Dark Photon Search at A Circular e^+e^- Collider

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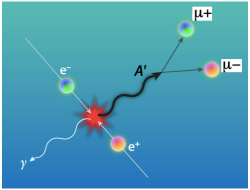
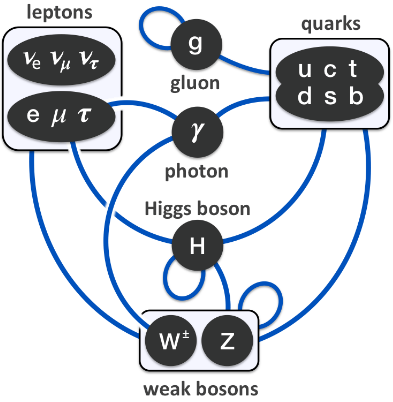


Outline

1. Motivation
2. The dark photon model
3. Dark photon at a circular e^+e^- collider
4. Sensitivities at CEPC and FCC-ee circular colliders
5. Summary

Motivation

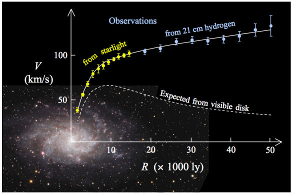
- The Standard Model has demonstrated huge successes in providing experimental predictions!



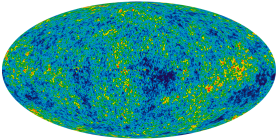
$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

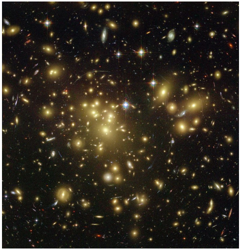
Motivation

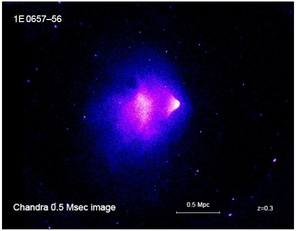
- But it leaves some phenomena unexplained. Evidences for DM.



(a) Galaxy rotation curves


(b) CMB


(c) Gravitational lens



(d) Bullet cluster

The dark photon model

- $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{A'}$ a new gauge group added
- Lagrangian with kinetic mixing of $U(1)_Y$ and $U(1)_{A'}$

$$L_{\text{kinetic}} = -\frac{1}{4} B_0^{\mu\nu} B_{0,\mu\nu} - \frac{1}{2} \sigma F'_{0,\mu\nu} B_0^{\mu\nu} - \frac{1}{4} F'_{0,\mu\nu} F_0'^{\mu\nu} \,. \quad (1)$$

  - $B_0 = c_W A_0 - s_W Z_0$: $U(1)_Y$ gauge field
  - $B_{0,\mu\nu} = \partial_\mu B_{0,\nu} - \partial_\nu B_{0,\mu}$: $U(1)_Y$ gauge field strength tensor
  - A'_0: dark photon field
  - $F'_{0,\mu\nu} = \partial_\mu A'_{0,\nu} - \partial_\nu A'_{0,\mu}$: dark photon field strength tensor
  - σ: mixing parameter
  - $c_W = \cos\theta_W$, $s_W = \sin\theta_W$

- After $U(1)_{A'}$ symmetry breaking, A'_0 receives a mass $m_{A'}$.

The dark photon model

- Redefine the fields to get rid of mixing terms.

$$\begin{pmatrix} A_0 \\ Z_0 \\ A'_0 \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\frac{c_W \sigma}{\sqrt{1-\sigma^2}} \\ 0 & 1 & \frac{s_W \sigma}{\sqrt{1-\sigma^2}} \\ 0 & 0 & \frac{1}{\sqrt{1-\sigma^2}} \end{pmatrix} \begin{pmatrix} A \\ Z \\ A' \end{pmatrix} . \qquad (2)$$

- The mass matrix for the redefined fields A, Z, A' is in the form

$$M = \begin{pmatrix} 0 & 0 & 0 \\ 0 & m_Z^2 & \frac{\sigma s_W}{\sqrt{1-\sigma^2}} m_Z^2 \\ 0 & \frac{\sigma s_W}{\sqrt{1-\sigma^2}} m_Z^2 & \frac{1}{1-\sigma^2} m_{A'}^2 + \frac{\sigma^2 s_W^2}{1-\sigma^2} m_Z^2 \end{pmatrix} . \qquad (3)$$

- We need to further diagonalize this mass matrix.

The dark photon model

- After diagonalizing the mass matrix, we get the mass eigenstates A_1, Z_1 and A'_1, also their masses. Restriction: $m_Z - m_{A'} \gg \sigma^2 m_Z$. In this work, $m_{A'}$: $1 \sim 60$GeV. σ: $10^{-3} \sim 10^{-2}$.

$$m_{A_1}^2 = 0, \tag{4}$$

$$m_{Z_1}^2 \approx m_Z^2 + \frac{m_Z^4 s_W^2 \sigma^2}{m_Z^2 - m_{A'}^2}, \tag{5}$$

$$m_{A'_1}^2 \approx m_{A'}^2 + \frac{(c_W^2 m_Z^2 - m_{A'}^2) m_{A'}^2 \sigma^2}{m_Z^2 - m_{A'}^2} \tag{6}$$

- Using notation $-c_W\sigma = \epsilon$, the effective Lagrangian concerning A_1, Z_1 and A'_1 interaction with SM currents is in the following form

$$L_{\text{int}} = J_{em}^{\mu} A_{1\mu} + J_Z^{\mu} Z_{1\mu} + \epsilon J_{em}^{\mu} A'_{1\mu} + \boxed{\frac{m_{A'}^2 s_W \epsilon}{(m_Z^2 - m_{A'}^2) c_W} J_Z^{\mu} A'_{1\mu}} \tag{7}$$

The dark photon model

- $m_{A'} < 1\text{MeV}$, $A' \to 3\gamma$, Landau-Yang theorem. The dark photon can be cosmologically stable, and can be the candidate of dark matter.

$$\Gamma_{V\to 3\gamma} = \frac{17\kappa^2\alpha^4}{2^7 3^6 5^3 \pi^3}\frac{m_V^9}{m_e^8}$$

Pospelov, Ritz, Voloshin 2008

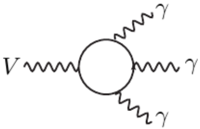


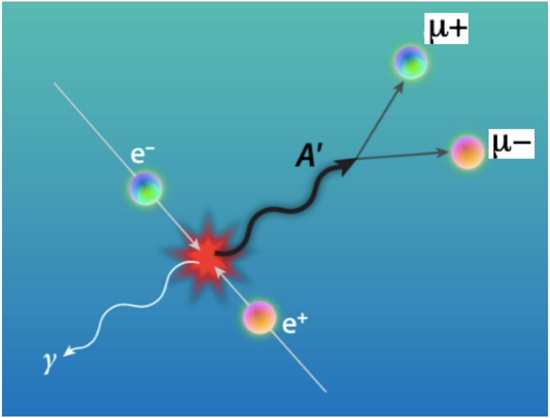
Figure: $V \sim A'$ and $\kappa \sim \sigma$

- $m_{A'} > 1\text{MeV}$, $A' \to e^+e^-$. The dark photon decays fast and can be the mediator of the dark force.

$$\Gamma_{A'} = \sum_f \Gamma(A' \to \bar{f}f) = \sum_f \epsilon^2 \frac{Q_f^2 \alpha_{em} m_{A'}}{3}\left(1 + \frac{2m_f^2}{m_{A'}^2}\right)\sqrt{1 - \frac{4m_f^2}{m_{A'}^2}}\,. \quad (8)$$

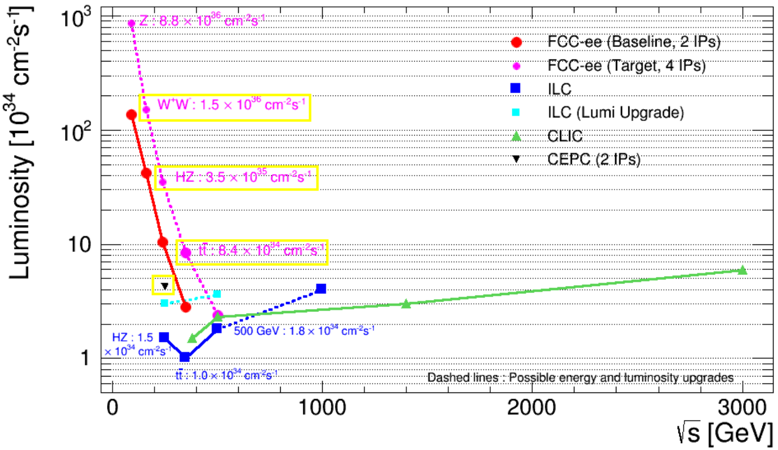
Dark photon at a circular e^+e^- collider

- What a circular e^+e^- collider can do for the dark photon?
- We study the prodcution and search for dark photon using porcess $e^+e^- \to \gamma A'^* \to \gamma\mu^+\mu^-$



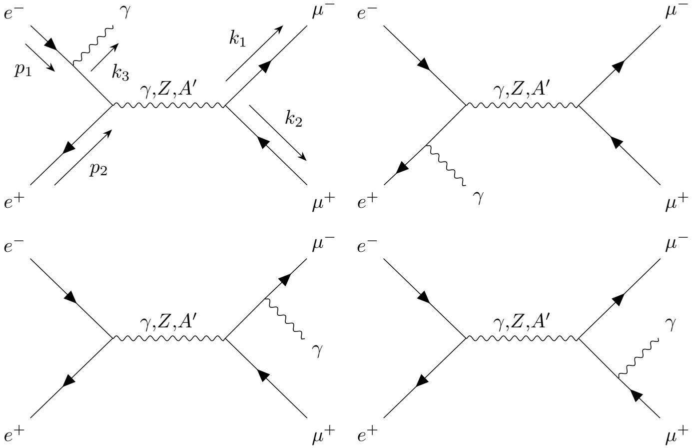
Dark photon at a circular e^+e^- collider

- Parameters for some future e^+e^- colliders.



Dark photon at a circular e^+e^- collider

- Feynman diagrams for $e^-e^+ \to \gamma\mu^-\mu^+$ process. $s = (p_1 + p_2)^2$, $s_3 = (k_1 + k_2)^2$



Dark photon at a circular e^+e^- collider

$d\sigma_{\gamma(\gamma,Z)}/ds_3$

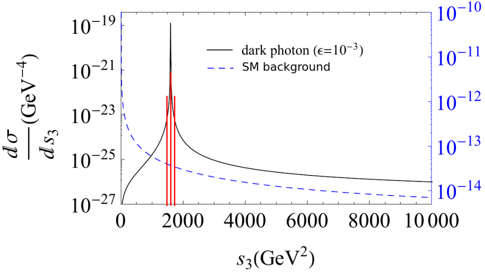
$$
\begin{aligned}
=& \frac{4\alpha_{em}^3(s^2+s_3^2)}{3s^3 s_3(s-s_3)}\left(s(\ln(s/m_e^2)-1)+s_3(\ln(s_3/m_\mu^2)-1)\right) \\
&+ \frac{\alpha_{em}^3(8\sin^4\theta_W-4\sin^2\theta_W+1)^2}{48\sin^4\theta_W\cos^4\theta_W}\frac{s^2+s_3^2}{s^2(s-s_3)} \\
&\times\left(\frac{s_3(\ln(s/m_e^2)-1)}{(s_3-m_Z^2)^2}+\frac{s(\ln(s_3/m_\mu^2)-1)}{(s-m_Z^2)^2}\right) \\
&- \frac{\alpha_{em}^3(1-4\sin^2\theta_W)^2}{16\sin^4\theta_W\cos^4\theta_W}\frac{s+s_3}{s^2(s-s_3)}\frac{ss_3}{(s-m_Z^2)(s_3-m_Z^2)} \\
&+ \frac{\alpha_{em}^3(1-4\sin^2\theta_W)^2}{6\sin^2\theta_W\cos^2\theta_W}\frac{s^2+s_3^2}{s^2(s-s_3)}\left(\frac{\ln(s/m_e^2)-1}{s_3-m_Z^2}+\frac{\ln(s_3/m_\mu^2)-1}{s-m_Z^2}\right) \\
&- \frac{\alpha_{em}^3}{4\sin^2\theta_W\cos^2\theta_W}\frac{s+s_3}{s^2(s-s_3)}\left(\frac{s_3}{s_3-m_Z^2}+\frac{s}{s-m_Z^2}\right) \qquad (9)
\end{aligned}
$$

Dark photon at a circular e^+e^- collider

$$\frac{d\sigma_{\gamma A'}}{ds_3} \approx \frac{4\alpha_{em}^3\epsilon^4 s_3(s^2+s_3^2)}{3s^2(s-s_3)((s_3-m_{A'}^2)^2+\Gamma_{A'}^2 m_{A'}^2)}\left(\ln(s/m_e^2)-1\right) \quad (10)$$

- Cross section near $m_{A'}$ ($\Gamma \ll \sigma_{\mu\mu} \ll m_{A'}$)

$$\sigma_{\gamma A'}^{m_{\mu\mu}}\left(\sigma_{\gamma(\gamma,Z)}^{m_{\mu\mu}}\right) = \int_{(m_{A'}-\sigma_{\mu\mu})^2}^{(m_{A'}+\sigma_{\mu\mu})^2} \frac{d\sigma_{\gamma A'}}{ds_3}\left(\frac{d\sigma_{\gamma(\gamma,Z)}}{ds_3}\right) ds_3 \quad (11)$$



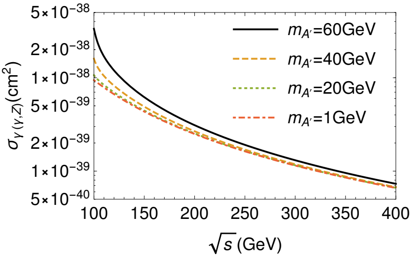
Sensitivities at CEPC and FCC-ee circular colliders

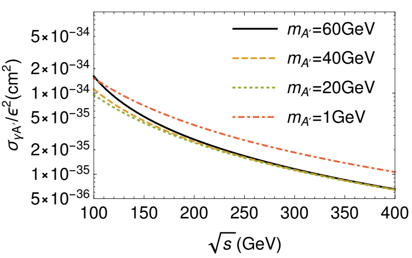
- The SM contributions $N_{\gamma(\gamma,Z)}$ and dark photon contribution $N_{\gamma A'}$

$$N_{\gamma(\gamma,Z)} = \sigma^{m_{\mu\mu}}_{\gamma(\gamma,Z)} LT \ , \quad N_{\gamma A'} = \sigma^{m_{\mu\mu}}_{\gamma A'} LT \ . \tag{12}$$

- Take the resolution of the invariant mass measurement similar to LHCb, $\sigma_{\mu\mu} = 0.5\% m_{A'}$.
- $N_{\gamma A'}$: signal
- $\sqrt{N_{\gamma(\gamma,Z)}}$: the statistic sensitivity for SM background
- $\chi = N_{\gamma A'}/\sqrt{N_{\gamma(\gamma,Z)}}$: indicator how well one can obtain constraints on ϵ^2 and $m_{A'}$

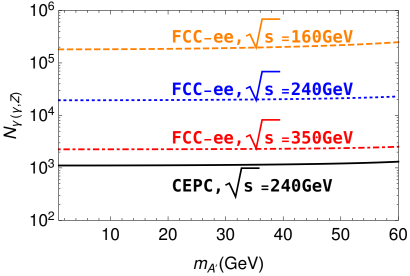
- Cross section for SM background and dark photon contribution for different dark photon masses.

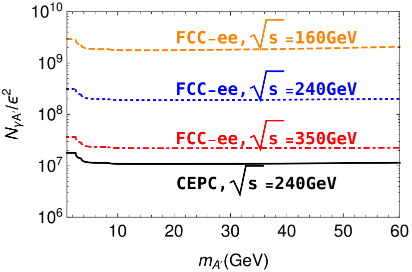




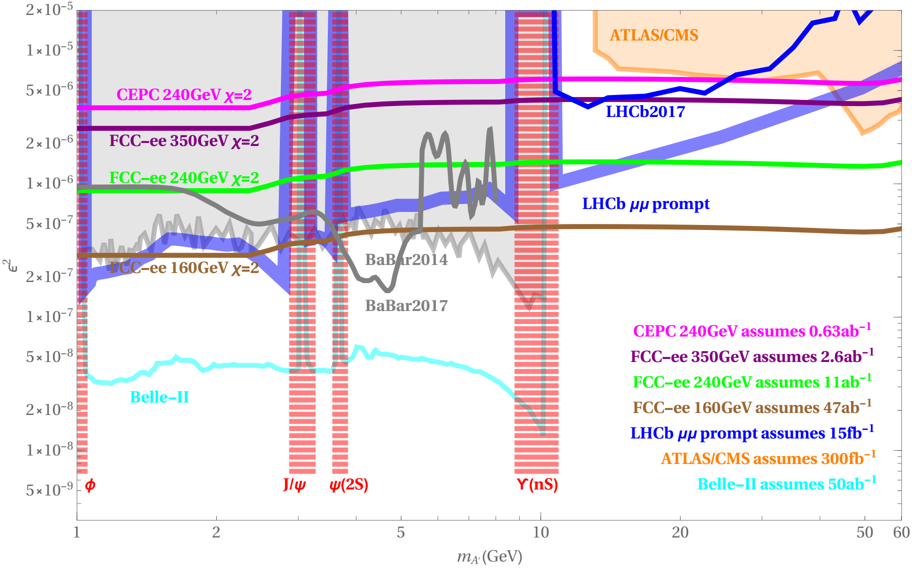
Sensitivities for CEPC and FCC-ee circular colliders

- One-year running events number for different colliders.





Sensitivities for CEPC and FCC-ee circular colliders



Summary

- We have studied the possibility of searching for dark photon at a circular e^+e^- collider through the process $e^+e^- \to \gamma A'^* \to \gamma\mu^+\mu^-$.
- The CEPC and FCC-ee e^+e^- colliders can provide good sensitivity especiallly for dark photon mass at range $20 \sim 60$GeV.
- In the range of 20 GeV to 60 GeV for $m_{A'}$, the smallest $\sigma_{\mu\mu}$ is 100 MeV which is reachable at the CEPC and FCC-ee.
- Still working on the detector simulation.

Backup

- $\sigma_{NLO}/\sigma_{\gamma(\gamma,Z)} = 5 \times 10^{-5}$

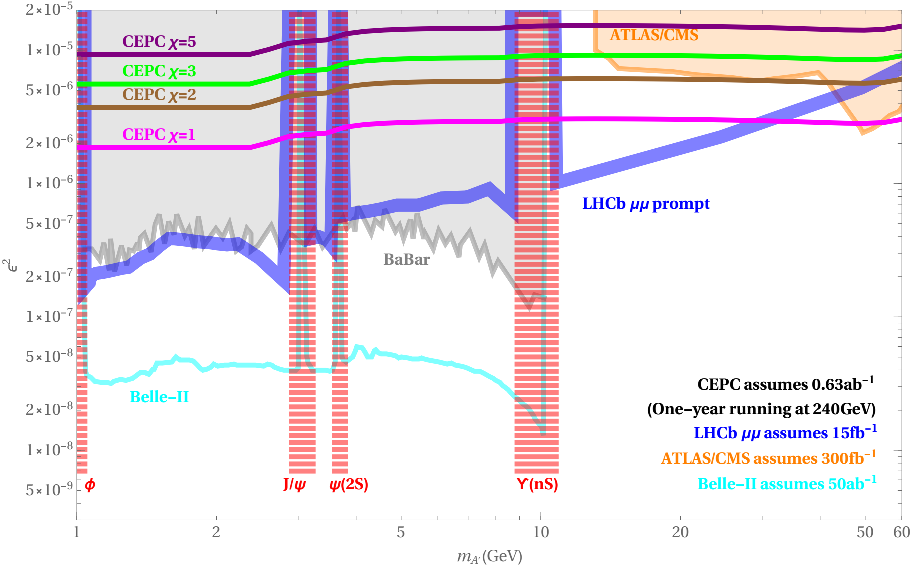
Table: ratio of interference term to dark photon contribution at $\epsilon = 10^{-2}$

$\frac{\sigma_{int}}{\sigma_{\gamma A'}}(10^{-5})$ $\sqrt{s}$(GeV) / $m_{A'}$(GeV)	160	240	350
1	3.1	3.1	3.1
30	6.0	5.4	5.2
60	12	9.3	8.1

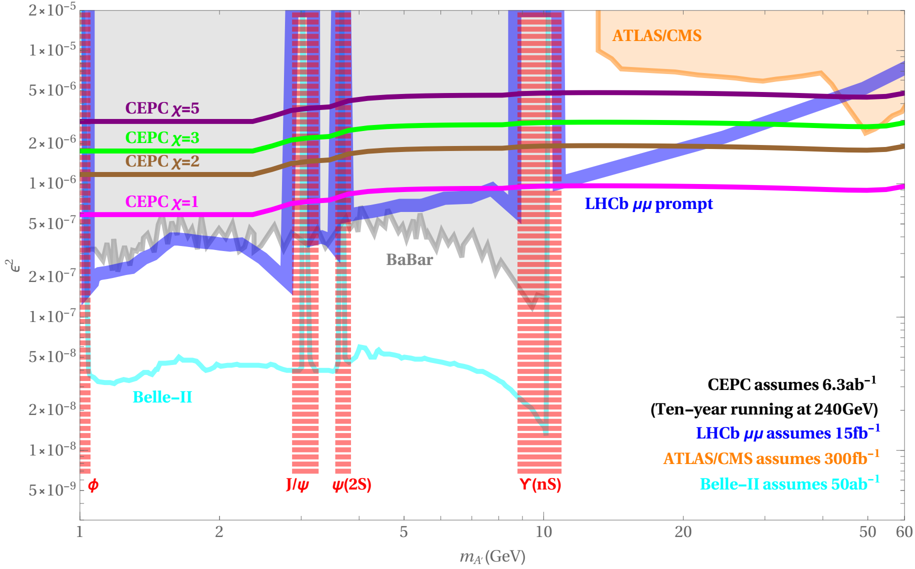
Table: ratio of additional dark photon contribution to old dark photon contribution at $\epsilon = 10^{-2}$

$\frac{\sigma^{new}_{\gamma A'} - \sigma_{\gamma A'}}{\sigma_{\gamma A'}}$ $m_{A'}$(GeV) \ $\sqrt{s}$(GeV)	160	240	350
1	3.7×10^{-11}	3.7×10^{-11}	3.7×10^{-11}
30	4.0×10^{-5}	4.0×10^{-5}	4.0×10^{-5}
60	5.2×10^{-3}	5.2×10^{-3}	5.2×10^{-3}

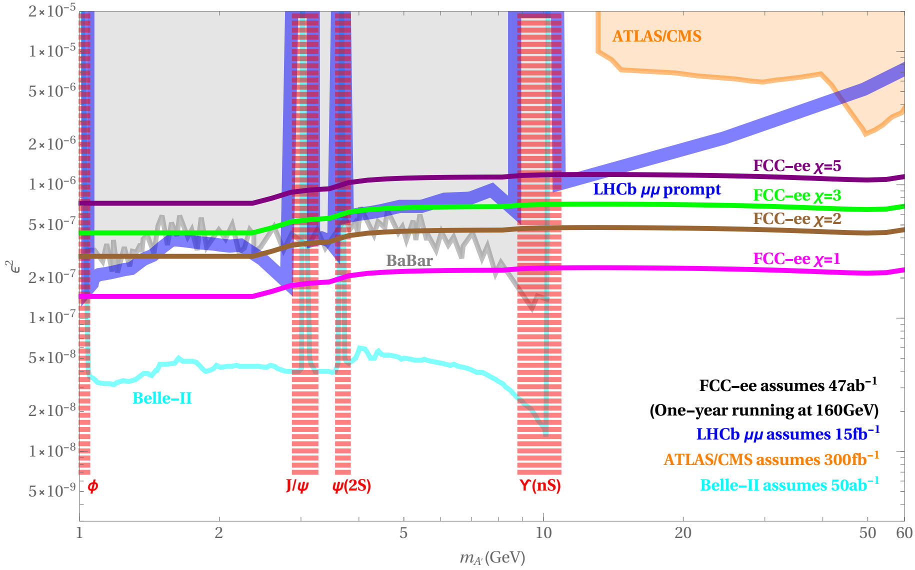
Sensitivities for CEPC and FCC-ee circular colliders



Sensitivities for CEPC and FCC-ee circular colliders



Sensitivities for CEPC and FCC-ee circular colliders



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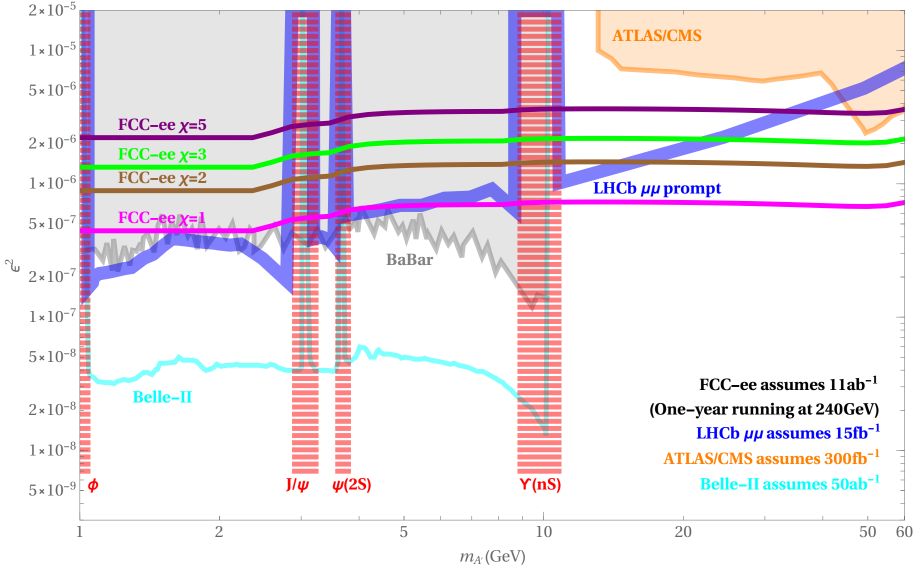

Sensitivities for CEPC and FCC-ee circular colliders