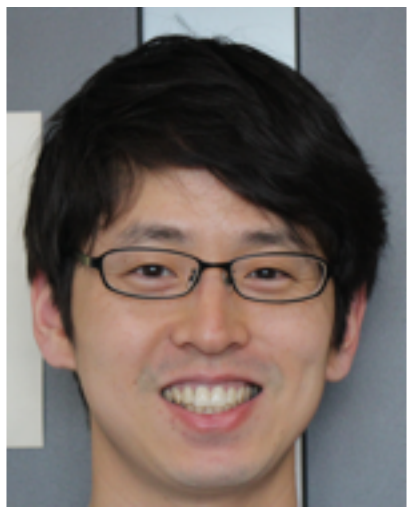
Quantum corrections in a DM model with pseudo-scalar mediators



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Nagoya U, KMI, Kavli IPMU

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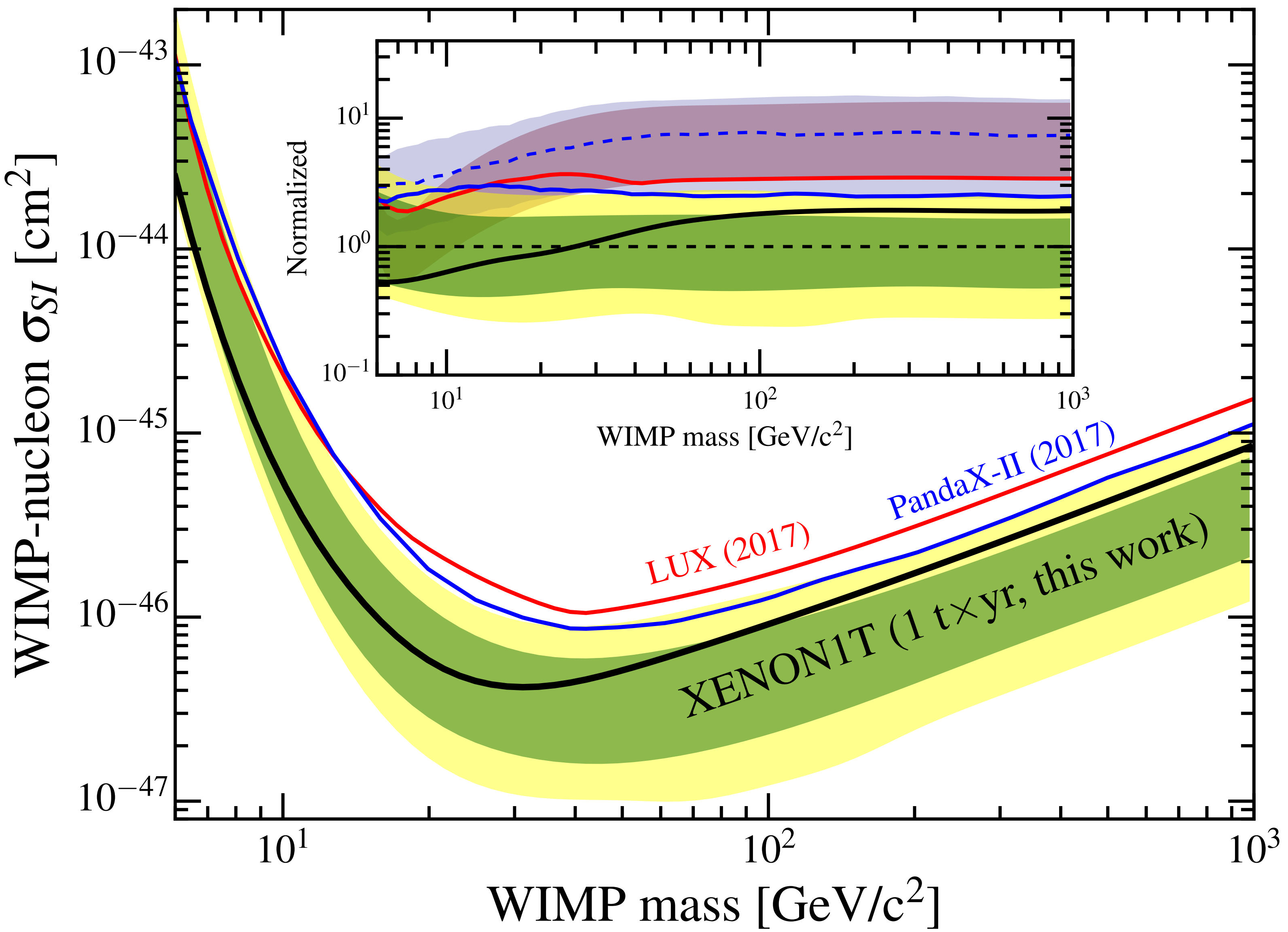
Nagoya U.

(work in progress)

Constraints from direct detection



[XENON1T (2018)]

- WIMP models have been severely constrained today
- We need ideas to avoid this strong constraint

fermion DM with Pseudo-scalar coupling

If DM has a pseudo-scalar interaction,

$$\mathcal{L} \supset \bar{\psi} i g \gamma_5 \psi a$$

ψ = DM, a = mediator (scalar)

then **we can avoid the constraints from the direct detections while keeping the WIMP scenario**

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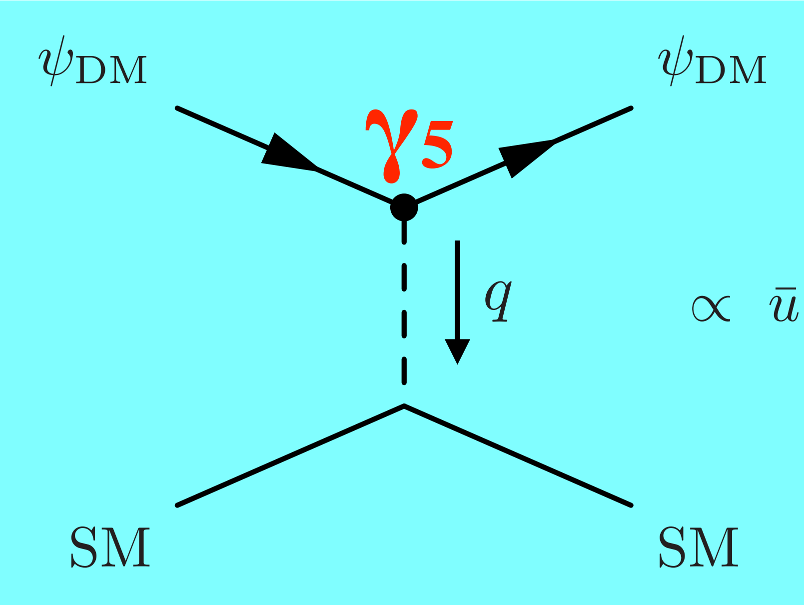
Suppression of the direct detection



$$\propto \; \bar{u}(p)\gamma^5 u(p) \; \simeq \; \vec{q}\cdot\vec{\sigma}$$

$$\psi = \sum_s \int \frac{d^3p}{(2\pi)^3\sqrt{2E_p}} \left(a_{p,s}u_s(p)e^{-ipx} + b^\dagger_{p,s}v_s(p)e^{ipx}\right)$$

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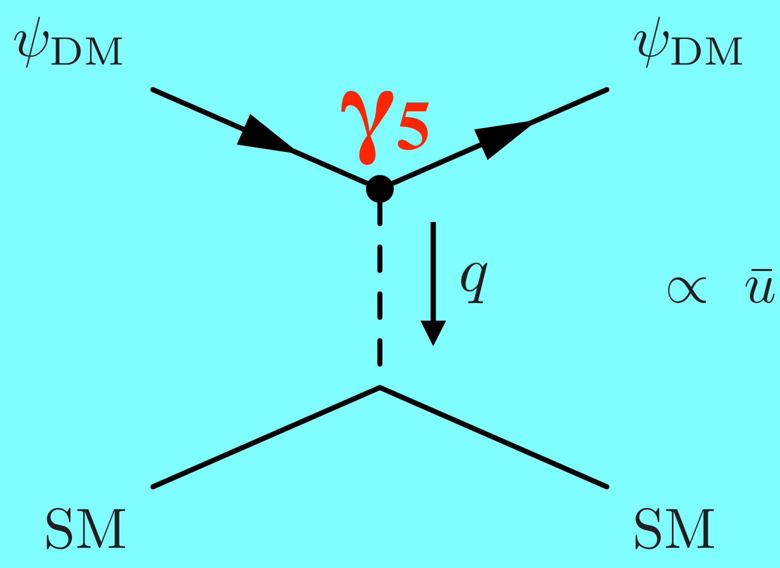

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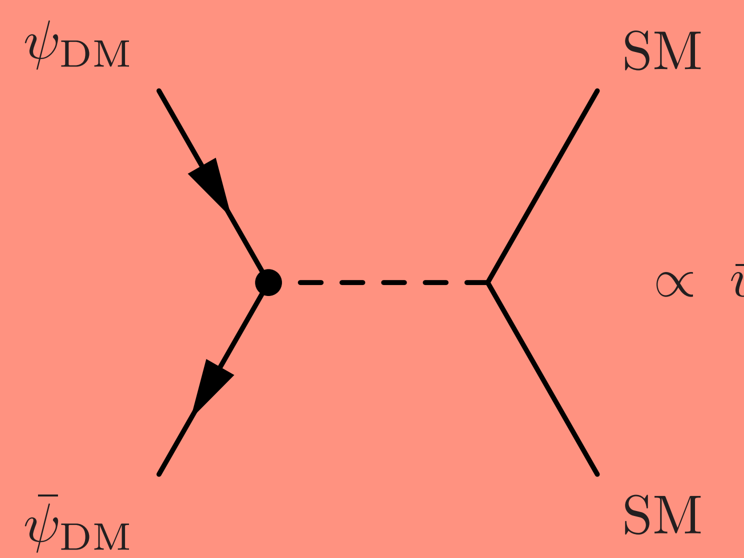
Annihilation cross section is not suppressed



$$\propto \; \bar{v}(p)\gamma^5 u(p) \;\simeq\; m_{\rm DM}$$

A model with pseudo-scalar mediator

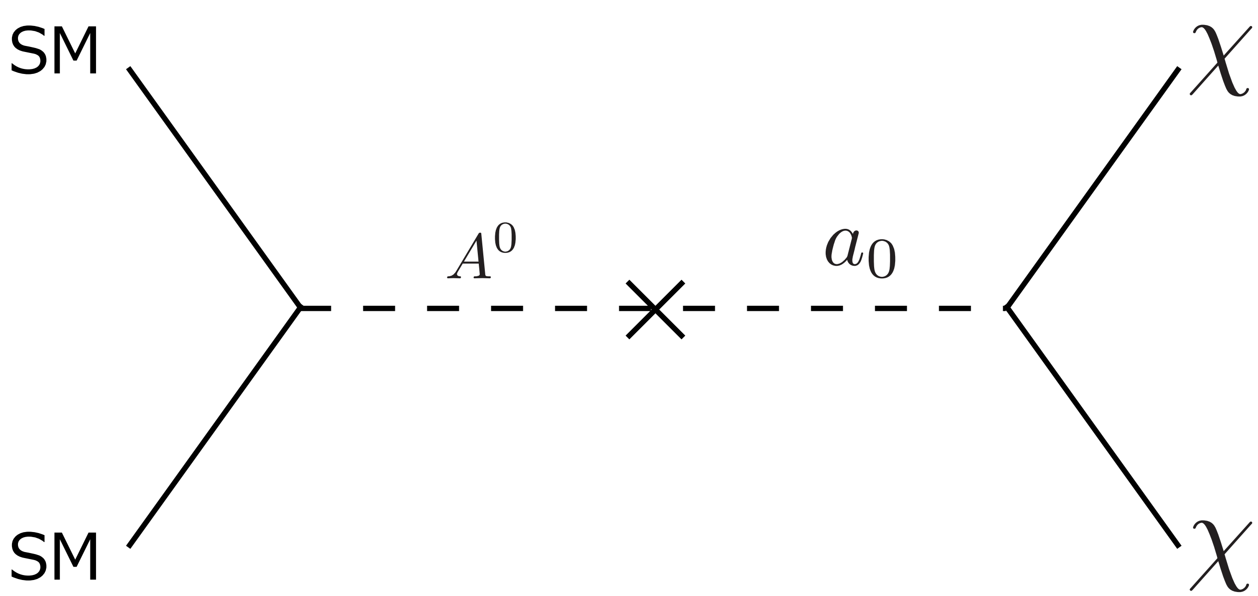
[Ipek et. al (2014)]

model

- a gauge singlet fermion χ
- a gauge singlet CP-odd scalar a_0
- SM Higgs sector is extended into a two-Higgs doublet model

$$H_1, H_2 \supset h, H^0, H^\pm, A^0$$

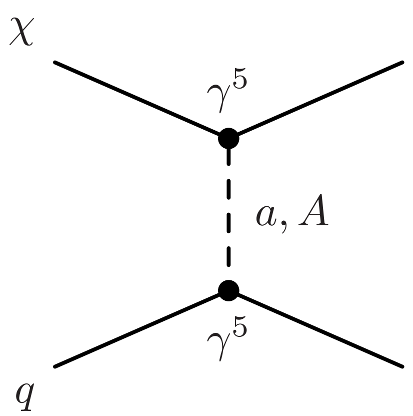
DM interacts with SM by the mixing between CP-odd scalars



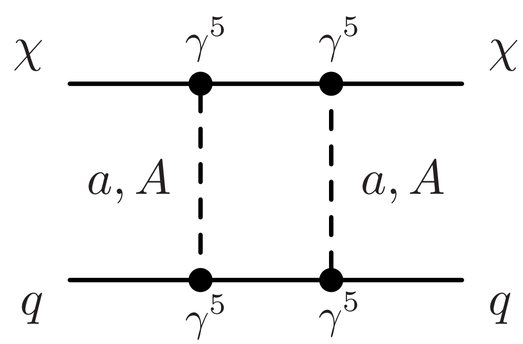
$$\begin{pmatrix} A \\ a \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A^0 \\ a_0 \end{pmatrix}$$

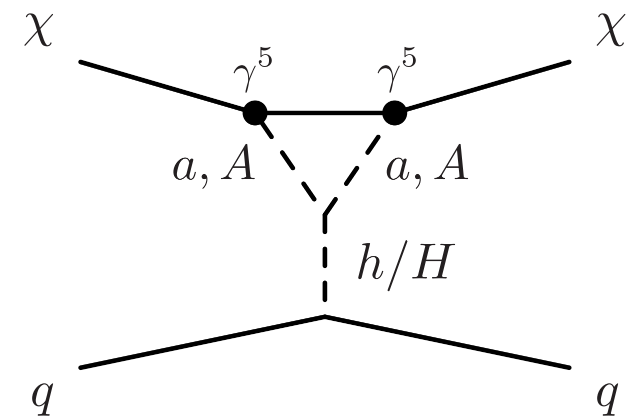
Loop diagrams are important for σ_{SI}

$\sigma_{SI} > 0$ at the loop level



$\simeq 0$





$\cdots$

$(\bar{\chi}\gamma^5\chi)(\bar{q}\gamma^5 q)$

$\bar{\chi}\chi\bar{q}q$

$\bar{\chi}\chi G^a_{\mu\nu}G^{a\mu\nu}$

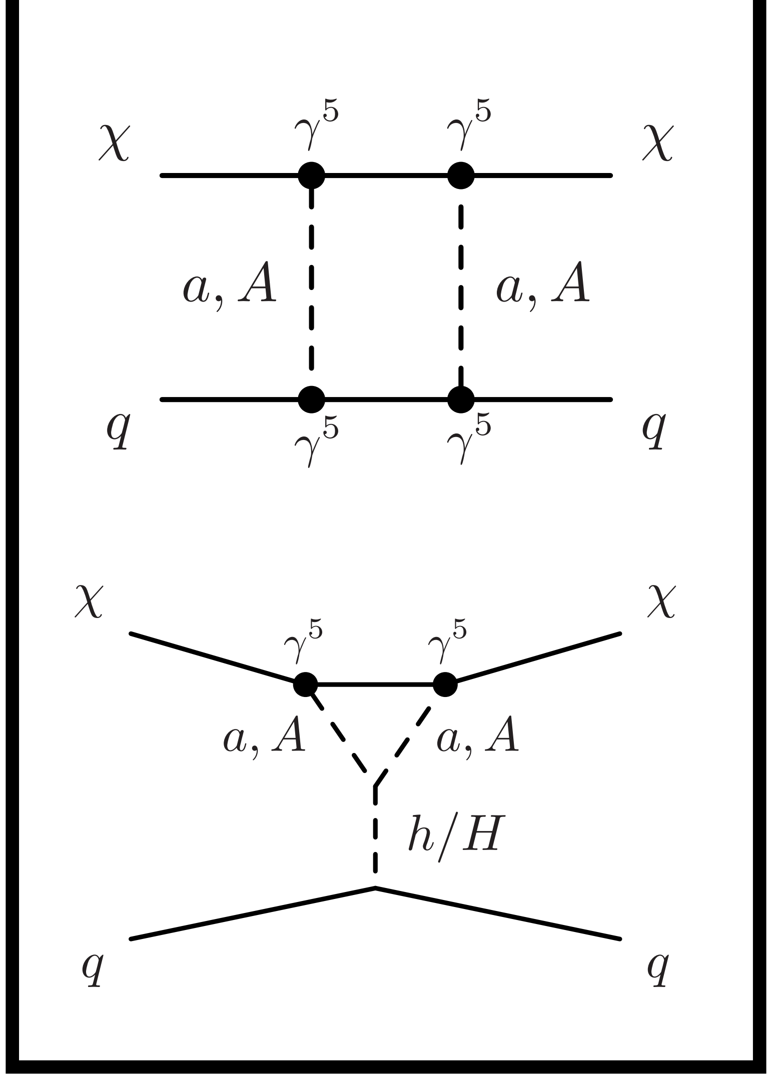
$(\gamma_5)^2 = 1$

loop calculation is important to test this model by DM direct detection experiments!

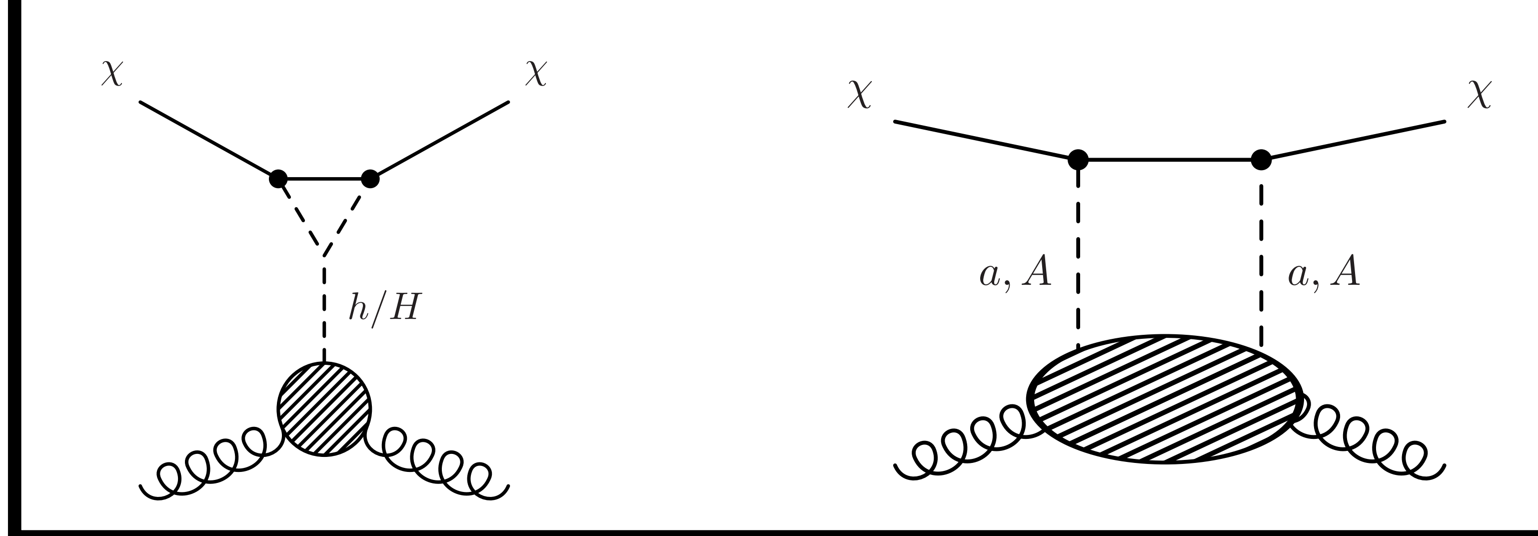
loop calculations were calculated

[Arcadi et. al (2018)]

$\bar{\chi}\chi\bar{q}q$



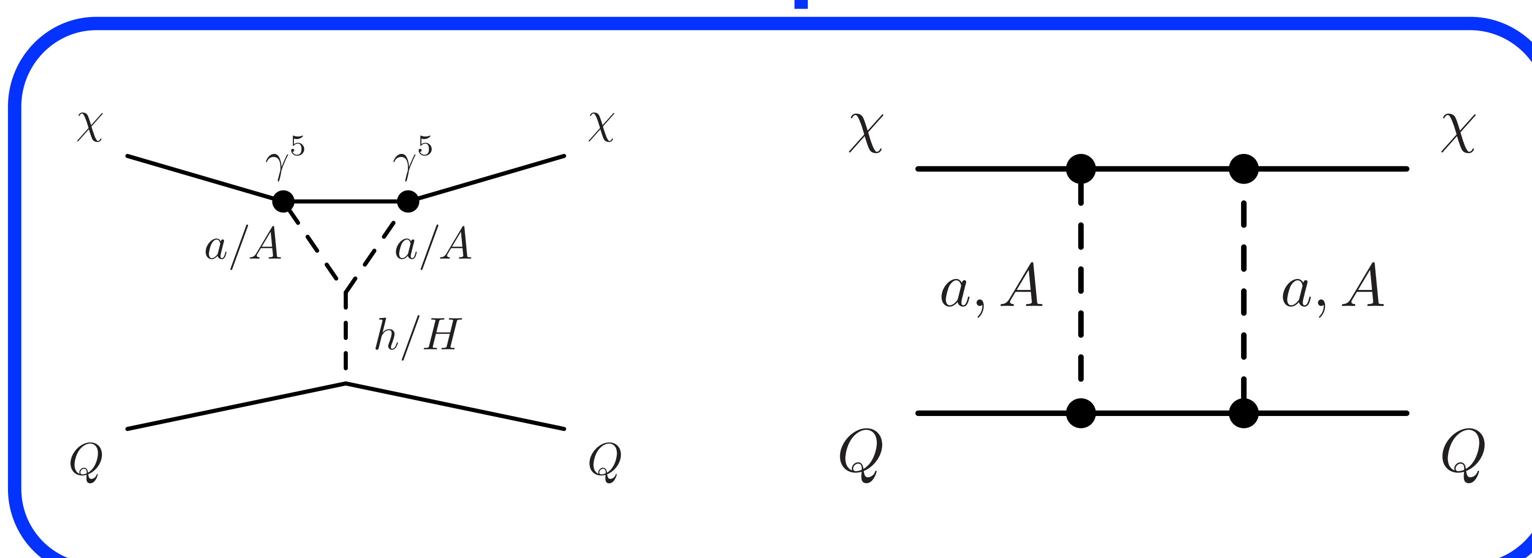
$\bar{\chi}\chi G^a_{\mu\nu} G^{a\mu\nu}$



estimated by using

$m_Q \bar{Q} Q = -\frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\mu\nu}$

$Q = t, b, c$ (heavy quarks)



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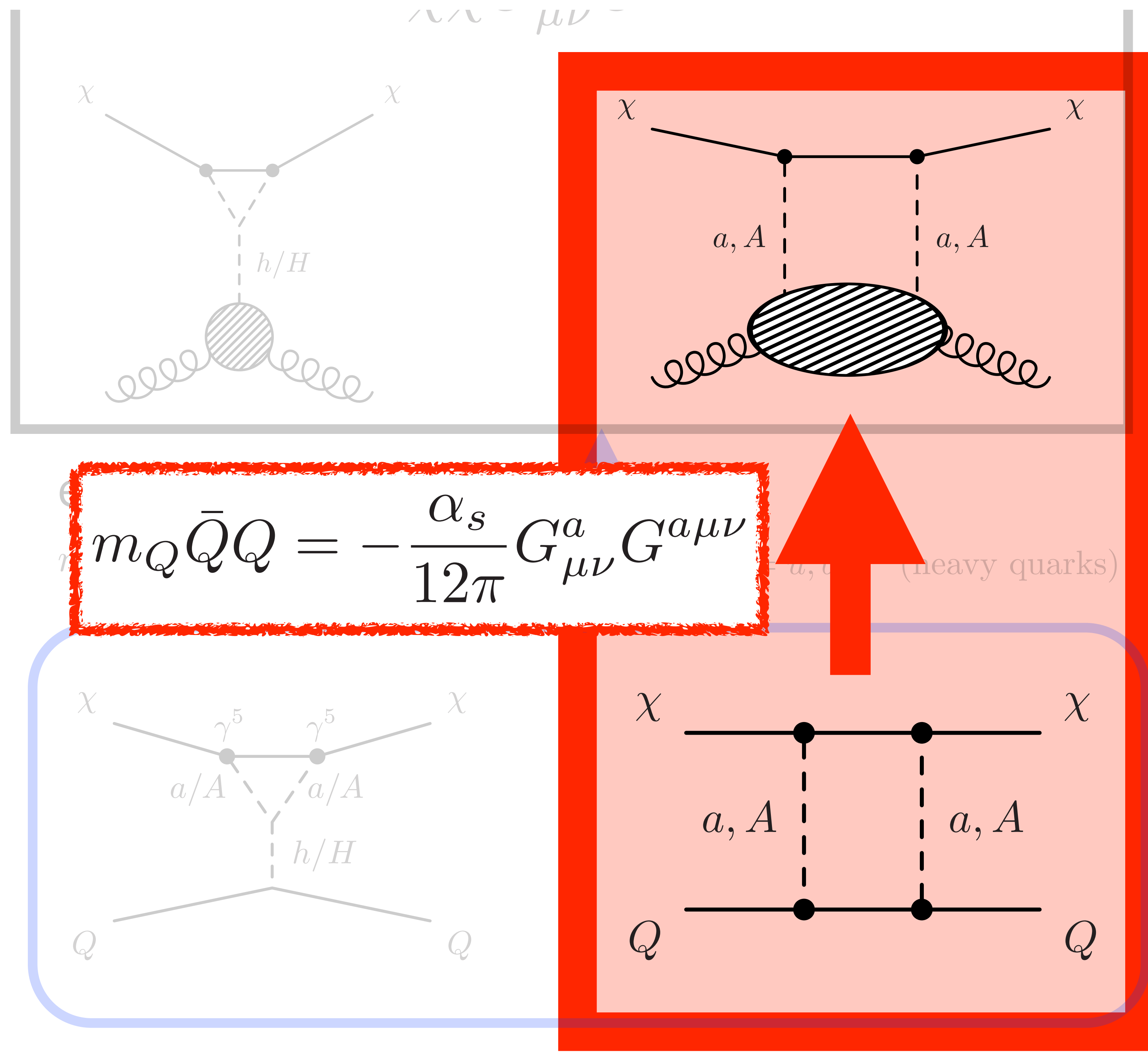
but this replacement is NOT justified!



$$m_Q \bar{Q} Q = -\frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\mu\nu}$$

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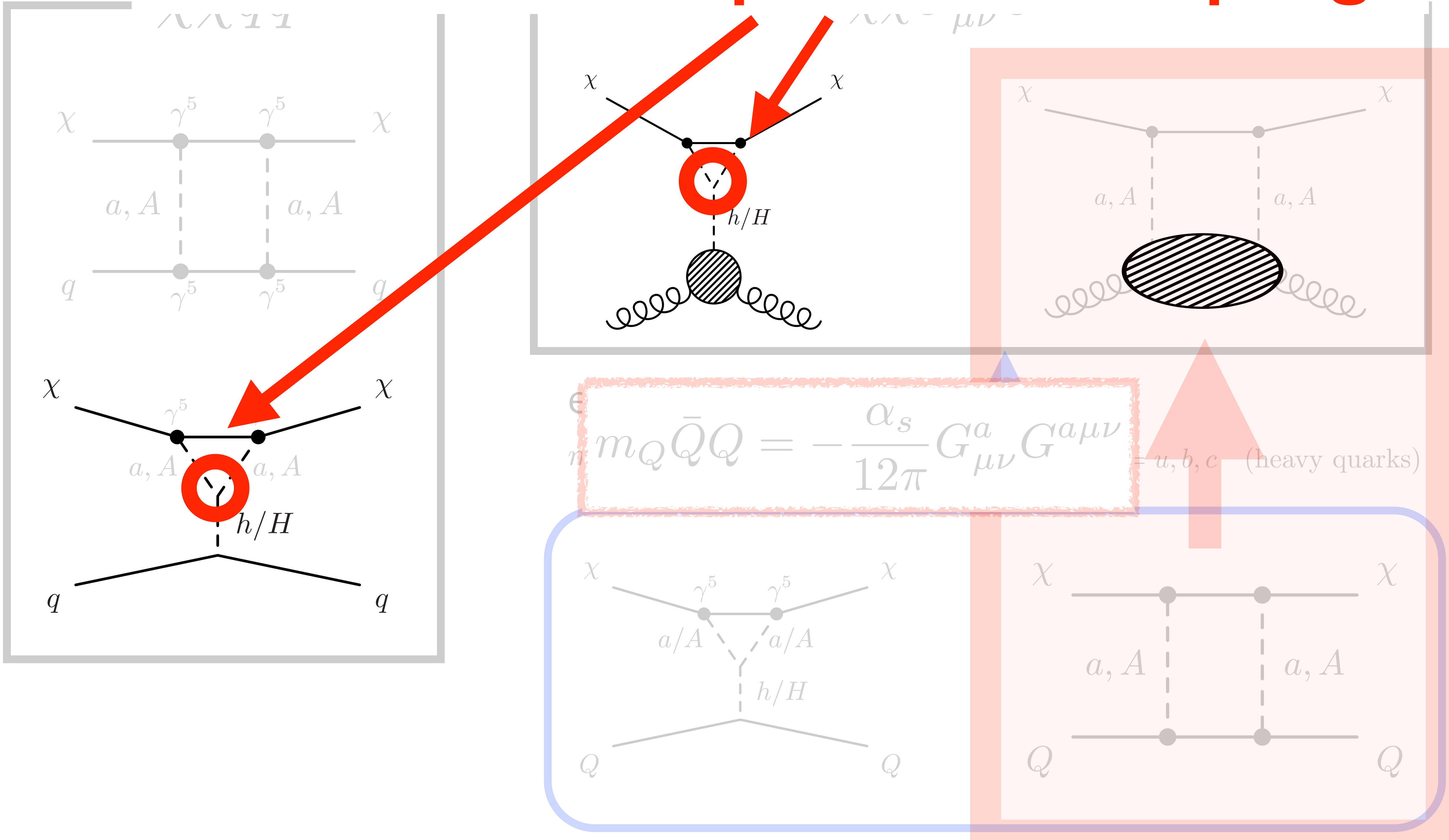
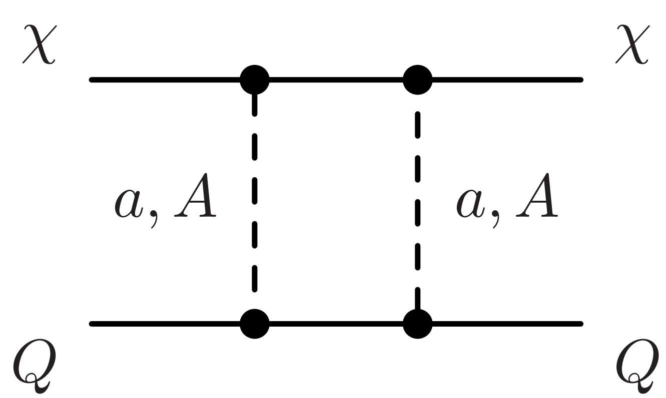
we revisit the triple-scalar couplings!



Our work (1) : two-loop calc for box-gluon

this replacement cannot be justified but used in [Arcadi et. al (2018)]



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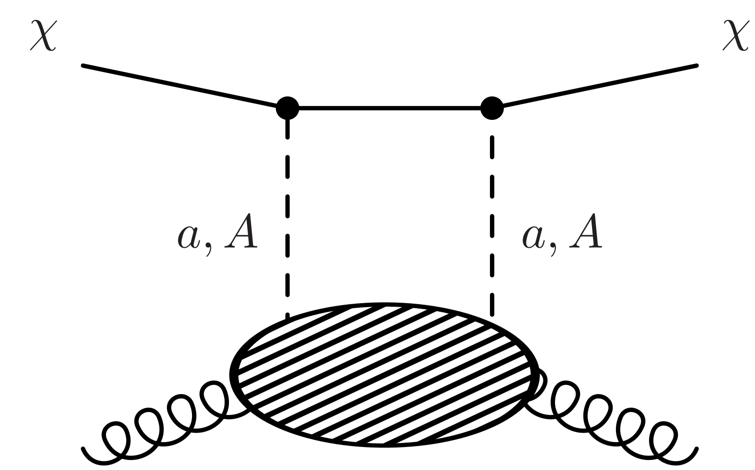

2-loop diagrams should be calculated!

[Arcadi et. al (2018)]

This procedure is justified if the loop that generates the four-fermion interaction and the loop that relates the quarks to the gluon-condensate factorize. While this assumption is reasonable for heavy new physics which can be integrated out at energies above the top mass, it is not fully appropriate in the scenario under scrutiny here since we are interested in $m_a < m_t$. In this case, the correct top mass dependence of the effective dark matter gluon interaction is only recovered by a two-loop computation of the effective dark matter gluon interaction [57] which is beyond the scope of this work.

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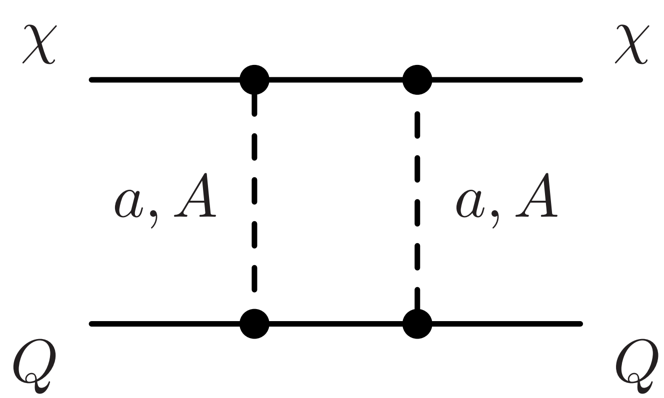

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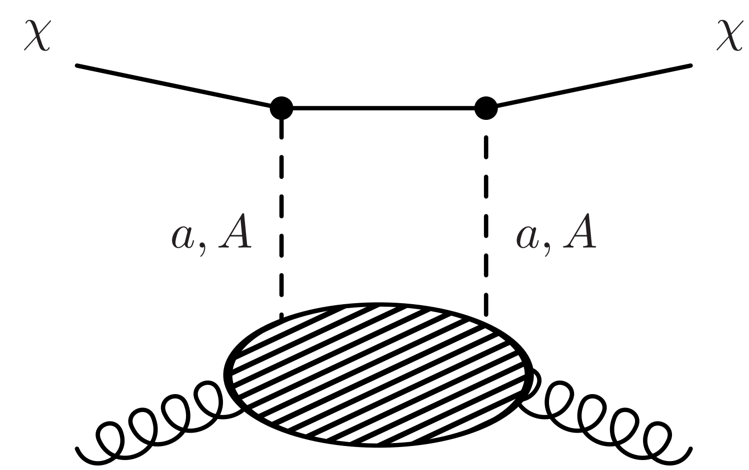

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two-loop computation is the scope of our work

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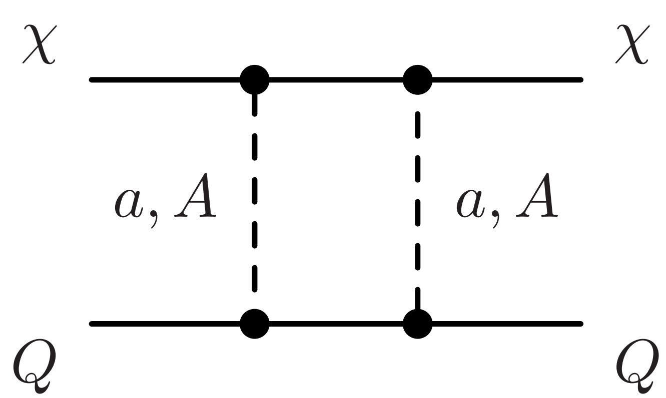

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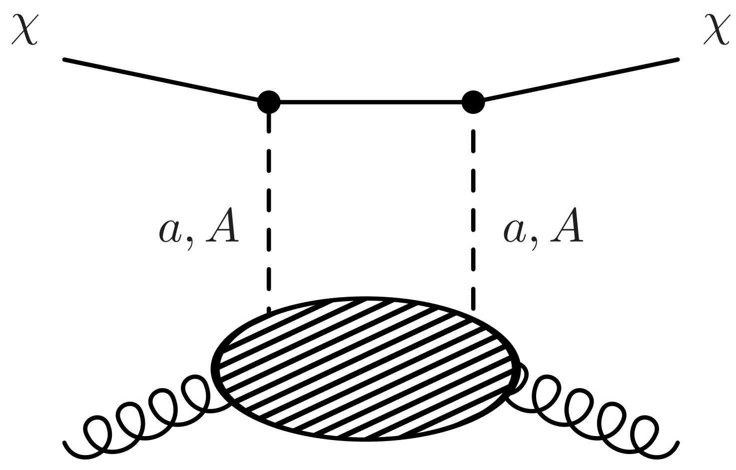
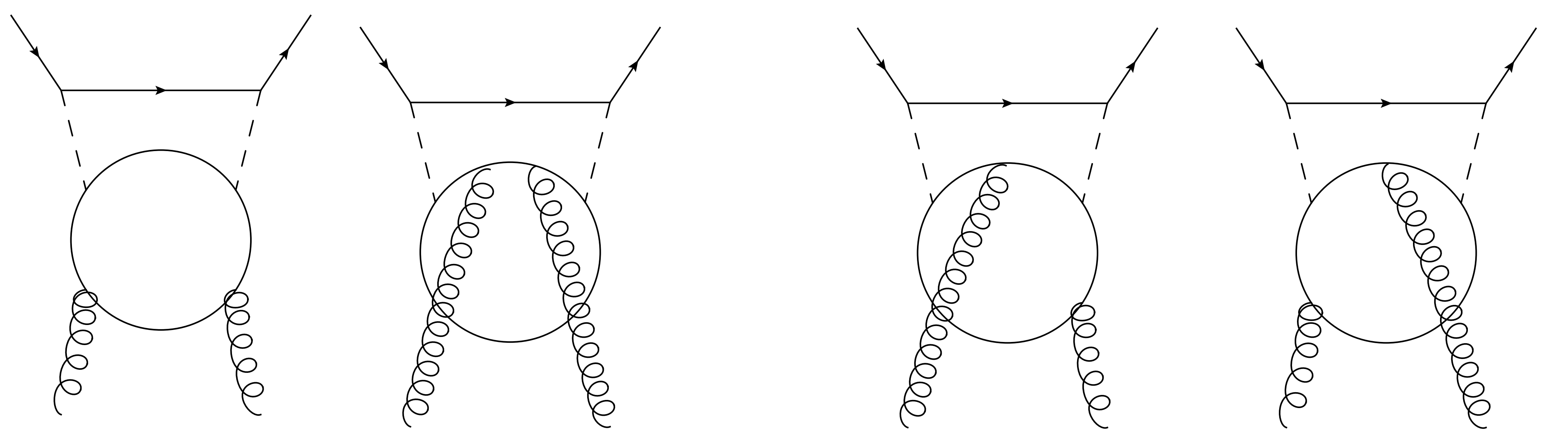


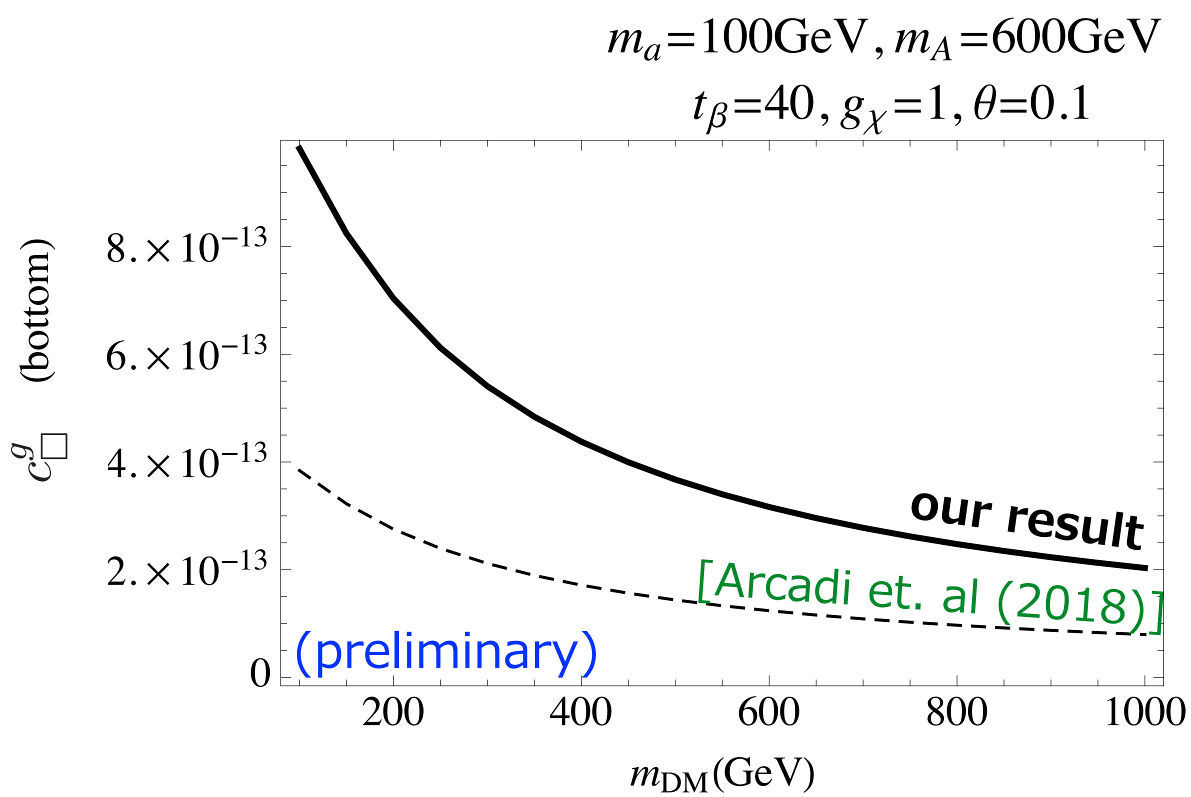
We calculate full two-loop diagrams for the box type diagrams

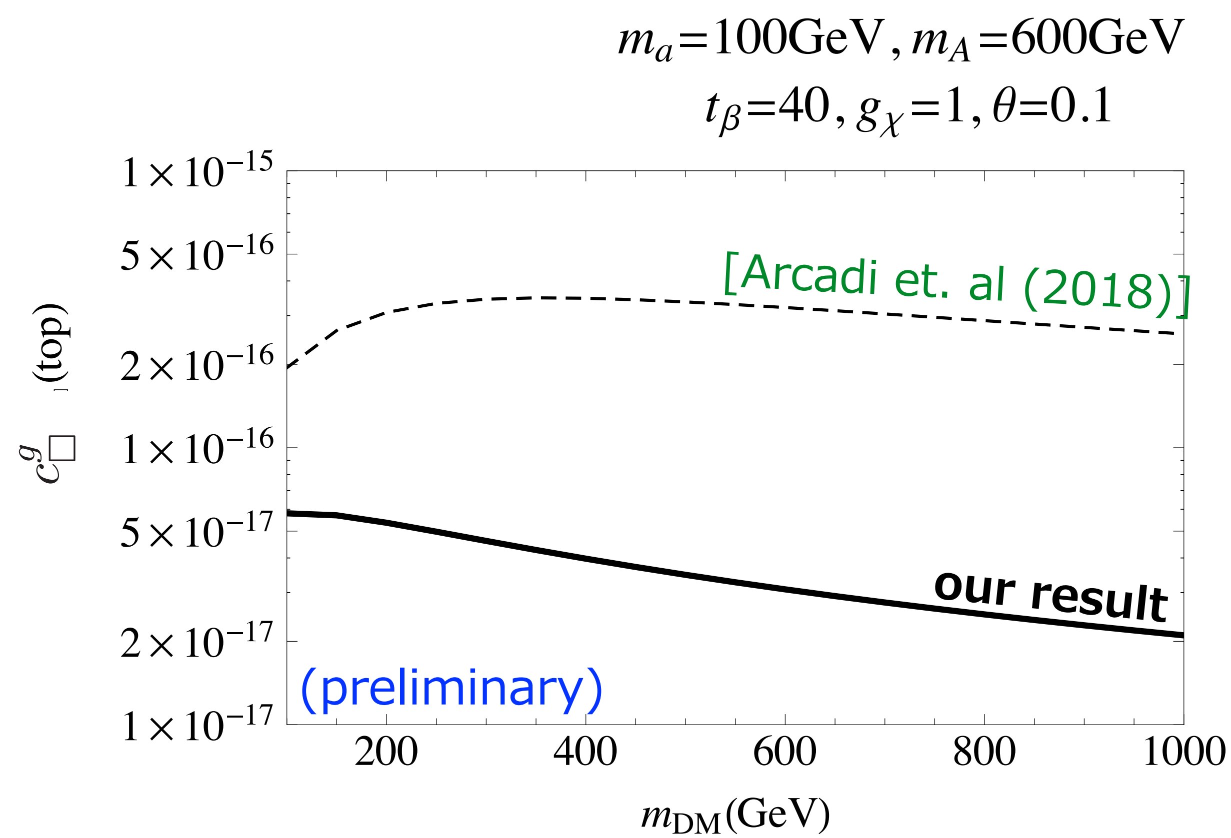
New



Comparison with the previous work

$$\mathcal{L}_{eff.} \supset -\frac{9\alpha_s}{8\pi} c^g_{\square} \bar{\chi}\chi G^a_{\mu\nu} G^{a\mu\nu}$$





The bottom contribution is *underestimated* in the previous work

The top contribution is *overestimated* in the previous work

Our work (2) : triple-scalar coupling revisit

revisit to the triple-scalar-couplings (aah coupling)

$$\kappa(ia_0H_1^\dagger H_2 + \text{h.c.}) + c_1a_0^2H_1^\dagger H_1 + c_2a_0^2H_2^\dagger H_2.$$

this term was used in the literatures

[Ipek et. al (2014), Arcadi et. al (2018), ⋯]

but they were not used!

sinθ suppression for the aah coupling

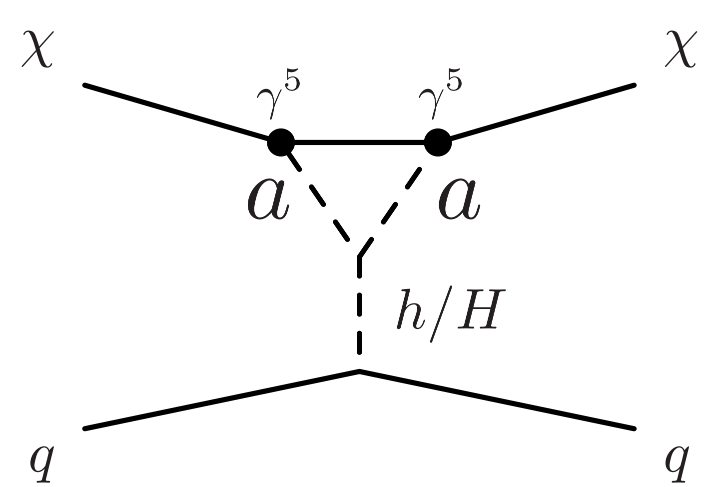
(θ is the mixing angle btw CP-odd states)

$$\propto (\kappa \sin\theta \cos\theta) aah$$

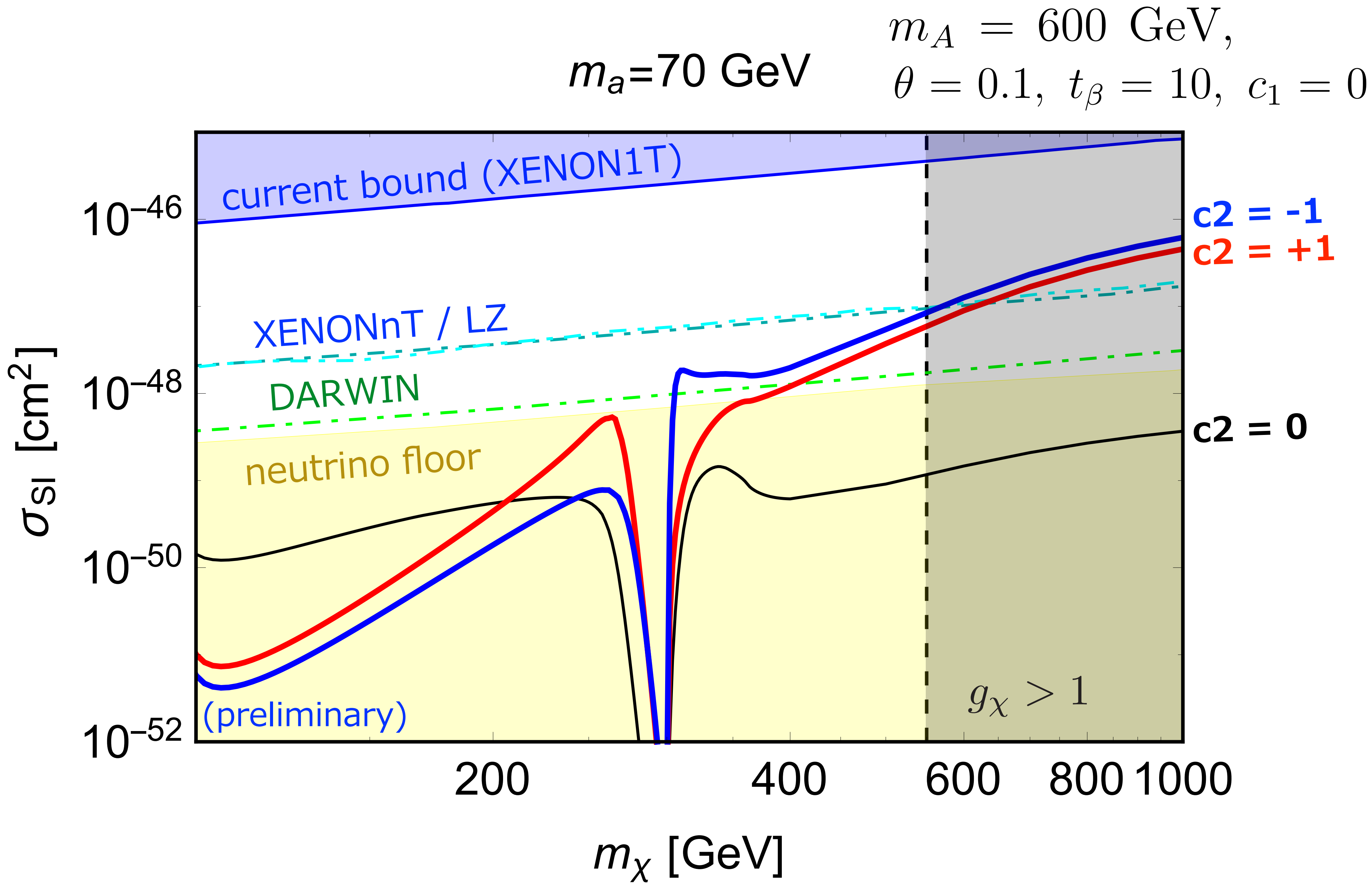
No suppression by sinθ !

$$\sim -v\cos^2\theta \left(\frac{c_1}{\tan^2\beta} + c_2\right) aah$$

c1 and c2 are important to see if σ_{SI} can be enhanced by the loop effects



σ_{SI} is large if C2 ≠ 0



c2 is important to make σ_{SI} larger then neutrino floor

Summary

two-Higgs doublet model + fermion DM + a_0

- one of the pseudo scalar mediator model
- σ_{SI} is suppressed at the tree level
- loop calculation is needed

We have improved the calculation for $\bar{\chi}\chi G^a_{\mu\nu} G^{a\mu\nu}$

- this was underestimated/overestimated in the result in the previous work

We have used quartic couplings $c_1 a_0^2 H_1^\dagger H_1 + c_2 a_0^2 H_2^\dagger H_2$

- they are often ignored in the literatures
- they significantly affects the cubic interaction term, aah
- σ_{SI} can be within the future prospects of XenonNT and LZ

Backup slides

A model with pseudo-scalar mediator

model

- a gauge singlet fermion (as a DM candidate)
- a gauge singlet CP-odd scalar (as a mediator)
- SM Higgs sector is extended into a two-Higgs doublet model

$$\mathcal{L} \supset +i\frac{g_\chi}{2}a_0\bar{\chi}\gamma^5\chi - (V_{\mathrm{THDM}} + V_{a_0} + V_{\mathrm{port}})$$

$$V_{a_0} = \frac{1}{2}m_{a_0}^2 a_0^2 + \frac{\lambda_{a_0}}{4}a_0^4,$$

$$V_{\mathrm{port}} = \kappa(ia_0 H_1^\dagger H_2 + \mathrm{h.c.}) + c_1 a_0^2 H_1^\dagger H_1 + c_2 a_0^2 H_2^\dagger H_2.$$

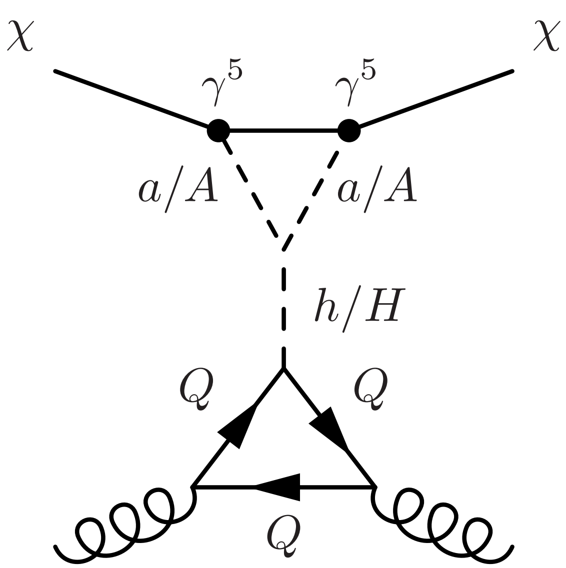
triangle diagrams with gluons

triangle diagram with gluons

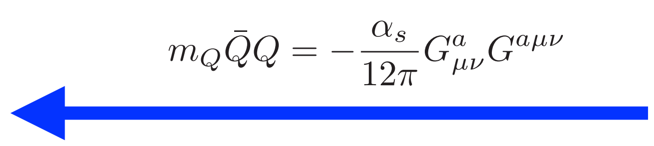
- two-loop
- can be calculated from the 1-loop diagram by using a relation

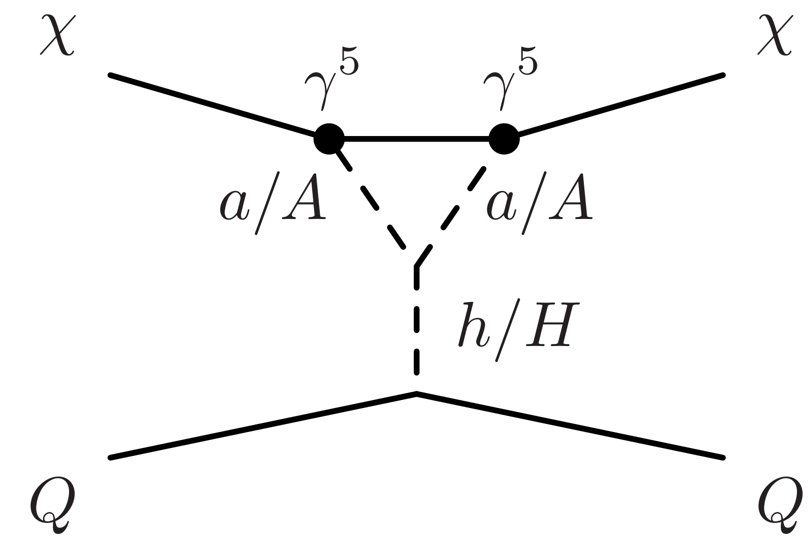
$$m_Q \bar{Q} Q = -\frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\mu\nu}$$

$Q = u, b, c$ (heavy quarks)



$$\bar{\chi}\chi G^a_{\mu\nu} G^{a\mu\nu}$$





$$\bar{\chi}\chi \bar{Q} Q$$

form factors

Matrix elements

- form factors for quarks are O(10^{-2})
- form factors for gluon is O(1)
- 1-loop factor in the gluon term is absorbed into the form factor

$$\langle N \,|\, m_q \overline{q} q \,|\, N \rangle = m_N f_{T_q}^{(N)}$$

$$-\frac{9\alpha_s}{8\pi} \left\langle N \,\middle|\, G^a_{\mu\nu} G^{a\mu\nu} \,\middle|\, N \right\rangle = m_N f_{T_G}^{(N)}$$