Dark Photon at the CEPC

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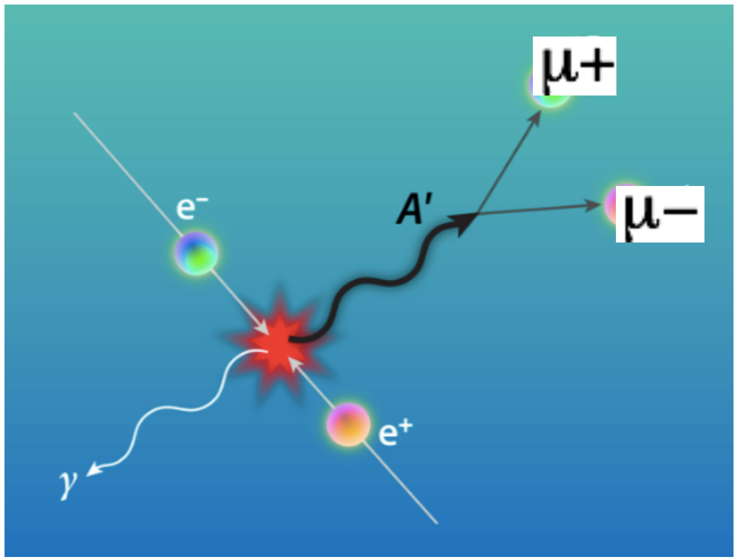
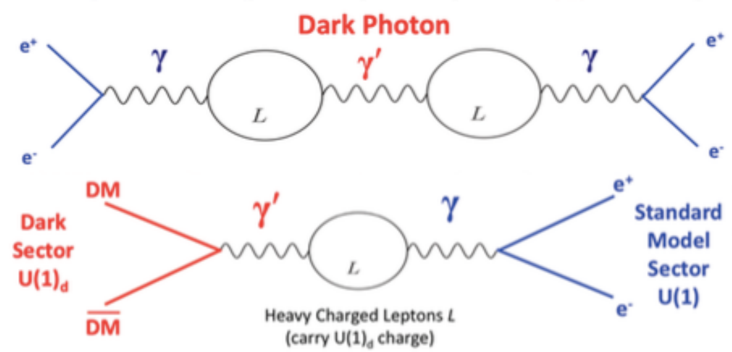


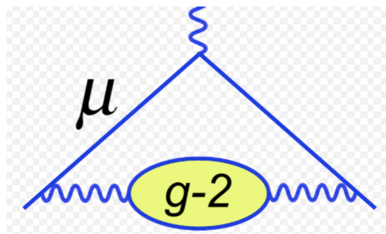
The Dark Photon

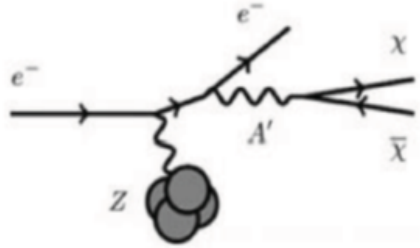
A vector boson X_{μ} couples to SM matter electromagnetic current J^{μ}_{em} as

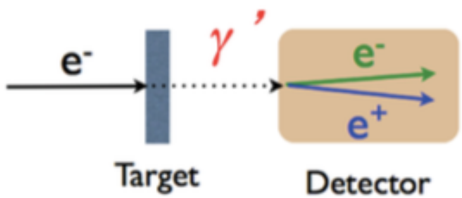
$$\varepsilon e Q_{em} j^{\mu}_{em} X_{\mu}$$

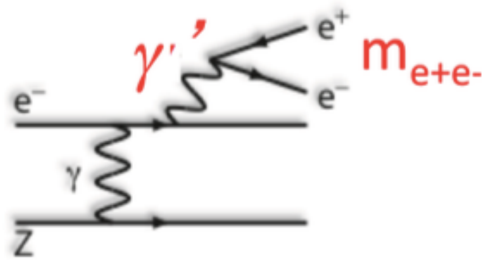
$\varepsilon << 1$











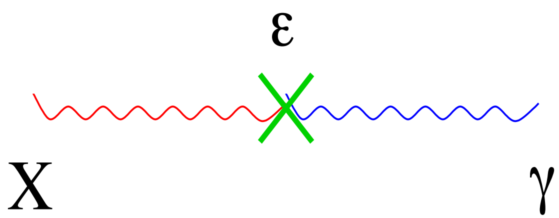
Generating Dark Photon Interaction through

Gauge Boson Kinetic Mixing

$$L = -\,¼\, F_{\mu\nu}F^{\mu\nu} - ¼\, X_{\mu\nu}X^{\mu\nu}$$

will use X or A′ for dark photon

$$\epsilon X_{\mu\nu} F^{\mu\nu}$$



$$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

X and A are gauge fields of $U(1)_X$ X $U(1)_A$

This term is renormalizable and gauge invariant

ε is a unknown number in a given model.

Holdom 1986, Foot and He 1991,….

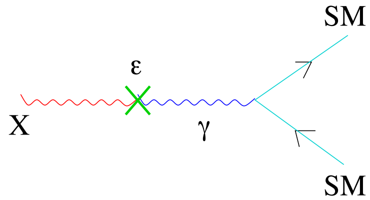
There are many interesting consequences

Consider $U(1)_A = U(1)_Y$ and

$U(1)_X$ a new gauge group: dark photon o

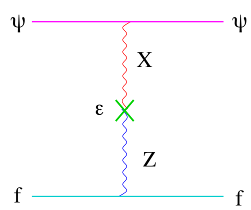
Dark photon connected to a hidden world

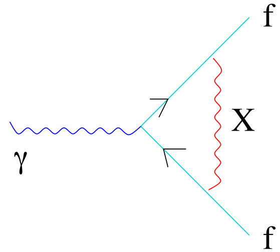
(dark sector…)



- $SU(2)_L \times U(1)_Y \times U(1)_x$ gauge invariance:

$$\mathcal{L} \supset -\frac{1}{4}(X_{\mu\nu})^2 - \frac{1}{4}(B_{\mu\nu})^2 - \frac{1}{4}(W^a_{\mu\nu})^2 - \frac{\epsilon}{2c_W} B_{\mu\nu}X^{\mu\nu}$$

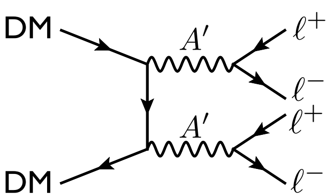


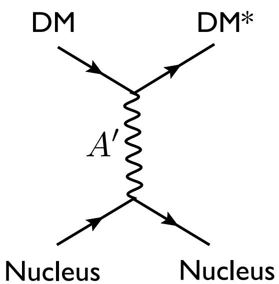


$$\rightarrow (\ldots) - \frac{\epsilon}{2} X_{\mu\nu}\left(F^{\mu\nu} - t_W Z^{\mu\nu}\right) \quad -\mathcal{L} \supset e j^\mu_{em} A_\mu$$

$$+ \left[g_x j^\mu_x - \epsilon e j^\mu_{em} - \epsilon t_W \left(\frac{\eta}{1-\eta}\right) g_Z j^\mu_Z\right] X_\mu$$

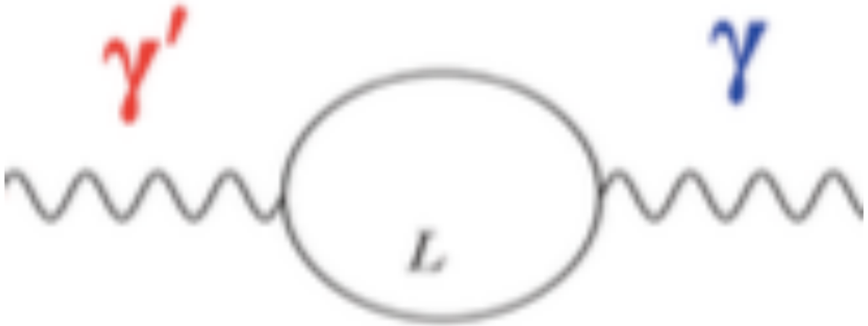
$$+ \left[g_Z j^\mu_Z + \epsilon t_W \left(\frac{1}{1-\eta}\right) g_x j^\mu_x\right] Z_\mu$$



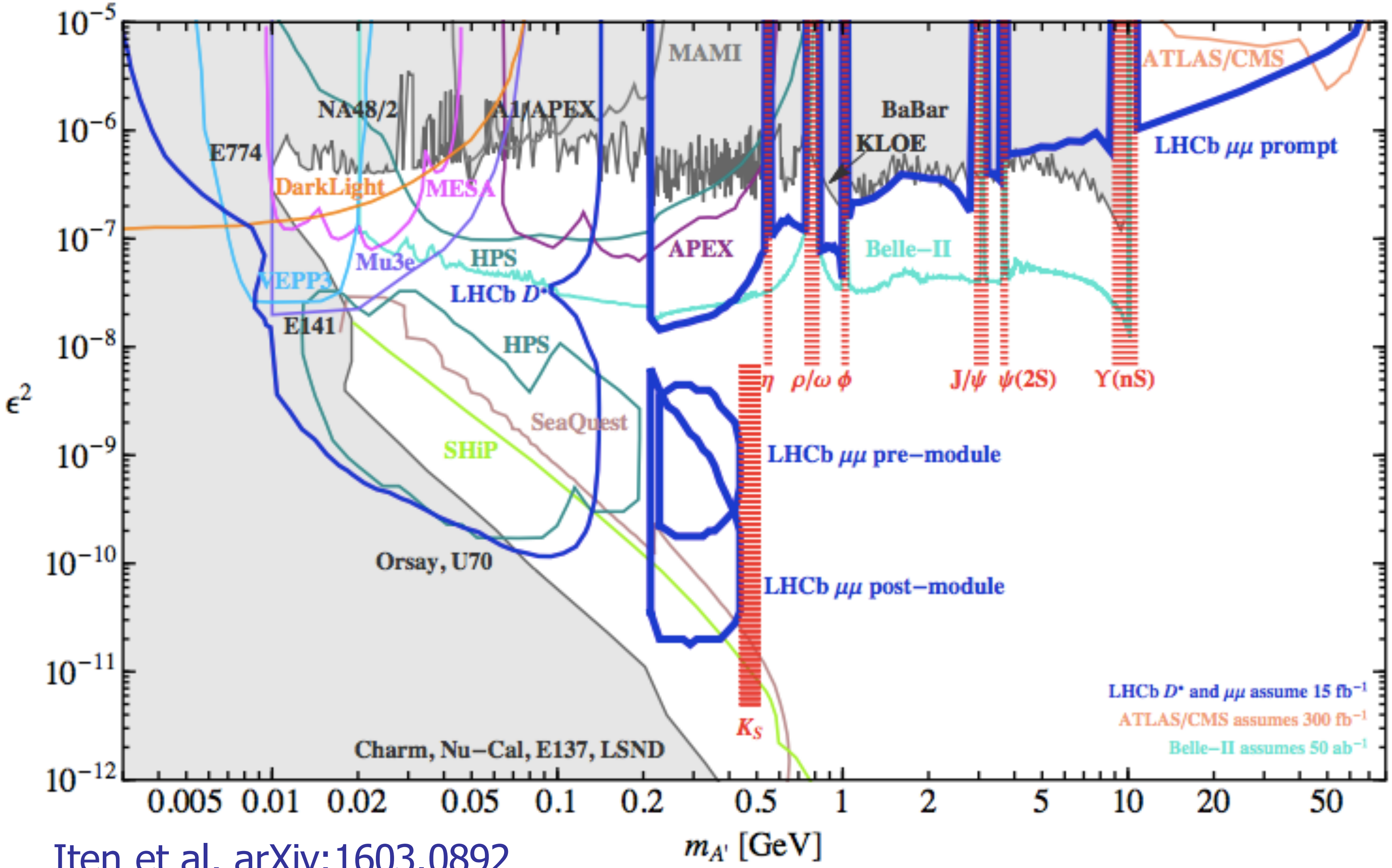


$$\mathcal{M}^2 = m_Z^2 \begin{pmatrix} \eta & \epsilon t_W \eta \\ \epsilon t_W \eta & 1 \end{pmatrix} \quad \text{with} \quad \eta = m_x^2/m_Z^2$$

Loop generation of photon and dark photon mixing



Summary of constraints on the dark photon mass and coupling

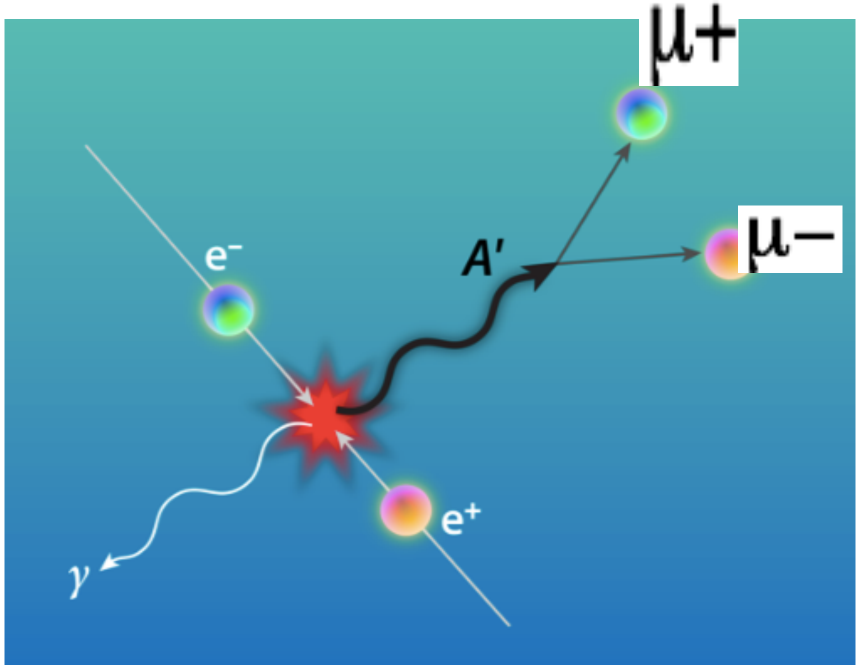


Iten et al, arXiv:1603.0892

What CEPC can do for dark photon?

This talk describe:

study dark photon using $e^+e^- \to \gamma A' \to \mu^+\mu^-$



CEPC project (Xinchou Lou)

A reminder about the CEPC-SppC

Phase 1: e^+e^- Higgs (Z) factory   two detectors, 1M ZH events in ~10yrs

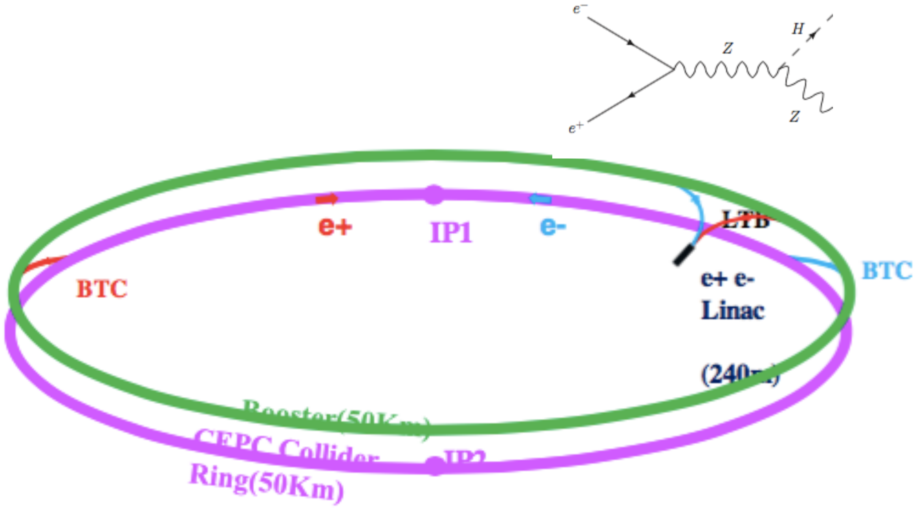
Circular Electron Positron Collider (CEPC)

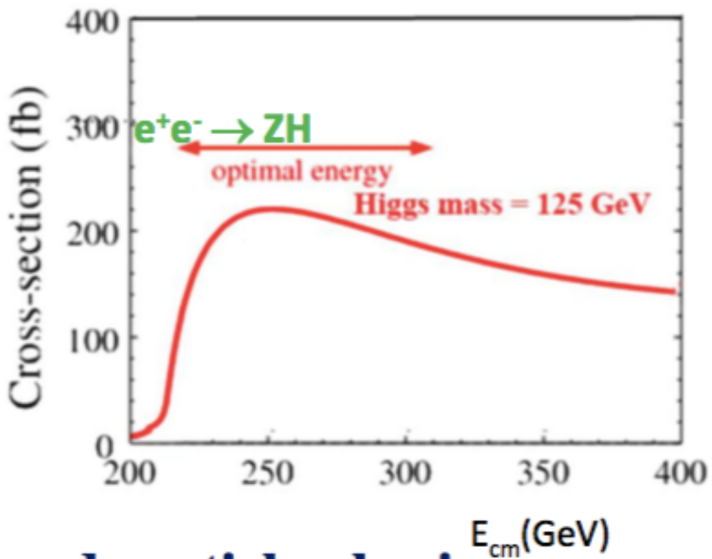
E_{cm}≈240GeV, luminosity ~2×10^{34} $cm^{-2}s^{-1}$, can also run at the Z-pole ~10^{10} Z bosons

Precision measurement of the Higgs boson (and the Z boson)

Phase 2: a discovery machine; pp collision with E_{cm} ≈ 50-100 TeV; ep, HI options

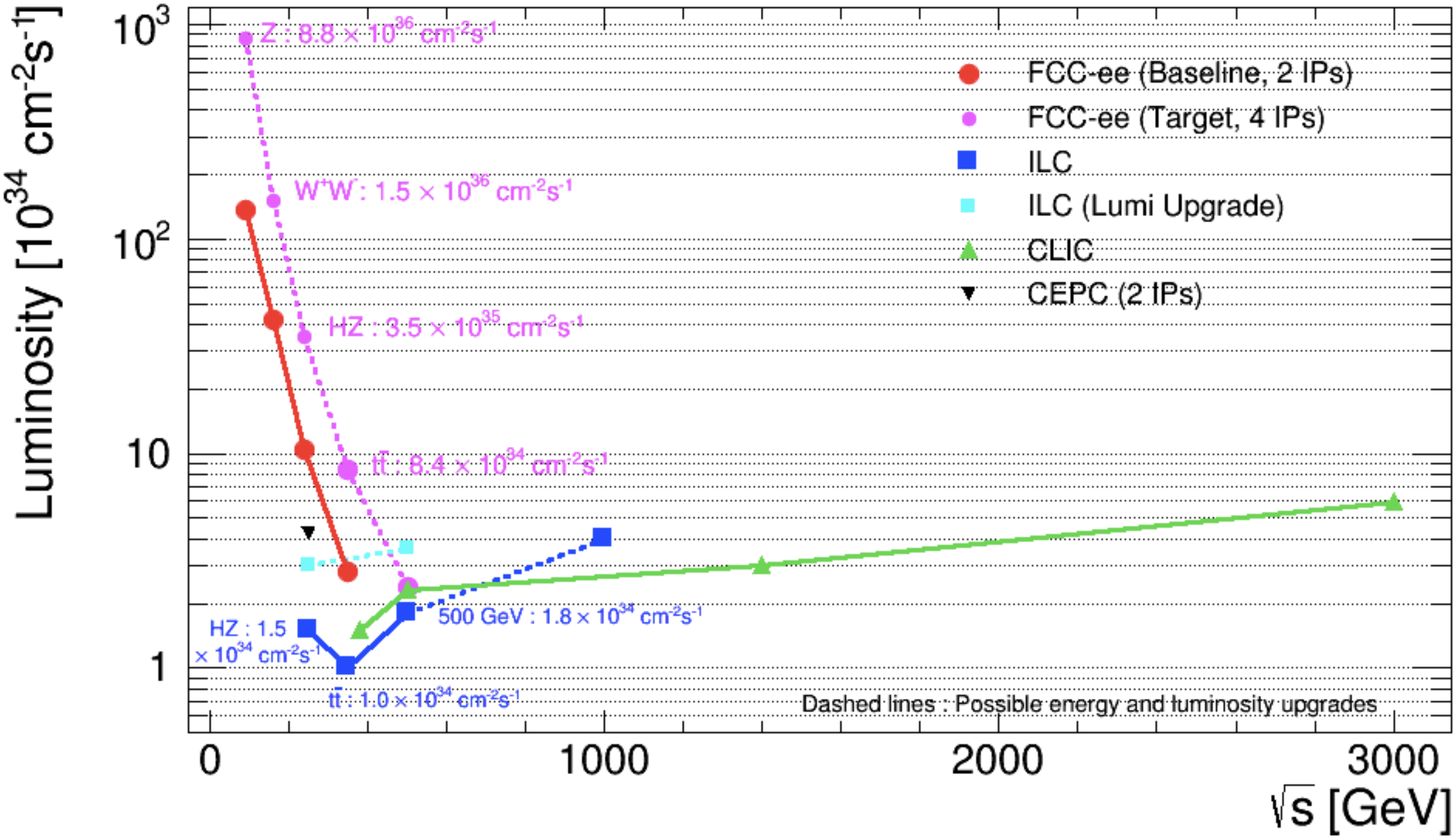
Super proton-proton Collider (SppC)



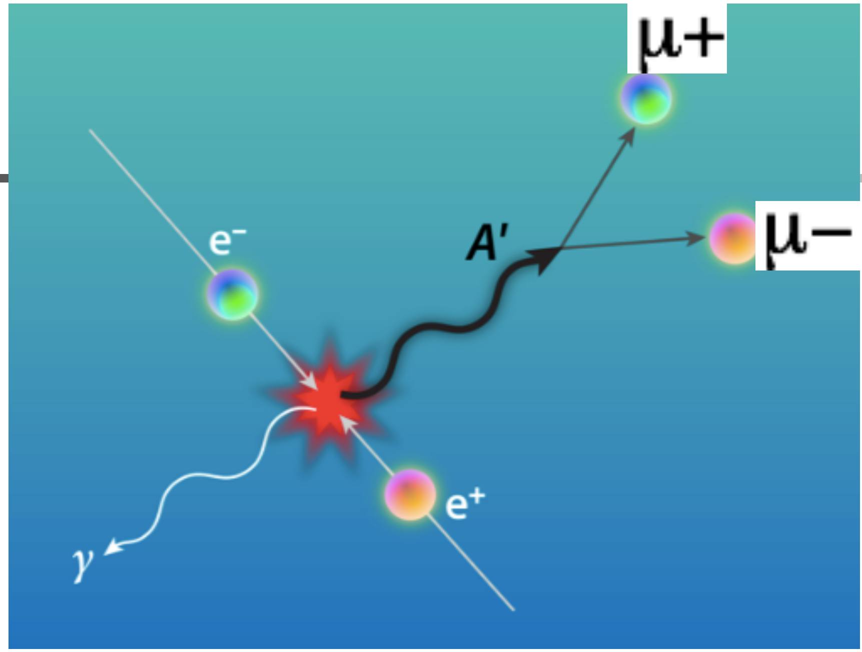


favored post BEPCII accelerator based particle physics program in China

September 2, 2016   3



Luminosity [10^{34} cm^{-2}s^{-1}]
10^3
10^2
10
1
0
1000
2000
3000
$\sqrt{s}$ [GeV]
Z : 8.8 × 10^{36} cm^{-2}s^{-1}
W^+W^- : 1.5 × 10^{36} cm^{-2}s^{-1}
HZ : 3.5 × 10^{35} cm^{-2}s^{-1}
$t\bar{t}$: 8.4 × 10^{34} cm^{-2}s^{-1}
HZ : 1.5 × 10^{34} cm^{-2}s^{-1}
$t\bar{t}$: 1.0 × 10^{34} cm^{-2}s^{-1}
500 GeV : 1.8 × 10^{34} cm^{-2}s^{-1}
FCC-ee (Baseline, 2 IPs)
FCC-ee (Target, 4 IPs)
ILC
ILC (Lumi Upgrade)
CLIC
CEPC (2 IPs)
Dashed lines : Possible energy and luminosity upgrades



$$\frac{d\sigma_{e^+e^-\to\gamma A'\to\gamma\mu^+\mu^-}}{d\sigma_{e^+e^-\to\gamma\gamma^*\to\gamma\mu^+\mu^-}}\Big|_{m_{\mu\mu}\sim m_{A'}} \sim \epsilon^4 \frac{m_{\mu\mu}^4}{(m_{\mu\mu}^2 - m_{A'}^2)^2 + \Gamma_{A'}^2 m_{A'}^2}\ .$$

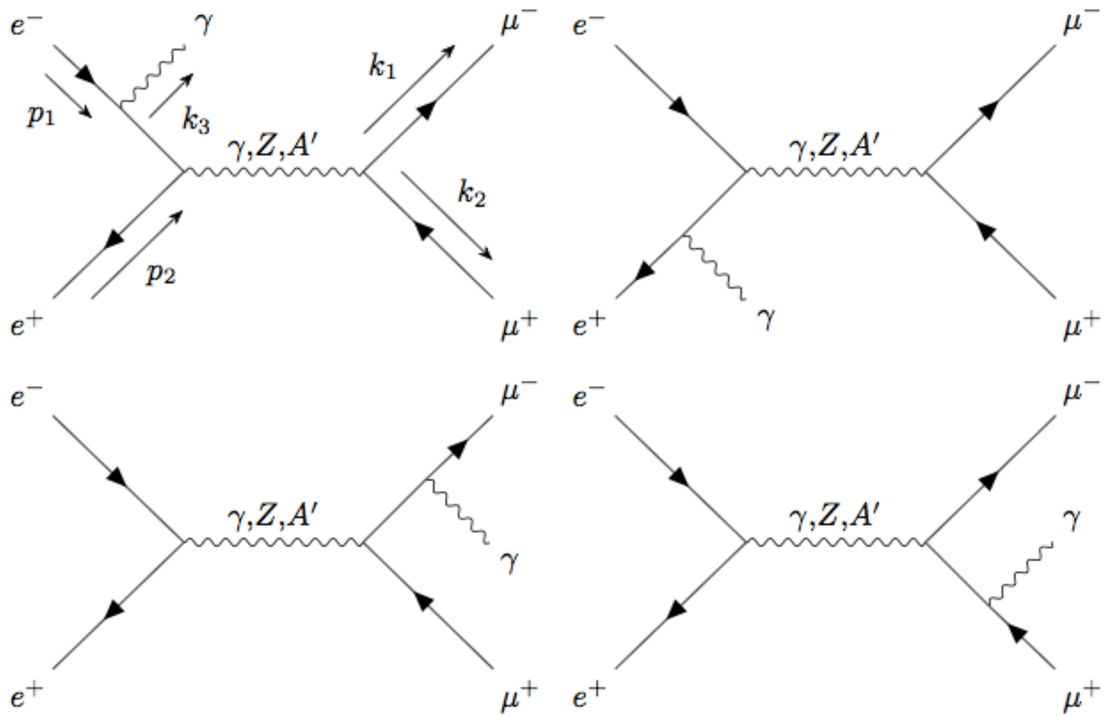
$$\frac{s}{B_{em-background}} \sim \epsilon^4 \frac{\pi}{8}\frac{m_{A'}^2}{\Gamma_{A'}\sigma_{\mu\mu}}\ ,$$

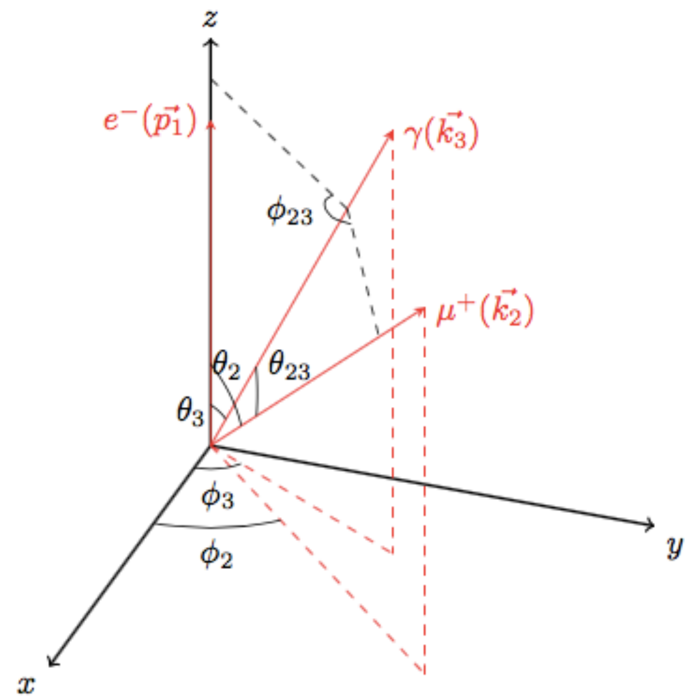
Naïve expectation

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

Integrate dimuon energy range $|m_{\mu\mu} - m_{A'}| < 2\sigma_{\mu\mu}$

Evaluation of the cross section

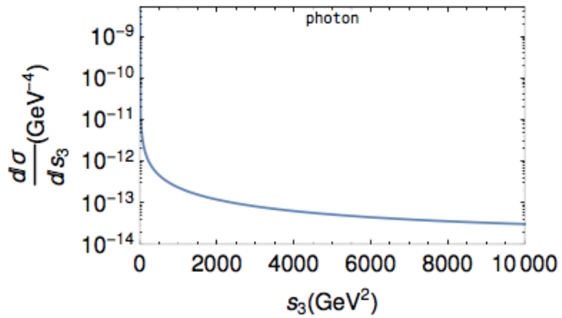




$$
\begin{aligned}
s &= (p_1 + p_2)^2, \\
s_1 &= (p_1 + p_2 - k1)^2 = (k_2 + k_3)^2 = s - 2\sqrt{s}E_1 + m_1^2, \\
s_2 &= (p_1 + p_2 - k2)^2 = (k_1 + k_3)^2 = s - 2\sqrt{s}E_2 + m_2^2, \\
s_3 &= (p_1 + p_2 - k3)^2 = (k_1 + k_2)^2 = s - 2\sqrt{s}E_3 + m_1^3,
\end{aligned}
$$

$$
\begin{aligned}
\sigma &= \frac{1}{2 \cdot \sqrt{s}/2 \cdot 2 \cdot \sqrt{s}/2 \cdot 2} \int d\Pi_3 |M|^2 \\
&= \frac{1}{64 s^2 (2\pi)^4} \int_{s_3^{min}}^{s_3^{max}} ds_3 \int_{s_2^{min}(s_3)}^{s_2^{max}(s_3)} ds_2 \int_{-1}^{1} d\cos\theta_3 \int_0^{2\pi} d\phi_{23} |M|^2
\end{aligned}
$$

$e^+e^- \to \gamma\,\gamma^* \to \gamma\,\mu^+\mu^-$



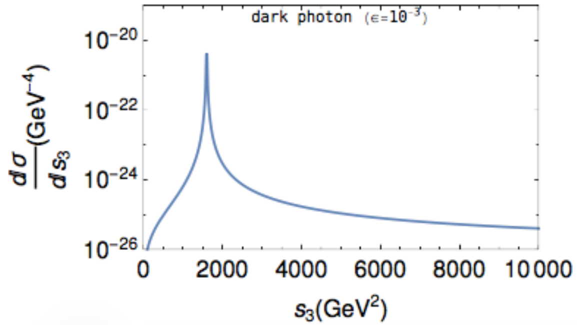
Using notation

$$s = (p_1 + p_2)^2, \qquad t = (p_2 - k_2)^2, \qquad u = (p_2 - k_1)^2,$$
$$s' = (k_1 + k_2)^2, \qquad t' = (p_1 - k_1)^2, \qquad u' = (p_1 - k_2)^2.$$

We set $m_e = m_\mu = 0$, then the squared amplitude for this process is

$$\frac{1}{4}\sum_{spins} |iM_0|^2 = \frac{4e^6(t^2 + t'^2 + u^2 + u'^2)[2ss'(t+t') + 2tt'(s+s') + u(st+s't') + u'(st'+s't)]}{(s'+t+u)(s'+t'+u')(s'+t+u')(s'+t'+u)}.$$

$e^+e^- \to \gamma\,A'^* \to \gamma\,\mu^+\mu^-$



$$\frac{4\epsilon^4 e^6[(s'-m_A^2)(s-m_A^2) + \Gamma^2 m_A^2](t^2 + t'^2 + u^2 + u'^2)[ss'(t+t'-u-u') + (tt'-uu')(s+s')}{[(s'-m_A^2)^2 + \Gamma^2 m_A^2][(s-m_A^2)^2 + \Gamma^2 m_A^2](s'+t+u)(s'+t'+u')(s'+t+u')(s'+t'+u)}$$

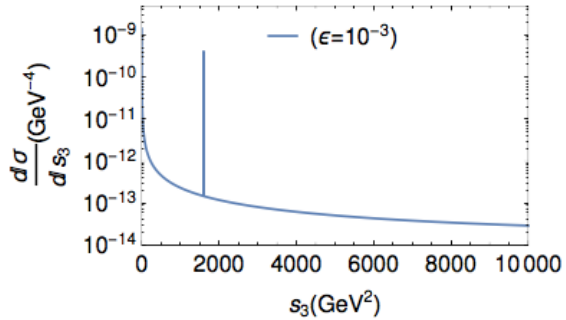
$$\sigma(e^+e^- \to \gamma\,\mu^+\mu^-) = \sigma(e^+e^- \to \gamma\,A')\mathrm{Br}(A' \to \mu^+\mu^-)$$

$$\frac{d\sigma(e^+e^- \to \gamma\gamma \to \gamma\mu^+\mu^-)}{ds_3},$$

$$\Gamma(A \to f\bar{f}) = \frac{g_f^2 m_A}{12\pi}\left(1 + \frac{2m_f^2}{m_A^2}\right)\left(1 - \frac{4m_f^2}{m_A^2}\right)^{\frac{1}{2}},$$

$$\Gamma = \sum_f \Gamma(A \to f\bar{f}),$$

$$\frac{d\sigma(e^+e^- \to \gamma A \to \gamma\mu^+\mu^-)}{ds_3}$$



$S_3 = (k_1+k_2)^2 = m^2_{\mu\mu}$ muon pair invariant mass squared

Observable

$$R = \frac{\sigma_{\gamma A'}^{m_{\mu\mu}}}{\sigma_{\gamma\gamma}^{m_{\mu\mu}}} = \frac{\int_{(m_{A'}-\sigma_{\mu\mu})^2}^{(m_{A'}+\sigma_{\mu\mu})^2} (d\sigma_{\gamma A}/ds_3)ds_3}{\int_{(m_{A'}-\sigma_{\mu\mu})^2}^{(m_{A'}+\sigma_{\mu\mu})^2} (d\sigma_{\gamma\gamma}/ds_3)ds_3}$$

Given σ with sensitivity on R,

ε^2 is a function of m_A, $\sigma = 0.5\%\ m_A$

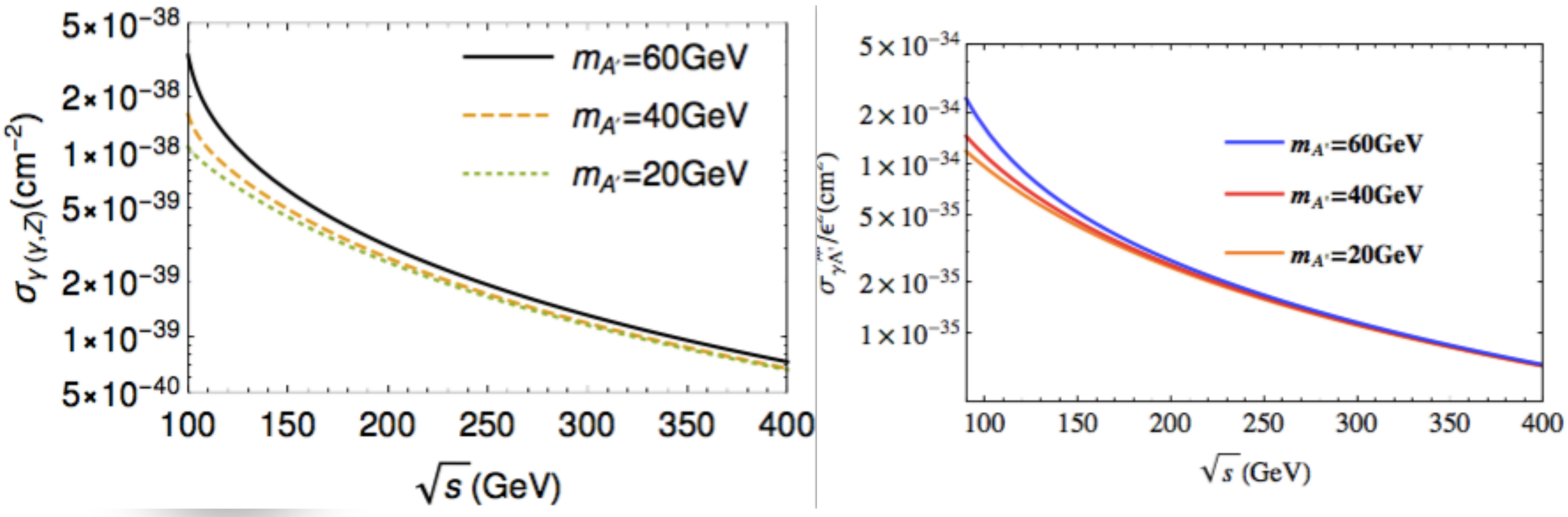


FIG. 2: Cross sections $\sigma_{\gamma\gamma}^{m_{\mu\mu}}$ and $\sigma_{\gamma A'}^{m_{\mu\mu}}$ as functions of $\sqrt{s}$. $m_{A'} = 20, 40$ and 60 GeV. The $m_{A'}$ dependence of $\sigma_{\gamma\gamma}^{m_{\mu\mu}}$ is due to integration ranges depend on $m_{A'}$.

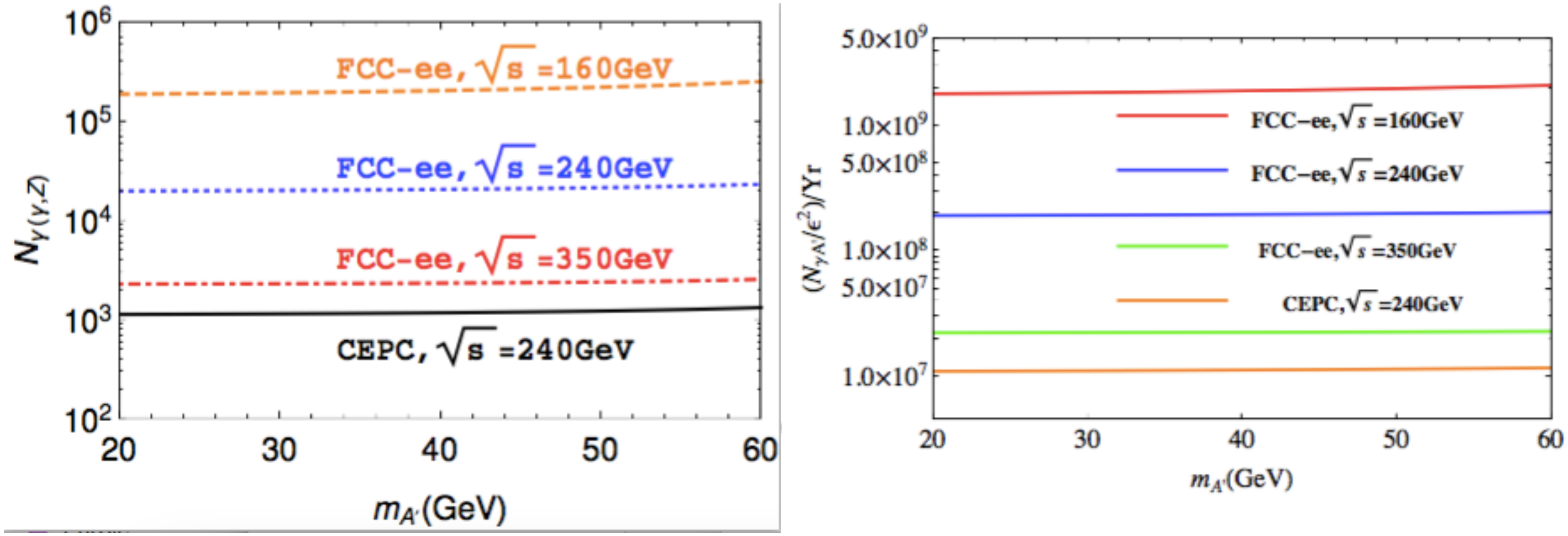
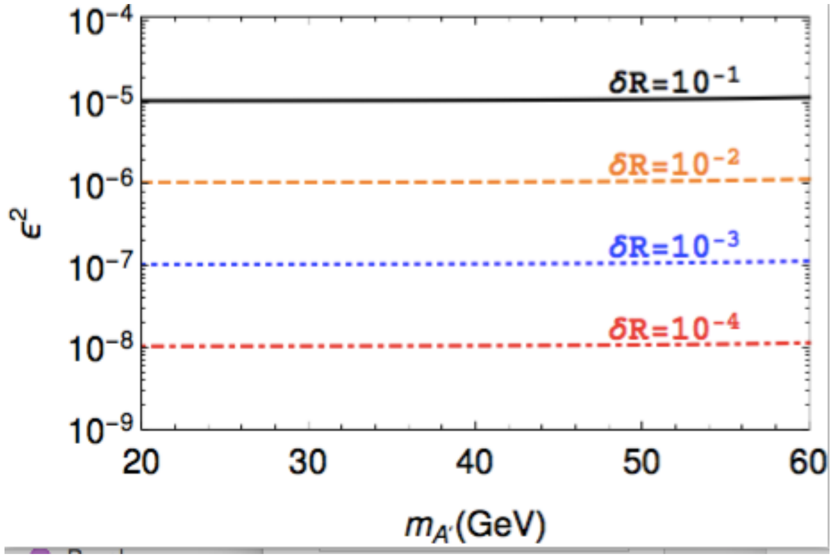
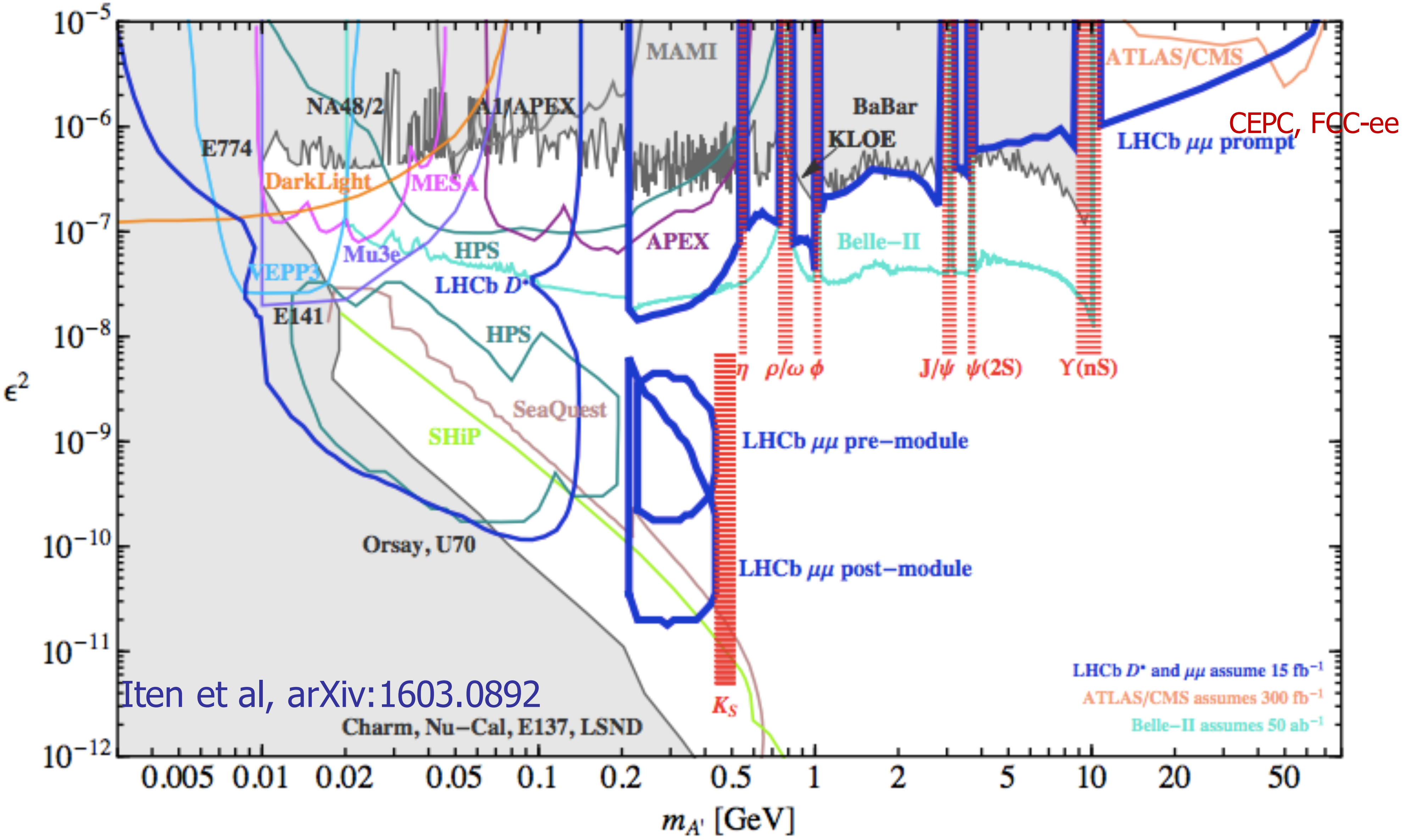


FIG. 3: $N_{\gamma\gamma}$ and $N_{\gamma A'}/\epsilon^2$ as functions of $m_{A'}$ for CEPC ($\sqrt{s} = 240$ GeV) and FCC-ee ($\sqrt{s} = 160,\ 240,\ 350$ GeV) for one year running.



CEPC may have advantage probing dark photon at 10 to a few 10s ($<<m_Z$) GeV mass range.



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Spontaneous symmetry breaking and Abelian-NonAbelian gauge fields mixing

Arguelles, XG He, G. Ovanesyan, T. Peng and M. Ramsey-Mulsof, arXiv:1604.00044

Assuming that there is a field Δ^a transforming as 3 under $SU(2)_W$, then one can make gauge singlet: $W^a_{\mu\nu} X^{\mu\nu} \Delta^a$

If the VEV of $<\Delta^a> = v_3/\mathrm{sqrt}(2)$ along a particular direction in group space is not zero, one can generate kinetic mixing term

$$W^3_{\mu\nu} X^{\mu\nu} v_3/\mathrm{sqrt}(2)$$

Problem: not renormalizable.

If one gives up renormalizability one can write higher order operators to generate abelian and non-abelian gauge fields mixing!

In fact in the SM, one can generate such a mixing between $SU(2)_L$ and $U(1)_Y$

$$W^a_{\mu\nu} X^{\mu\nu} (H^+ \tau^a H)$$

Here H is the usual SM doublet!

Possible to have kinetic mixing between ablian and non-abelian gauge fields. Chen, Cline, and Frey, 2009; He, Ovanesyan, Ramesy-Musolf, 2014.

UV completion of kinetic mixing of Abeliand-NonAbelian gauge field?

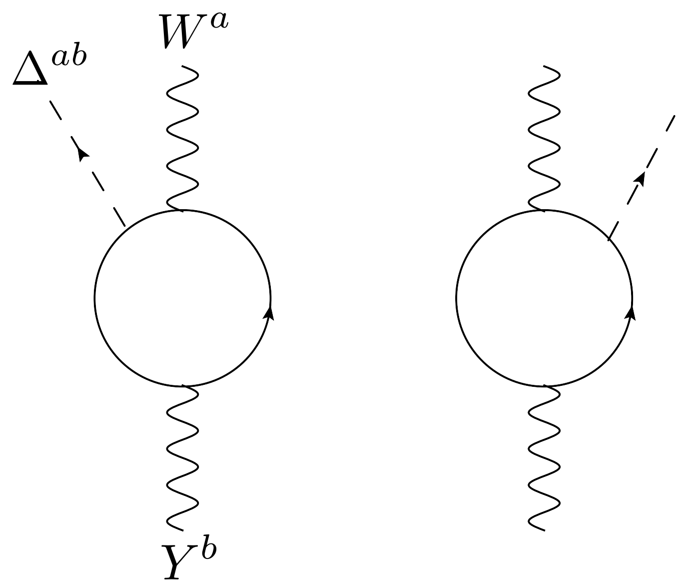
Yes, they can be generated at loop level starting from a renormalizable theory.

The particle in the loop carry both abelian and non-abelian charges.

One can even talking about

SU(N) and SU(m) kinetic mixing

$$W^a_{\mu\nu} Y^{b\mu\nu} \Delta_{ab}$$



Kinetic mixing between an Abelian and a non-Abelian fields should be very common when going beyond SM.

A triplet Δ^a (0,3,0) and W-B mixing

$SU(2)_W = SU(2)_L$, $U(1)_X = U(1)_Y$

$$L_{k-mixing} = -\frac{1}{2}\alpha\frac{v_\Delta/\sqrt{2}}{\Lambda}B^{0,\mu\nu}W^{3,0}_{\mu\nu} \qquad m_W^2 = (m_W^0)^2\left(1+4\frac{v_\Delta^2}{v^2}\right)$$

$$= -\frac{1}{2}\epsilon\left(s_W c_W A^0_{\mu\nu}A^{0,\mu\nu} - s_W c_W Z^0_{\mu\nu}Z^{0,\mu\nu} + (c_W^2 - s_W^2)A^0_{\mu\nu}Z^{0,\mu\nu}\right)$$

Analysis the effects through S,T, U parameters

$$\Delta L_{eff} = -\frac{A}{4}A^0_{\mu\nu}A^{0,\mu\nu} - \frac{B}{2}W^{+0}_{\mu\nu}W^{-0,\mu\nu} - \frac{C}{4}Z^0_{\mu\nu}Z^{0,\mu\nu} + \frac{G}{2}A^0_{\mu\nu}Z^{0,\mu\nu}$$
$$+\ w(m_W^0)^2 W^{+,0}_\mu W^{-,0,\mu} + \frac{z}{2}(m_Z^0)^2 Z^0_\mu Z^{0\mu}\ ,$$

$$A = 2s_W c_W\epsilon\ ,\quad B = 0\ ,\quad C = -2s_W c_W\epsilon\ ,\quad G = -(c_W^2 - s_W^2)\epsilon\ ,\quad w = 4\frac{v_\Delta^2}{v^2}\ ,\quad z = 0.$$

$$\alpha S = 4s_W^2 c_W^2\left(A - C - \frac{c_W^2 - s_W^2}{s_W c_W}G\right) = 4s_W^2 c_W^2\left(4s_W c_W + \frac{(c_W^2 - s_W^2)^2}{s_W c_W}\right)\epsilon\ ,$$

$$\alpha T = w - z = 4\frac{v_\Delta^2}{v^2}\ ,$$

$$\alpha U = 4s_W^4\left(A - \frac{1}{s_W^2}B + \frac{c_W^2}{s_W^2}C - 2\frac{c_W}{s_W}G\right) = 0\ .$$

Some phenomenological implications

$$\mathcal{O}^{(5)}_{WX} = -\frac{\beta}{\Lambda}\,\mathrm{Tr}\left(W_{\mu\nu}\Sigma\right) X^{\mu\nu} \qquad \epsilon = \beta \sin\theta_W \left(\frac{v_\Sigma}{\Lambda}\right)$$

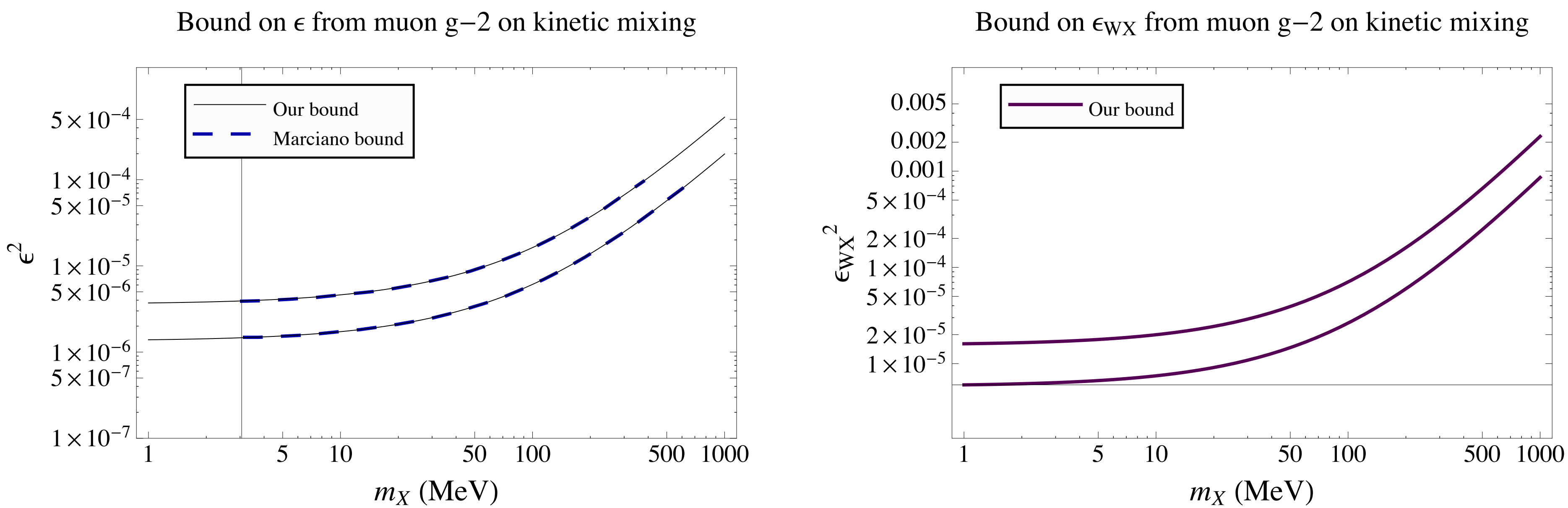
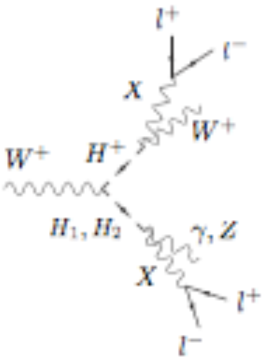
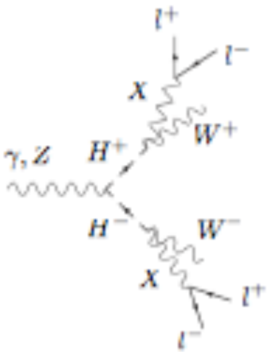


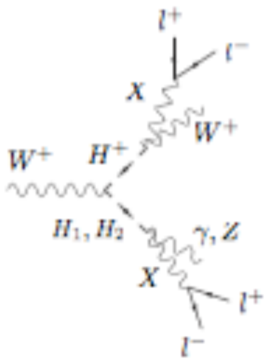
FIG. 1: Bound on abelian mixing parameter ϵ (left) and non-abelian mixing parameter ϵ_{WX} (right).



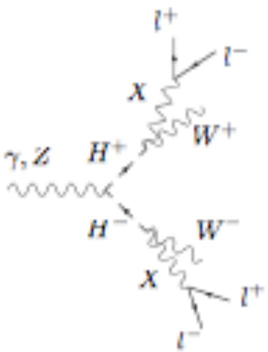
(a)



(b)



(a)



(b)

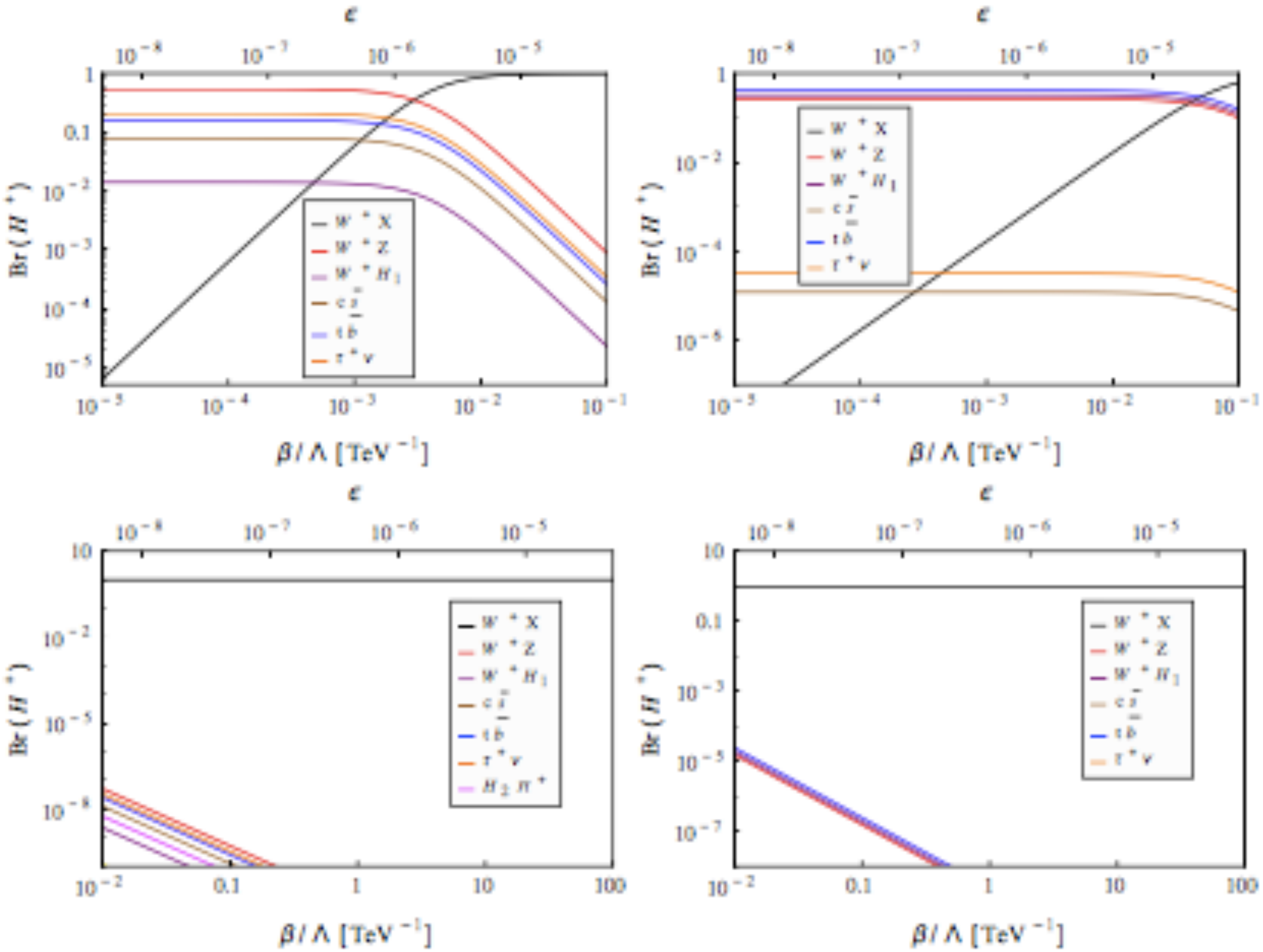


Figure 4. Branching ratios for H^+ decays as a function of β/Λ (bottom horizontal axis) and ϵ (upper horizontal axis) for $m_X = 0.4$ GeV. The top (bottom) row corresponds to $v_\Sigma = 1$ GeV ($v_\Sigma = 10^{-3}$ GeV), while the left (right) column corresponds to $m_{H^+} = 130$ GeV ($m_{H^+} = 130$ GeV). The solid black line indicates the branching ratio for $H^+ \to W^+X$. Branching ratios for other final states are as indicated by the legend insert.

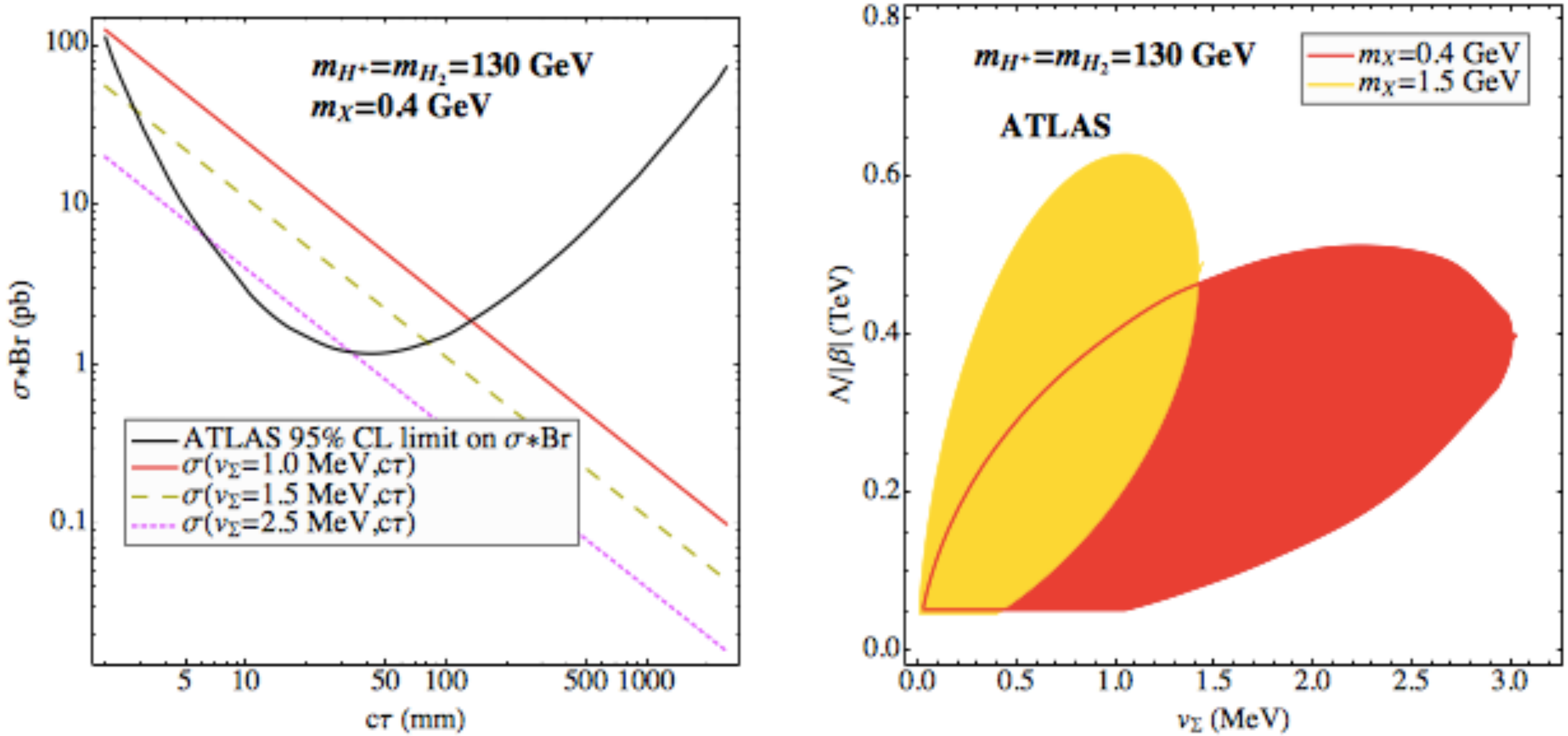


Figure 5. Constrains on triplet-assisted non-abelian kinetic mixing, recast from the ATLAS search reported Ref. [12]. The left panel gives the exclusion in the ($c\tau$, $\sigma \times$ BR) plane, where the region above the parabola is excluded. The diagonal lines indicate the dependence of $\sigma \times$ BR on $c\tau$ for different representative choices of v_Σ. The right panel gives the exclusion region in the(v_Σ, Λ/β) plane for $m_X = 0.4$ GeV (red region) and $m_X = 1.5$ GeV (yellow region).