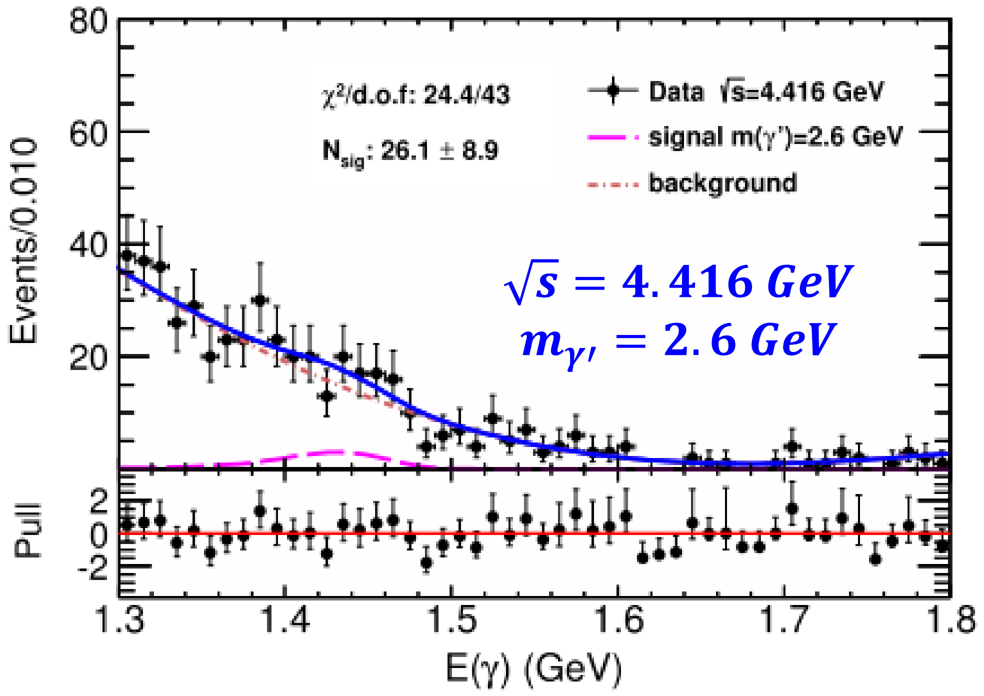
- Invisible in the detector
- Missing energy



- Data: 14.9 fb^{-1} data taken at $\sqrt{s} = 4.13 \sim 4.60\ GeV$
- Ignore the width of the invisible dark photon
- Single energy photon

Photon energy spectrum of $e^+e^- \to \gamma\gamma'$





- Below 1.3 GeV: The trigger efficiency for single photon is low, also high background
- Above 2 GeV: Saturate the EMC electronics, lead to high background
- Detection efficiencies: $1\%\sim6\%$ ($|cos\theta_\gamma| < 0.6$ to suppress the di-gamma background)

$$E_\gamma = \frac{s - m_{\gamma'}^2}{2\sqrt{s}}$$

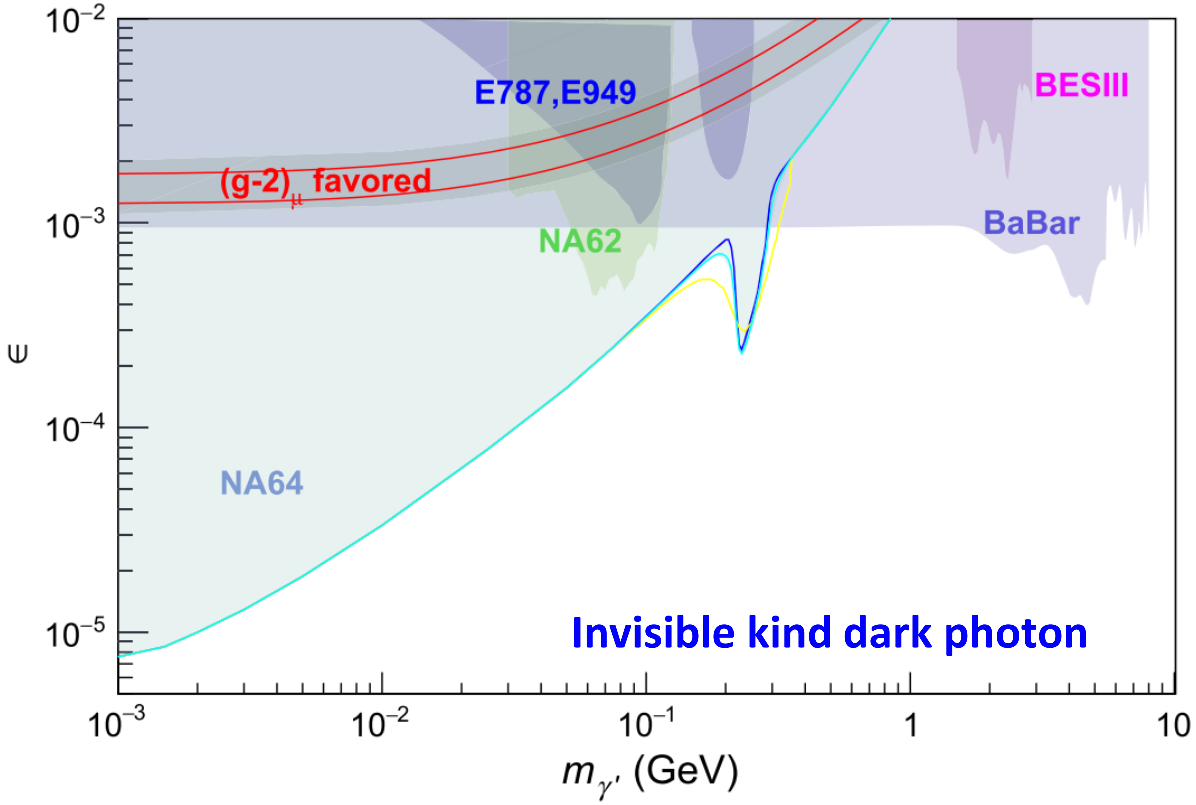
Dark photon mass range: $[1.5, 2.9]\ GeV$

Phys.Lett.B 839 (2023) 137785

Mixing strength from $e^+e^- \to \gamma\gamma'$

$$\sigma(e^+e^- \to \gamma\gamma') = \frac{2\pi\alpha^2}{s}\epsilon^2\left(1-\frac{m_{\gamma'}^2}{s}\right)\times\left(\left(1+\frac{2\frac{m_{\gamma'}^2}{s}}{\left(1-\frac{m_{\gamma'}^2}{s}\right)^2}\right)\log\frac{(1+\cos\theta_c)^2}{(1+\cos\theta_c)^2}-2\cos\theta_c\right)$$

$\cos\theta_c = 0.6$ is the $\cos\theta$ cut for the signal photon polar angle

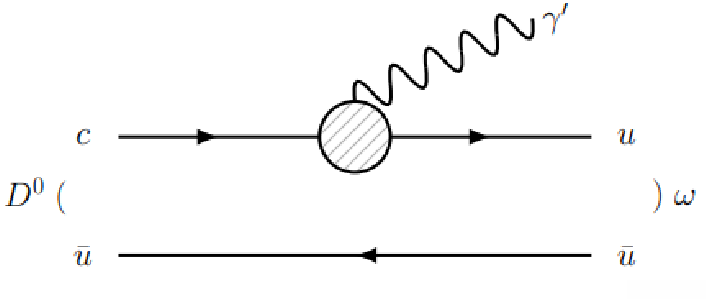


Phys.Lett.B 839 (2023) 137785

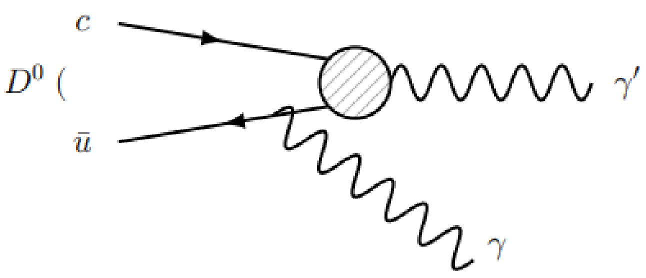
The future?

- ☐ $(20-2.93)\ fb^{-1}$ **data @3.773 GeV**
  - Lower mass region
  - Limit improvement with the statistic
  - $\epsilon \sim \sqrt{s}$, improved by $\frac{4.2\ GeV}{3.773\ GeV} < 1.113$
- ☐ **New method: gamma conversion to tag γ**
  - Better solution, lower background
  - Wider mass range
  - But only $\sim\frac{1}{100}$ statistic
- ☐ $J/\psi \to \gamma'\eta'$ **with 10^{10} J/ψ, invisible γ'**
  - Lower mass region
  - $\epsilon \sim 10^{-3}$ level

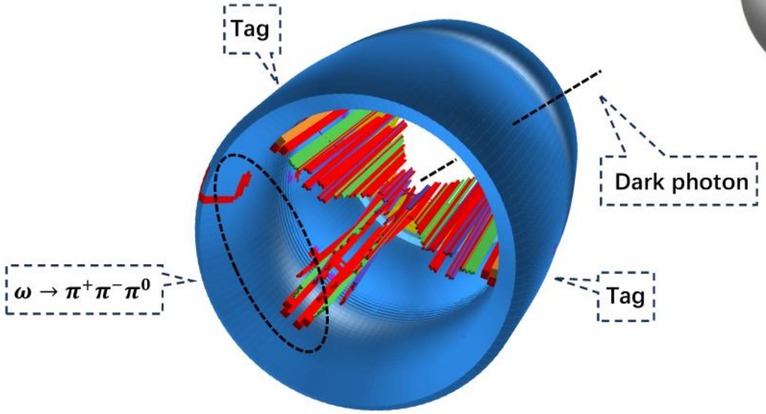
$D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$

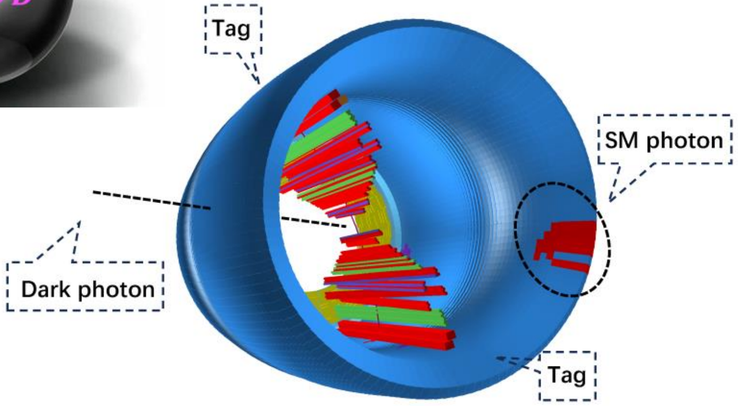


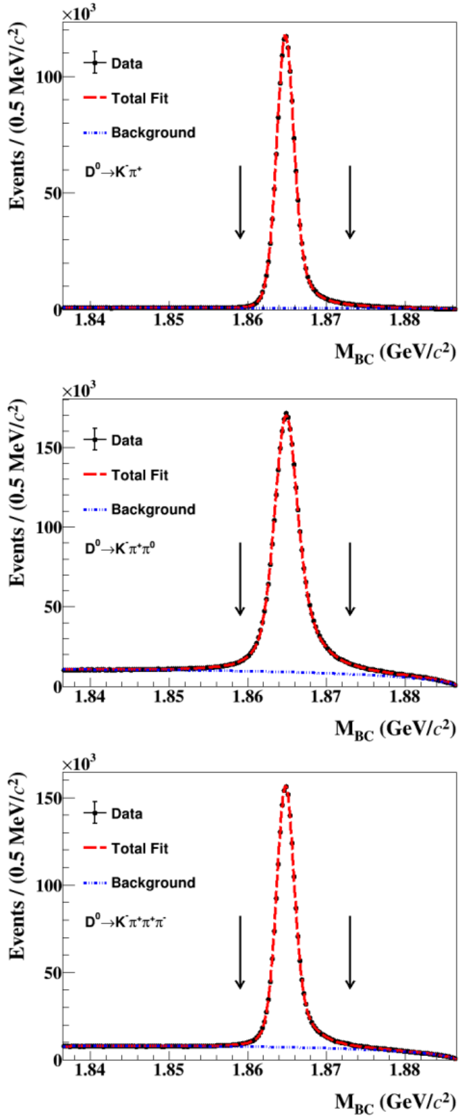
(a) $D^0 \to \omega\gamma'$



(b) $D^0 \to \gamma\gamma'$







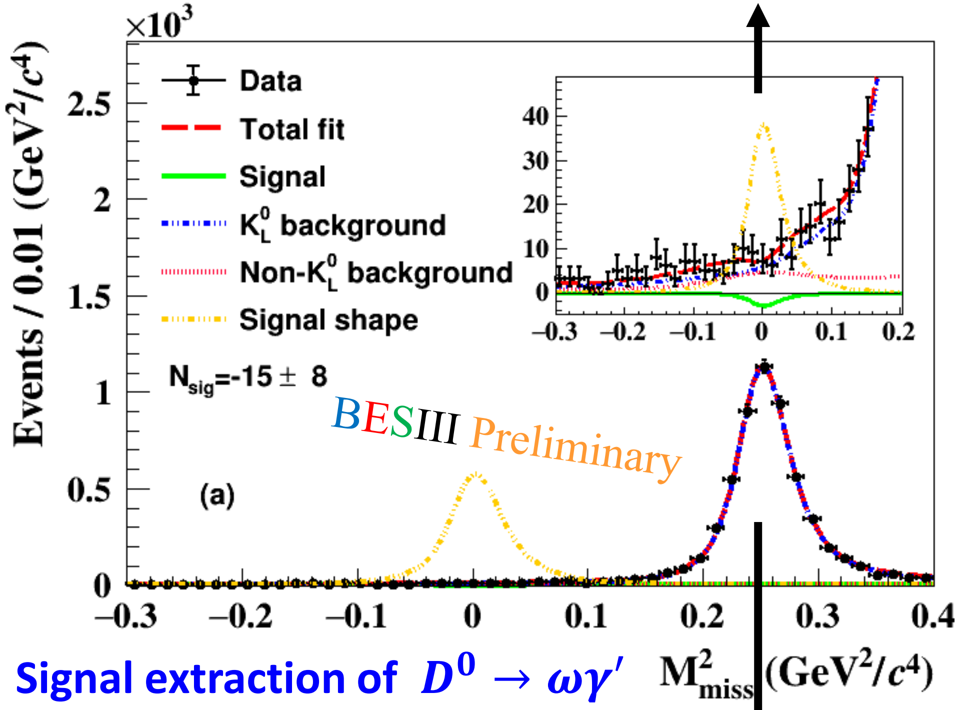
- **Double tag method**: $\sim 6 \times 10^6\ D^0(\bar{D}^0)$ are tagged with 7.9 fb^{-1} data @3.77 GeV
- ω is reconstructed with $\omega \to \pi^+\pi^-\pi^0$
- **The massless dark photon is invisible**

M_{miss}^2 spectrum of $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$

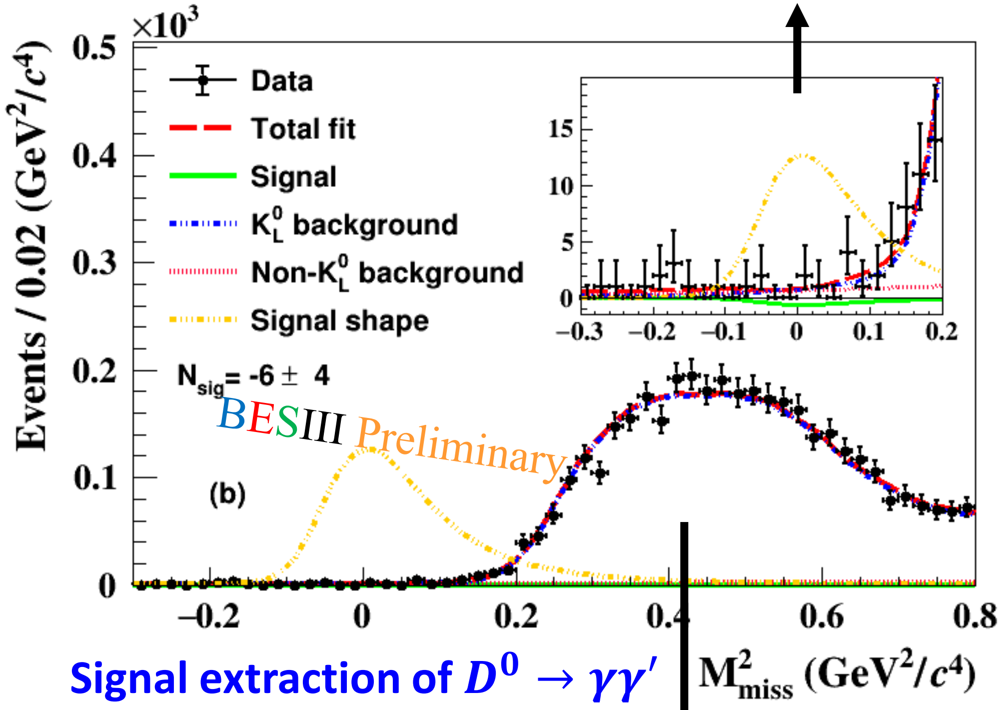
Signal should peak at zero

Signal should peak at zero

$7.9\ fb^{-1}$ data



Signal extraction of $D^0 \to \omega\gamma'$



Signal extraction of $D^0 \to \gamma\gamma'$

$D^0 \to \omega K_L$ background

$D^0 \to \pi^0 K_L$ background

Upper limit of $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$

$$\mathcal{B}(D \to V\gamma') = \frac{\tau_D f_{DV}^2 (m_D^2 - m_V^2)^3}{2\pi m_D^3}(|\mathbb{C}|^2 + |\mathbb{C}_5|^2)$$

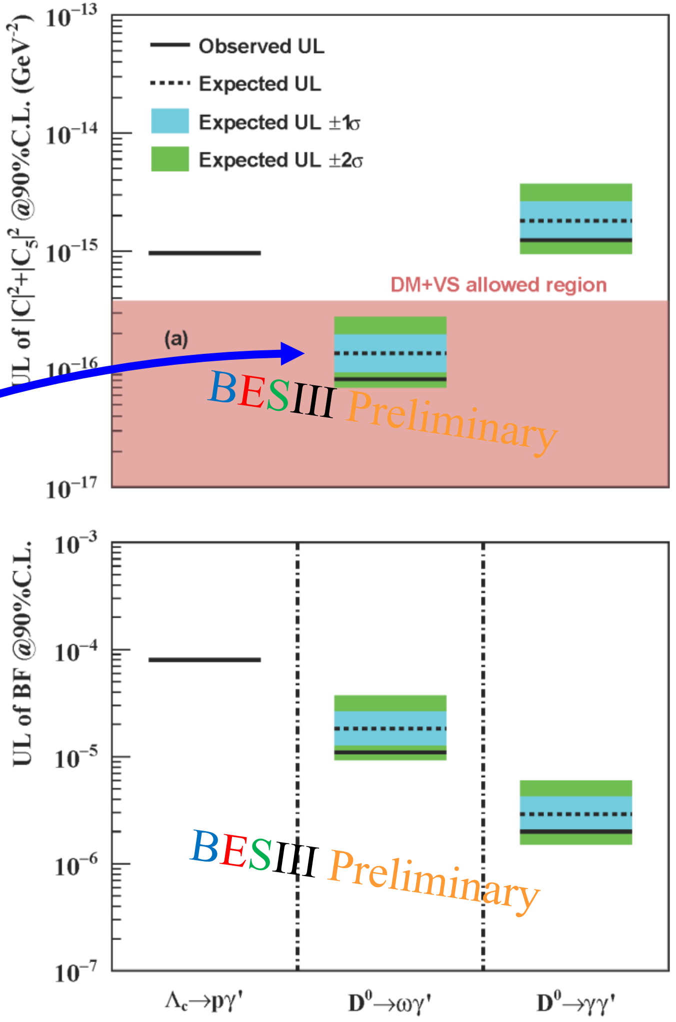
$$\mathcal{B}(D \to \gamma\gamma') = \frac{\alpha_e}{2}\tau_D f_{D\gamma}^2 m_D^3 (|\mathbb{C}|^2 + |\mathbb{C}_5|^2)$$

$$\mathcal{B}(\Lambda_c \to p\gamma') = \frac{\tau_{\Lambda_c} f_{\Lambda_c p}^2 (m_{\Lambda_c}^2 - m_p^2)^3}{2\pi m_{\Lambda_c}^3}(|\mathbb{C}|^2 + |\mathbb{C}_5|^2)$$

PRD 102, 115029 (2020)

- $\mathbb{C} = \boldsymbol{\Lambda_{NP}^{-2}}(C_{12}^U + C_{21}^{U*})v/\sqrt{8}$
- $\mathbb{C}_5 = \boldsymbol{\Lambda_{NP}^{-2}}(C_{12}^U - C_{21}^{U*})v/\sqrt{8}$
- v: Higgs vacuum expectation value
- Λ_{NP}: effective heavy mass

The constraint from $D^0 \to \omega\gamma'$ goes into the dark matter (DM) and vacuum stability (VS) allowed region for the first time, the most stringent constraint



$7.9\ fb^{-1}$ data

Lower limit of Λ_{NP}

PRL 94, 151802 (2005)

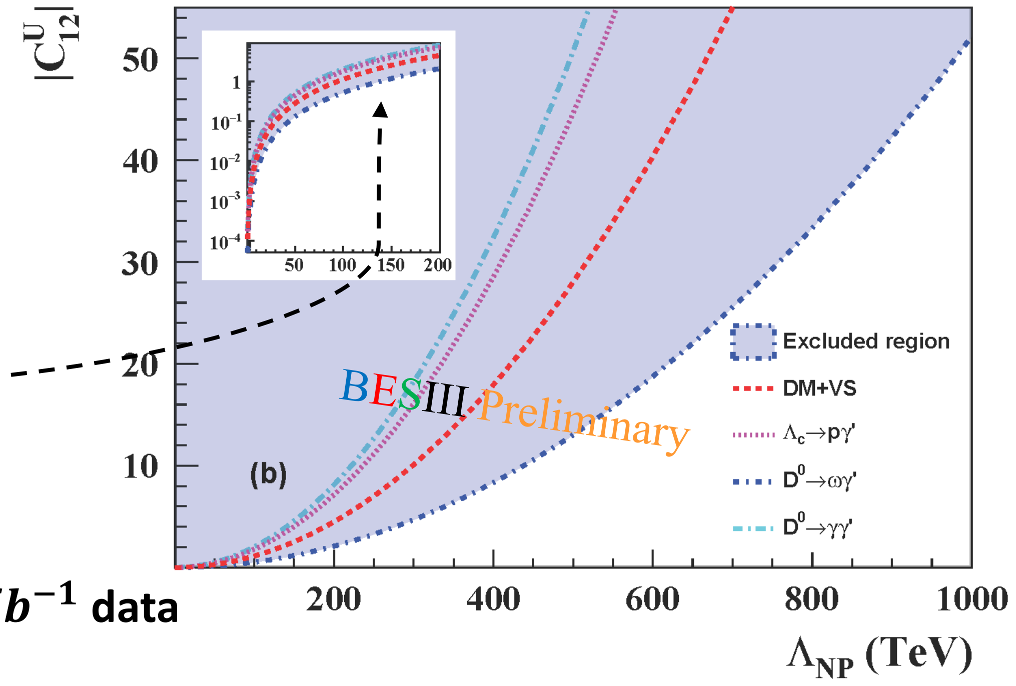
$$\mathcal{L}_{NP} = \frac{1}{\Lambda_{NP}^2}\big(\underbrace{C_{jk}^{U}\bar{q}_j\sigma^{\mu\nu}u_k\tilde{H}}_{\text{Up type quarks coupling}} + \underbrace{C_{jk}^{D}\bar{q}_j\sigma^{\mu\nu}d_kH}_{\text{Down type quarks coupling}} + \underbrace{C_{jk}^{L}\bar{l}_j\sigma^{\mu\nu}e_kH}_{\text{Charged leptons coupling}} + h.c.\big)\underbrace{\bar{F}_{\mu\nu}}_{\text{Massless dark photon}}$$

Λ_{NP}^2: NP energy scale

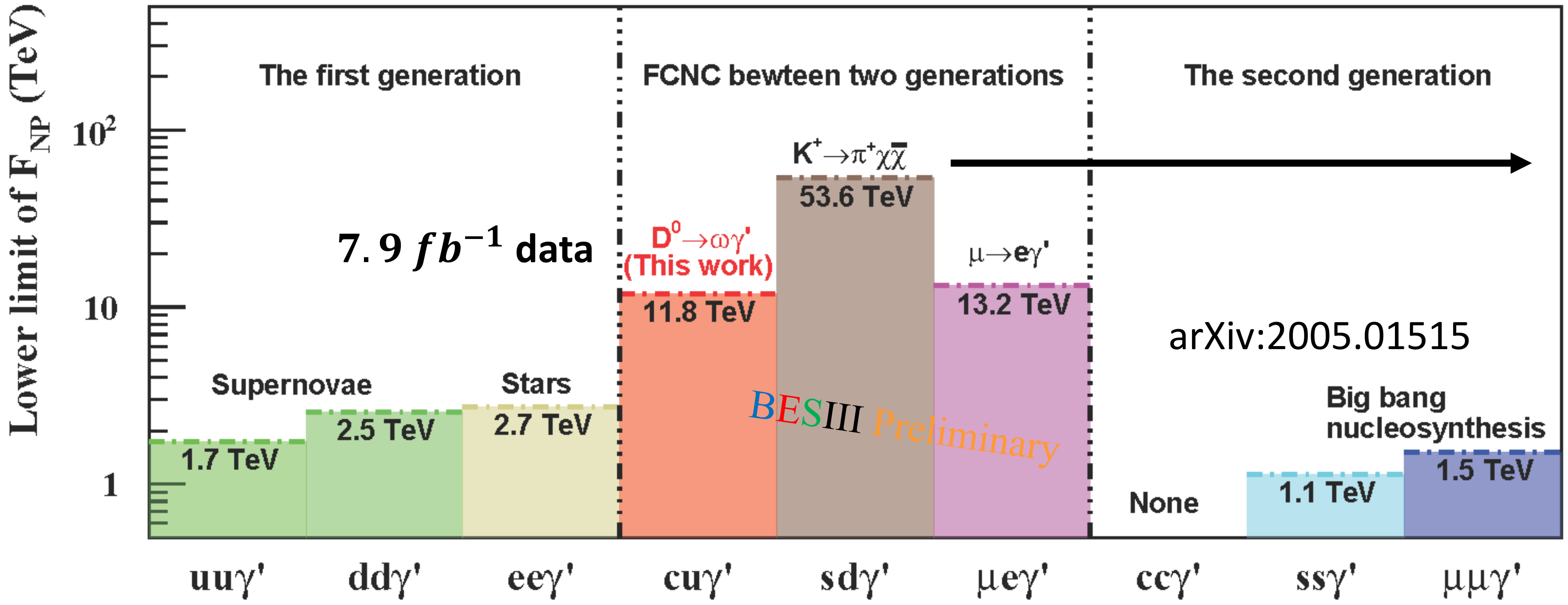
C_{jk}^{U}: dimensionless coefficient

- **Providing the most stringent constraint on Λ_{NP} associated with $cu\gamma'$ coupling to date**
- **If assuming $|C_{12}^{U}| = 1 \rightarrow \Lambda_{NP} > 138\ TeV$**

$7.9\ fb^{-1}$ data



Summary of the massless dark photon couplings



- $K^+ \to \pi^+ \chi\bar{\chi}$: Massless dark photon as the virtual particle
- $K_L \to \gamma\gamma'$ result in ICHEP2024: $F_{NP} > 19.5\ TeV$

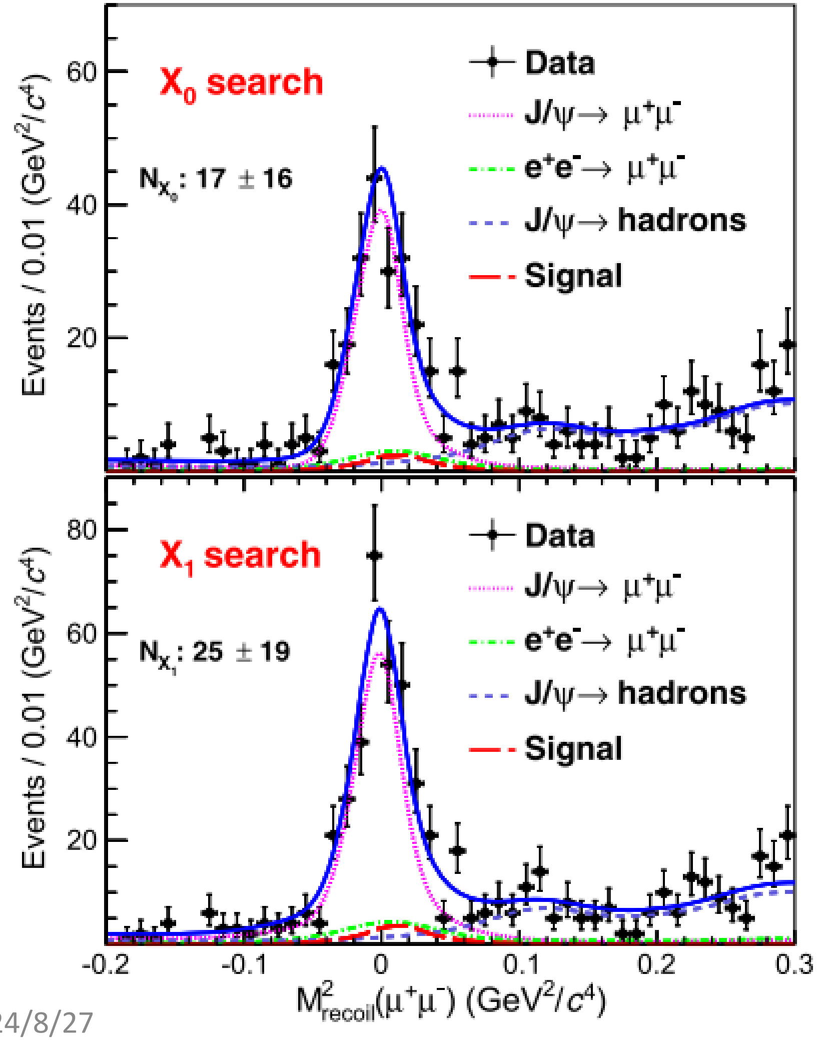
The future?

- $F_{NP} \sim \frac{1}{\sqrt[4]{BF}} \to F_{NP} \sim 13.3\ TeV$ with 20 fb^{-1} data, improvement of 1.5 TeV
- $D \to \rho\gamma'$
- Massive dark photon FCNC

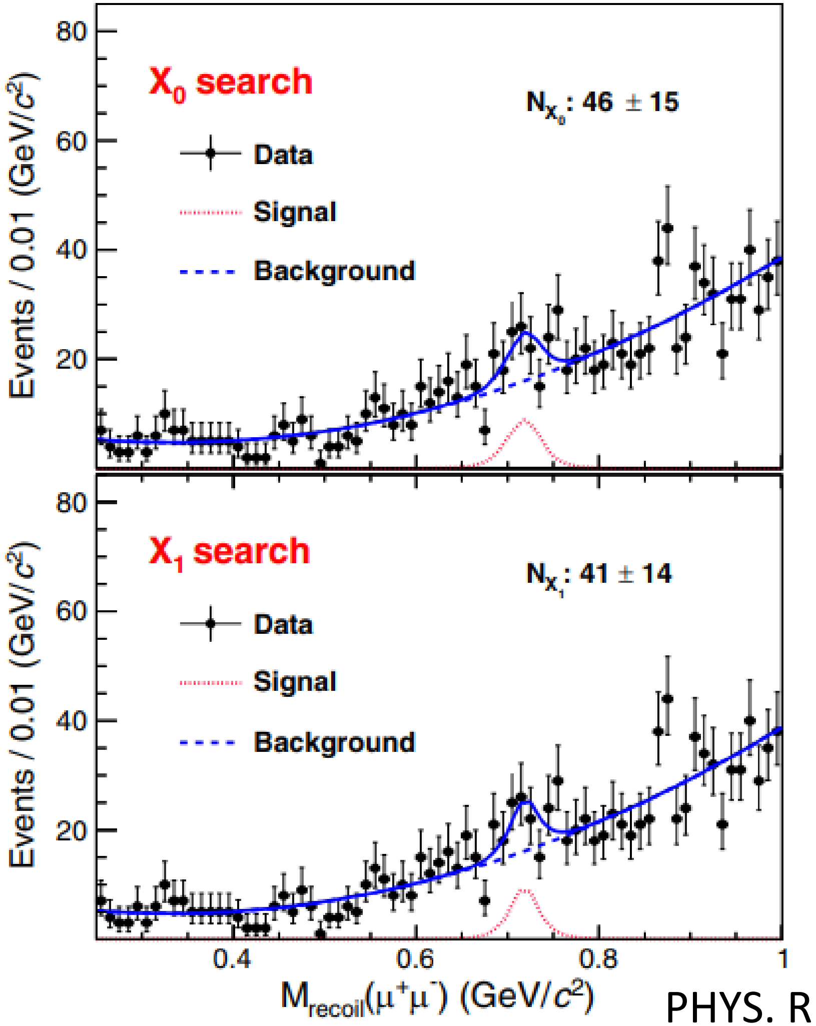
- $F_{NP} = \Lambda_{NP} / \sqrt{\left|C_{jk}^{i}\right| v / \sqrt{2m^2}} \to$ The new physics energy Λ_{NP} when $\left|C_{jk}^{i}\right| = \frac{\sqrt{2}m}{v}$
- m: the mass of the heavier SM particle in the coupling
- **In principle, these couplings are not necessarily related to one another.**
- **Playing a unique role in the dark sector of the charm field.**

Recoil mass spectrum of $J/\psi \to \mu^+\mu^- X$

Low mass region



High mass region



- Data samples: $\sim 9 \times 10^9$ J/ψ events
- Above 1 GeV, poor understanding of the background ($J/\psi \to hadron$)
- **No evidence** for signals from $X_{0,1}$ invisible decays

PHYS. REV. D 109, L031102 (2024)