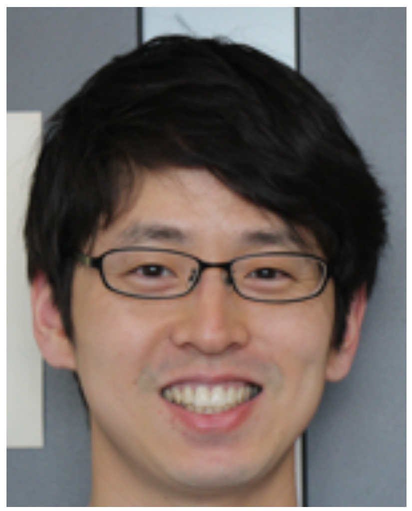
Quantum corrections in a DM model with pseudo-scalar mediators



Tomohiro Abe
Institute for Advanced Research, KMI, Nagoya U.

共同研究者

Junji Hisano
Nagoya U, KMI, Kavli IPMU

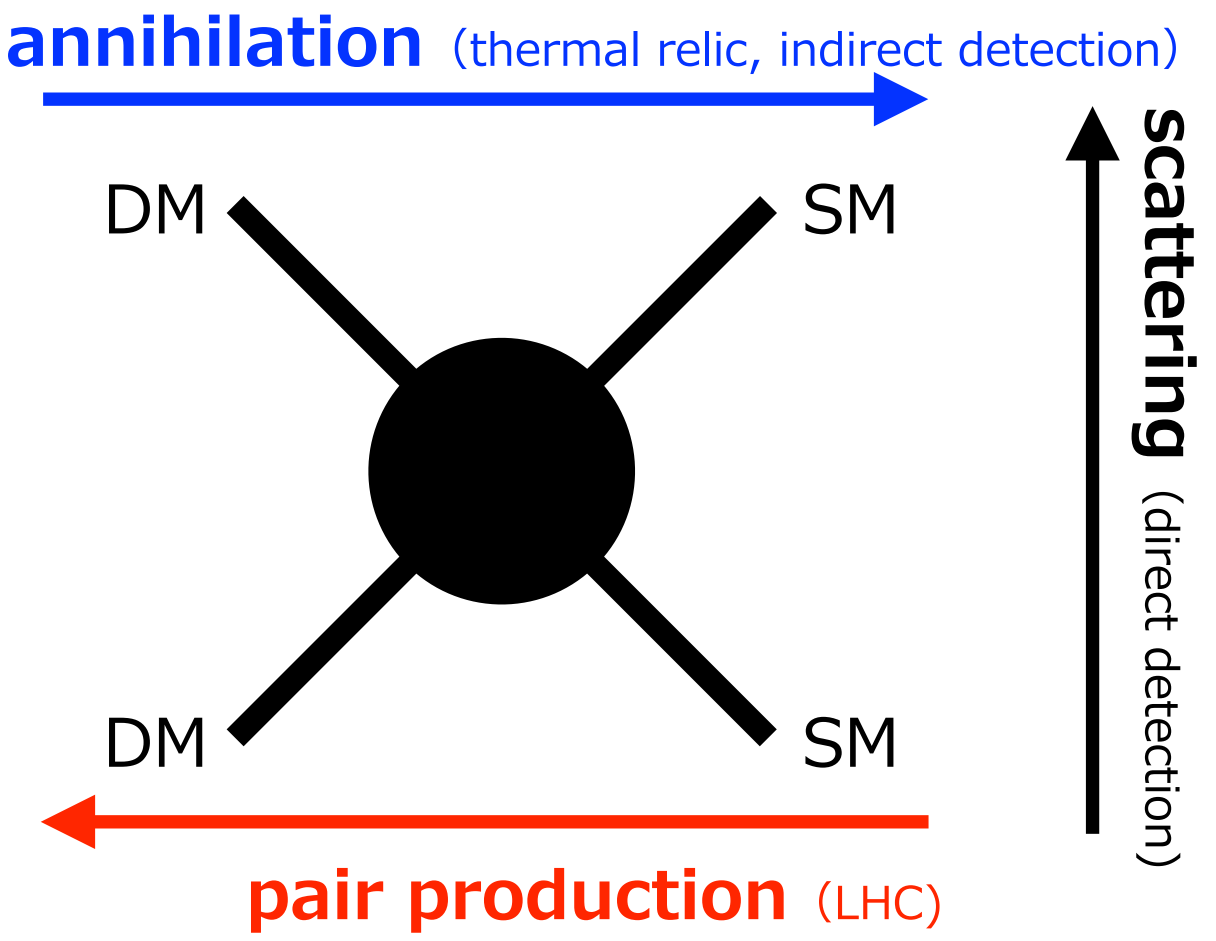
Motomo Fujiwara
Nagoya U.

based on **arXiv:1810:01039** **(today!)**

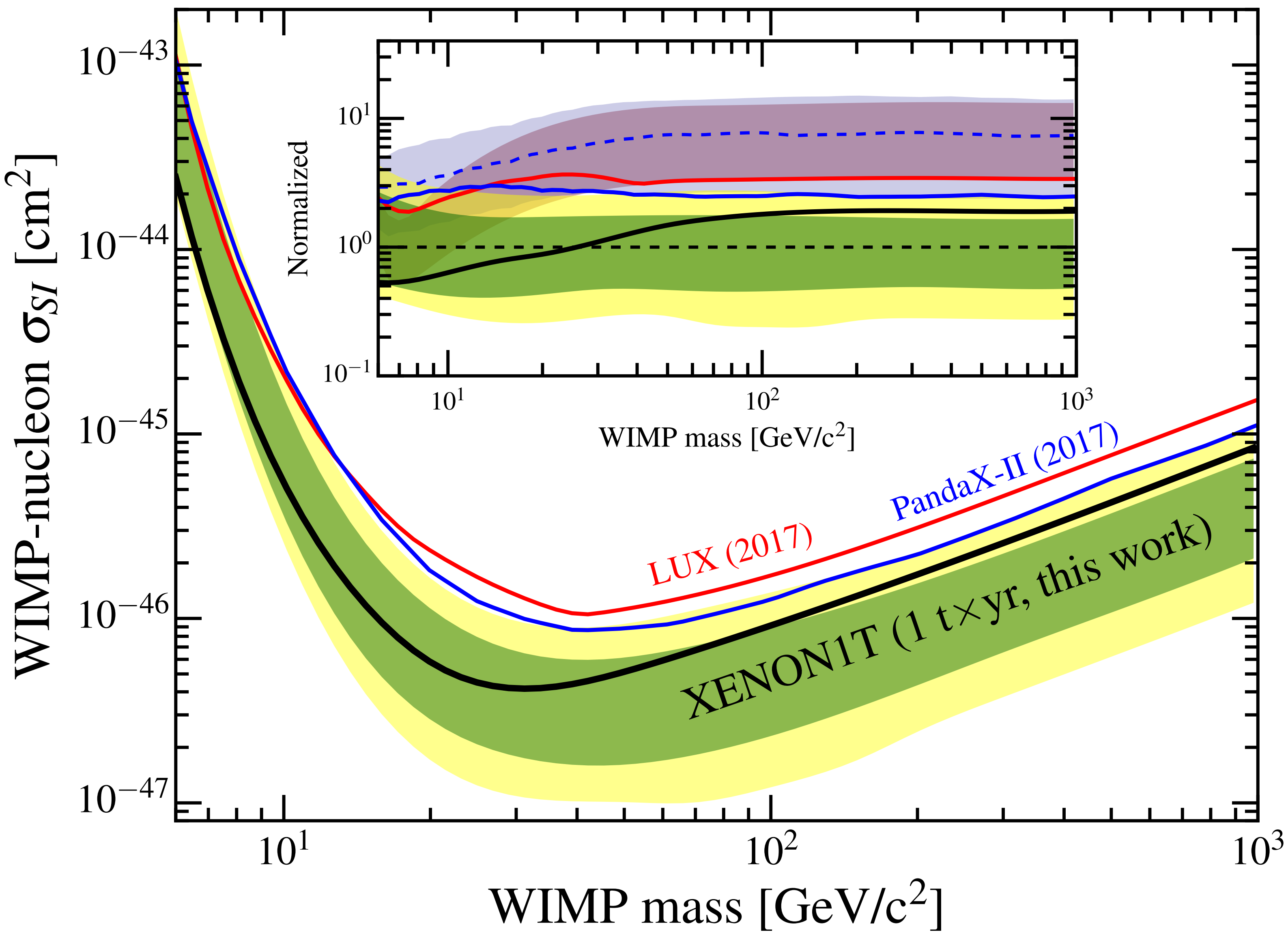
WIMP dark matter

Features of WIMP (Weakly Interacting Massive Particle)

- weakly interacting to the SM
- freeze out mechanism
- correlation among various observables
- simple and attractive



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,

$$\mathcal{L} \supset \bar{\psi} i g \gamma_5 \psi a \qquad \psi = \text{DM}, \ a = \text{mediator (scalar)}$$

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

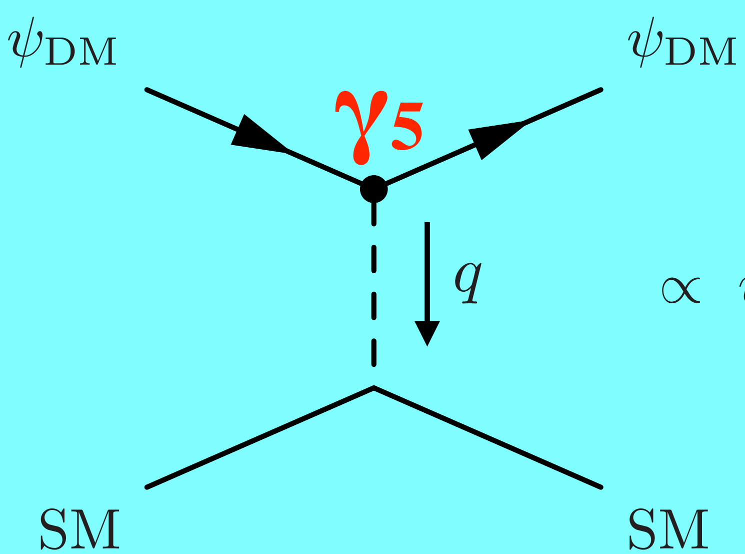
fermion DM with Pseudo-scalar coupling

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**

Suppression of the direct detection



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

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

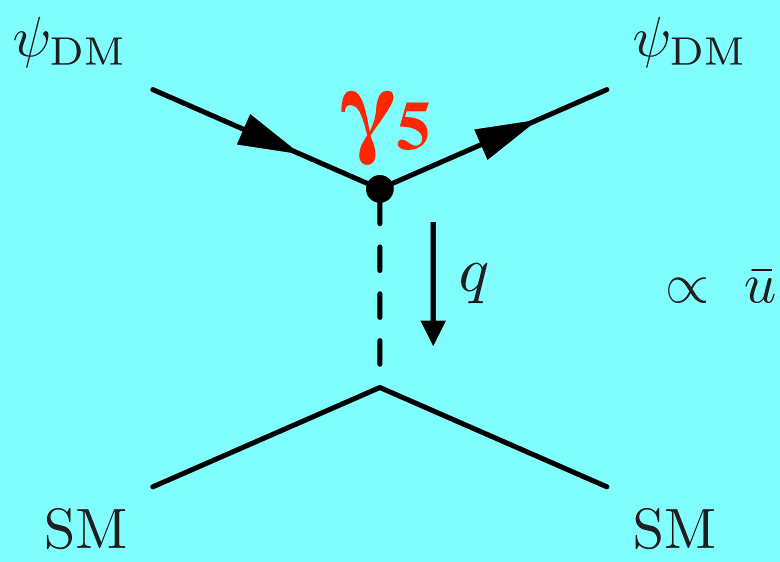
fermion DM with Pseudo-scalar coupling

If DM has a pseudo-scalar interaction,

$$\mathcal{L} \supset \bar{\psi} i g \gamma_5 \psi a$$ ψ = DM, a = mediator (scalar)

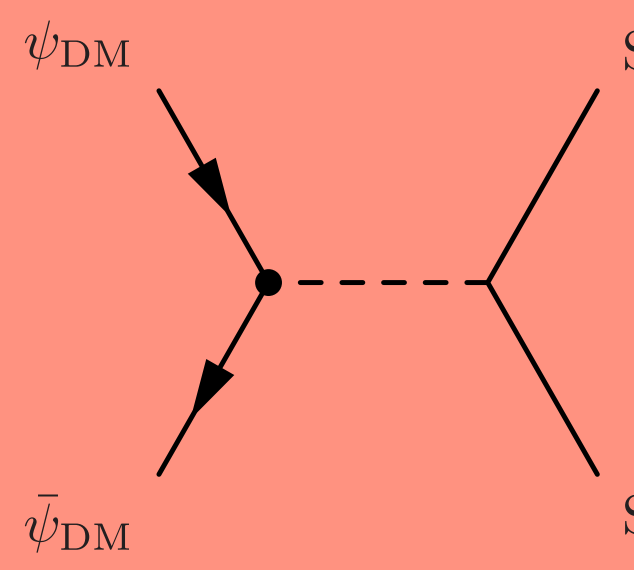
then **we can avoid the constraints from the direct detections while keeping the WIMP scenario**

Suppression of the direct detection



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

Annihilation cross section is not suppressed

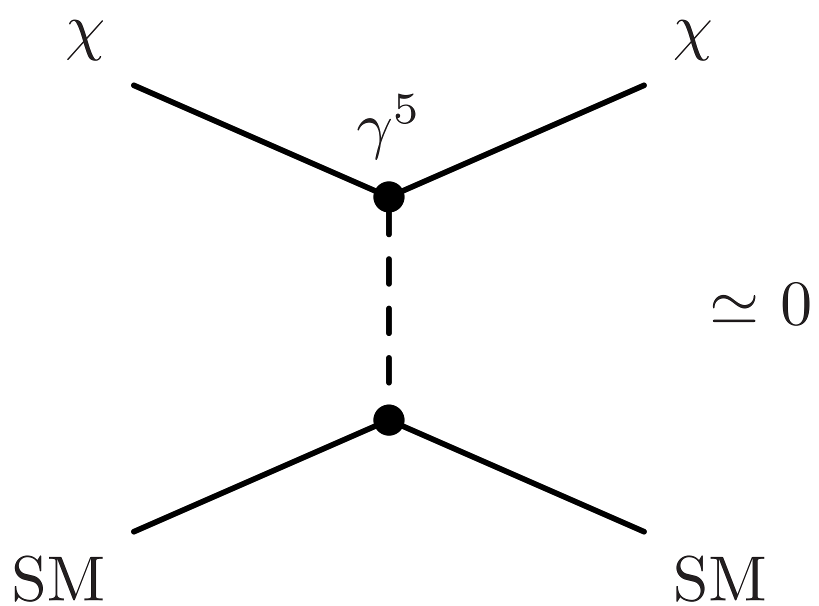


$$\propto \bar{v}(p)\gamma^5 u(p) \simeq m_{\rm DM}$$

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

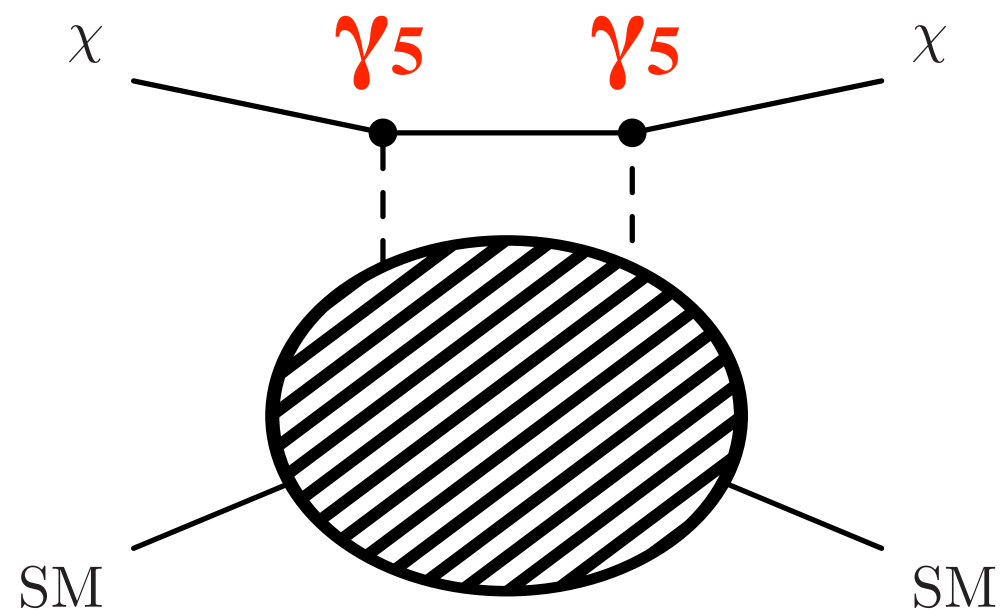
Loop diagrams are essential for σ_{SI}

σ_{SI} =0 at the tree level



$$(\bar{\chi}\gamma^5\chi)\mathcal{O}_{\rm SM}$$

σ_{SI} > 0 at the loop level



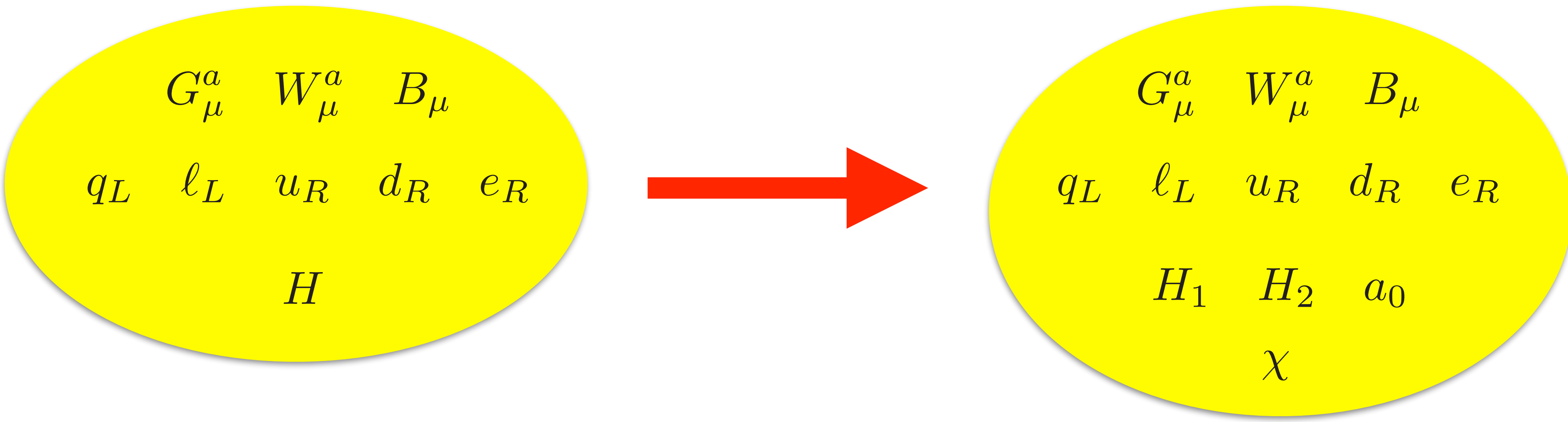
$$(\bar{\chi}\chi)\mathcal{O}_{\rm SM}$$

$(\gamma_5)^2 = 1$

loop correction is essential if models predict σ_{SI} = 0 at the tree level!

a model to realize σ_{SI} = 0 at the tree level (I)

SM | **a model** [Ipek et. al (2014)]



What' new

- H_1 and H_2 (two Higgs doublet)
- a_0 (a gauge singlet CP-odd scalar)
- χ (a gauge singlet Z_2-odd fermion: DM)

- assume CP invariance in the new physics sector

a model to realize σ_{SI} = 0 at the tree level (2)

[Ipek et. al (2014)]

Interaction terms

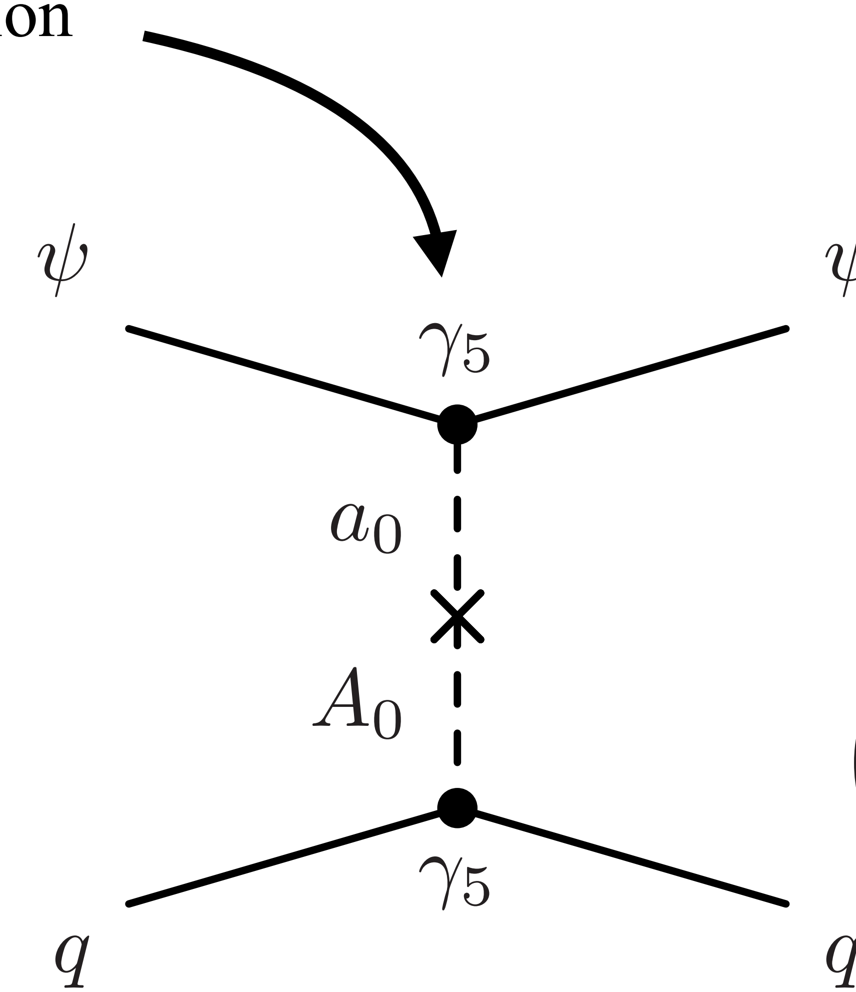
$$\mathcal{L} \supset \quad g_\chi \bar{\psi} i \gamma_5 a_0 \psi + \kappa \left(i a_0 H_1^\dagger H_2 + (h.c.) \right)$$

CP invariant

Note that other cubic terms breaks CP invariance

$$a_0 H_1^\dagger H_1, \ a_0 H_2^\dagger H_2$$

only pseudo-scalar interaction thanks to CP invariance

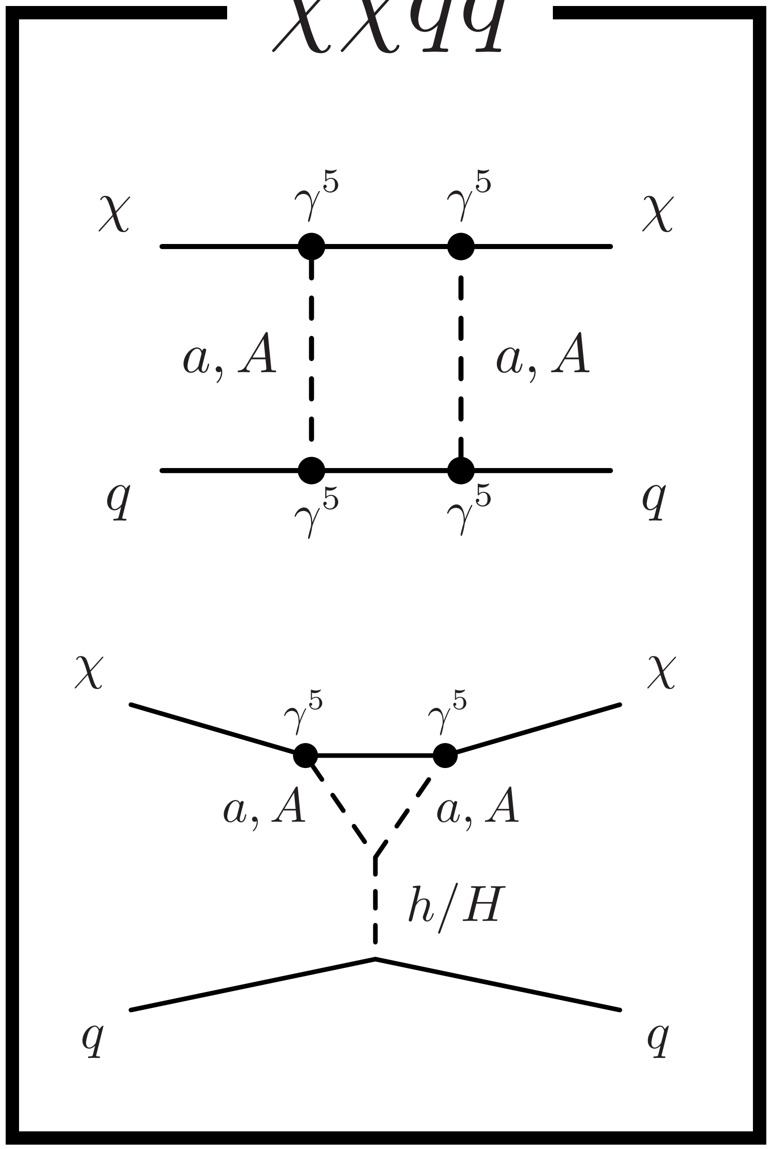


$$\begin{pmatrix} A \\ a \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A^0 \\ a_0 \end{pmatrix}$$

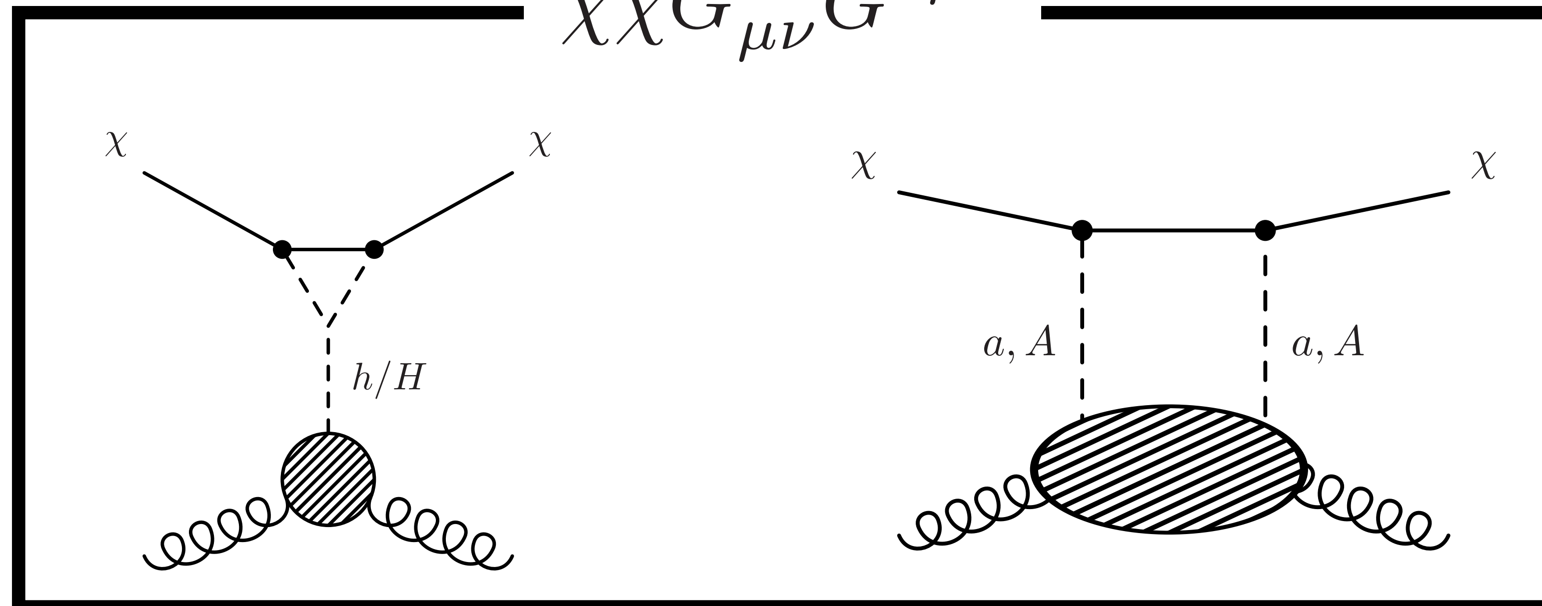
loop calculations were calculated

[Arcadi et. al (2018)]

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



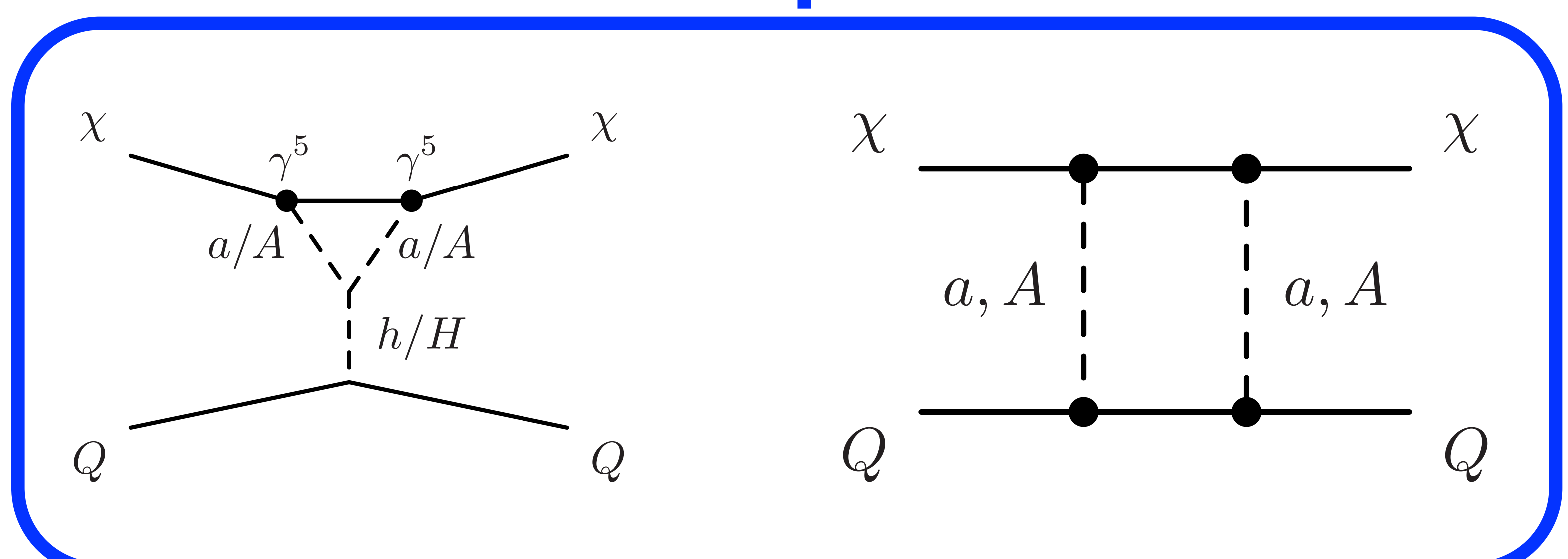
$\bar{\chi}\chi G^a_{\mu\nu} G^{a\mu\nu}$



estimated by using

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

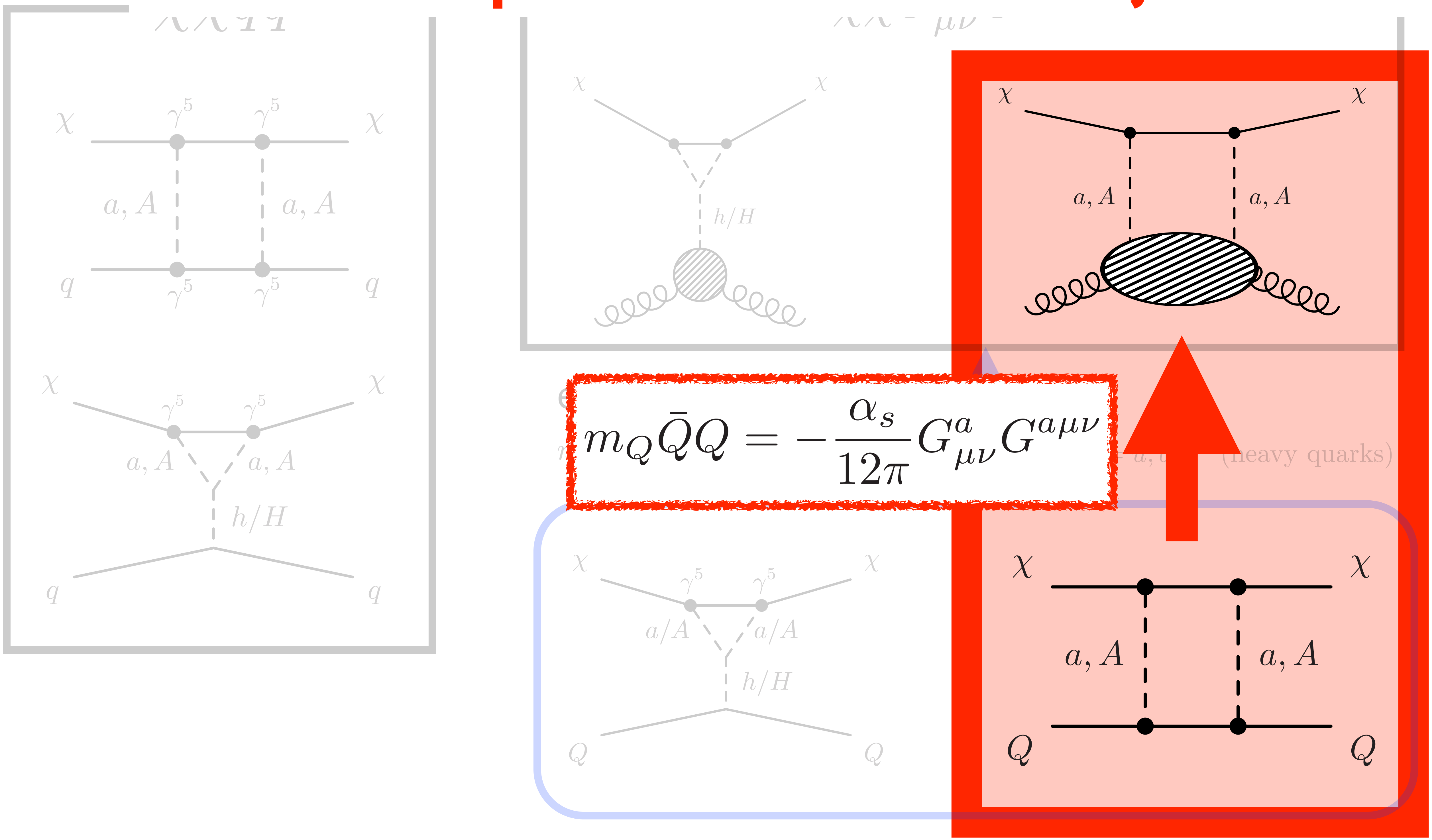
$Q = t, b, c$ (heavy quarks)



loop calculations were calculated

[Arcadi et. al (2018)]

but this replacement is NOT justified!

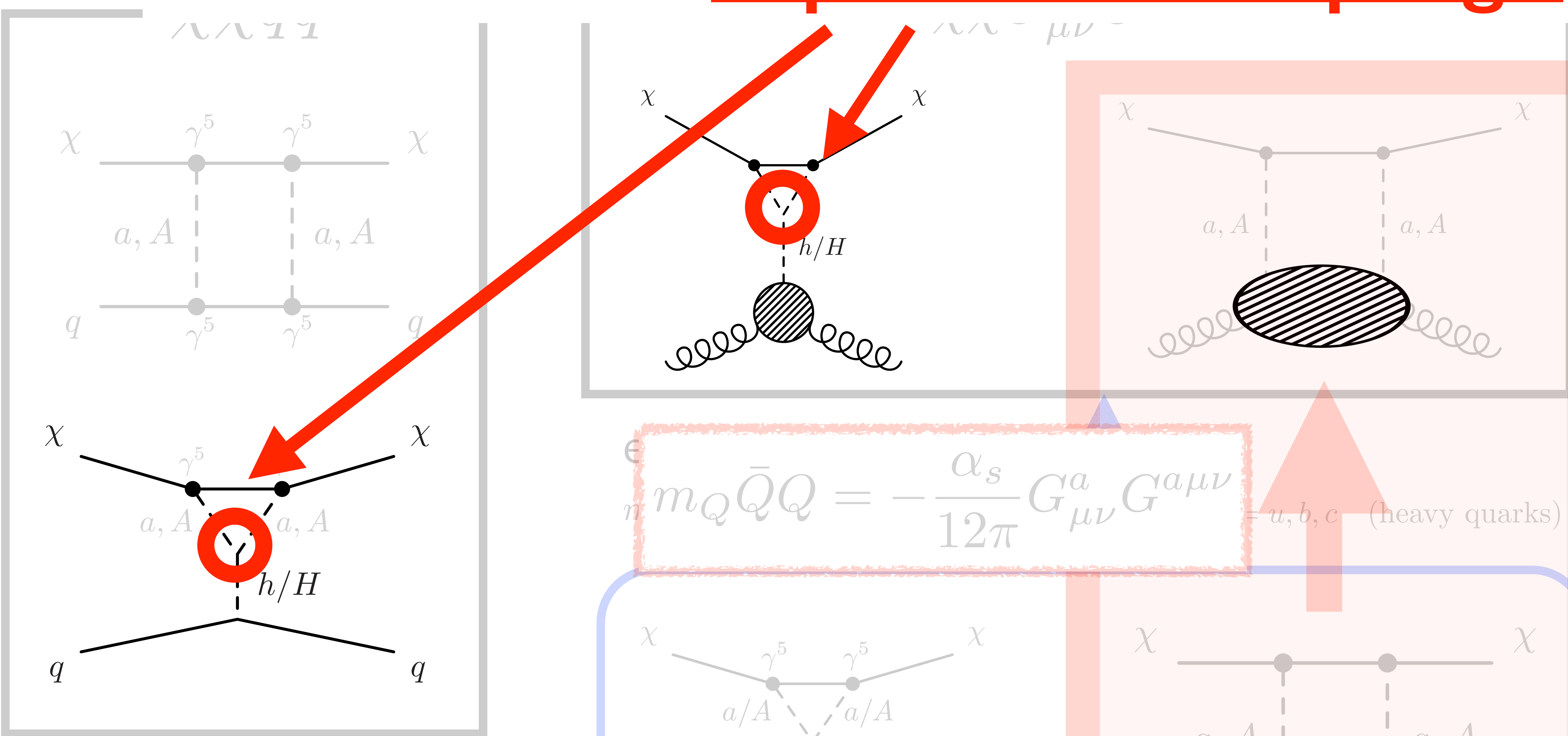


$$m_Q \bar{Q} Q = -\frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\mu\nu}$$

[Arcadi et. al (2018)]

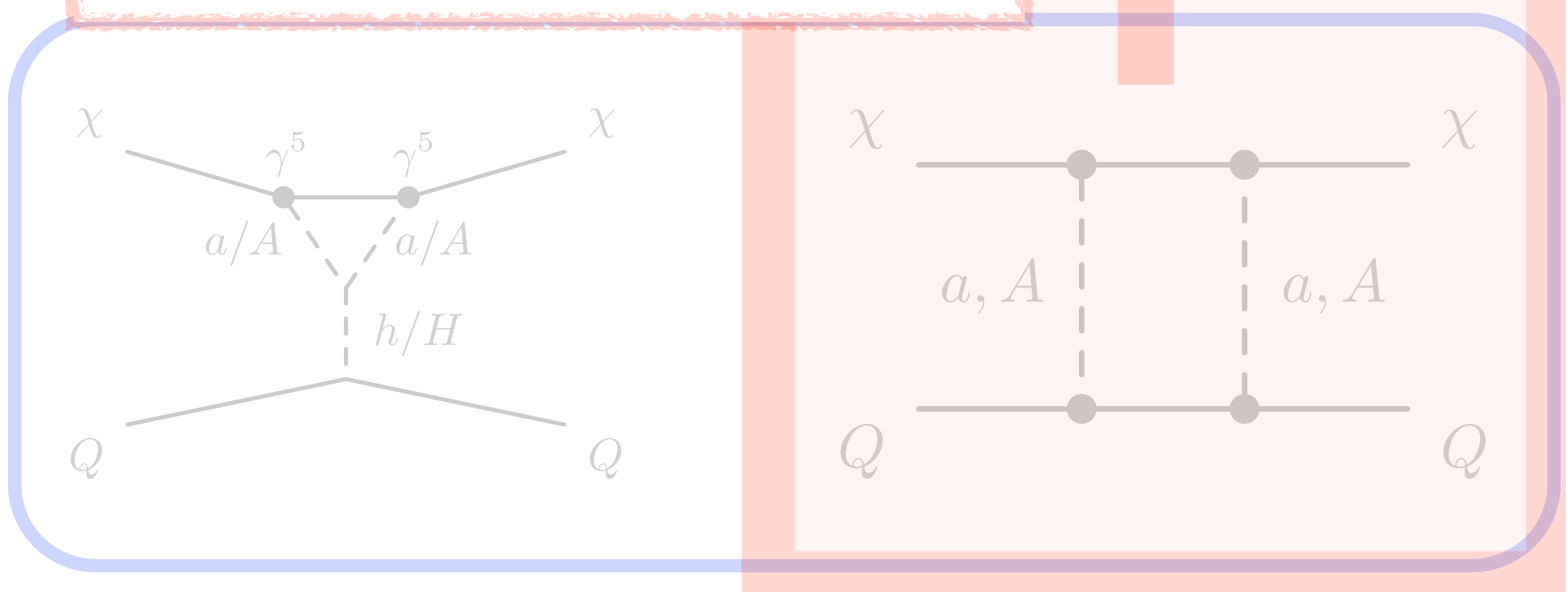
loop calculations were calculated

we revisit the triple-scalar couplings!



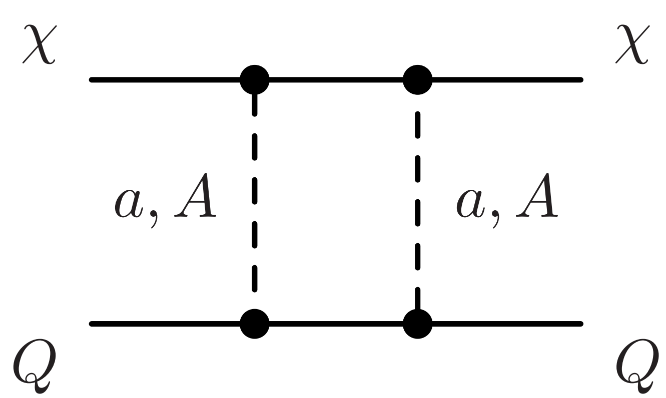
$$m_Q \bar{Q} Q = -\frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\mu\nu}$$

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

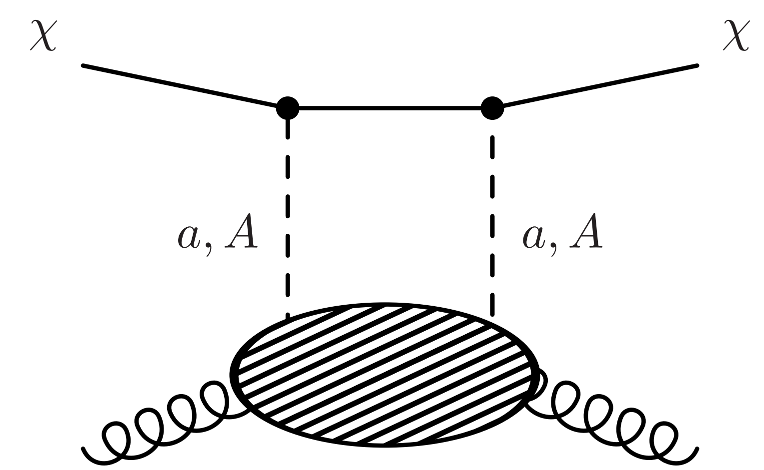


Our work (1) : two-loop calc for box-gluon

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



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



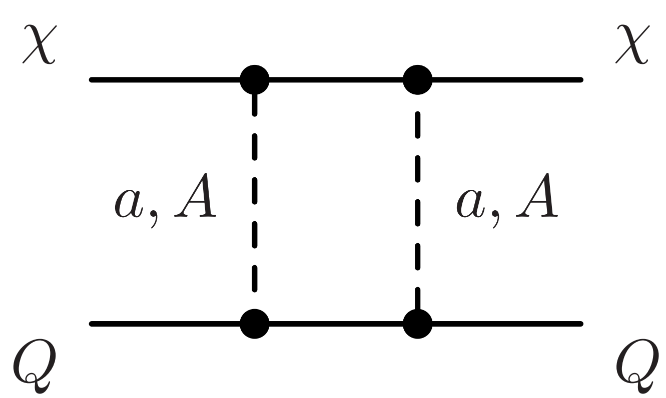
2-loop diagrams should be calculated!

[Arcadi et. al (2018)]

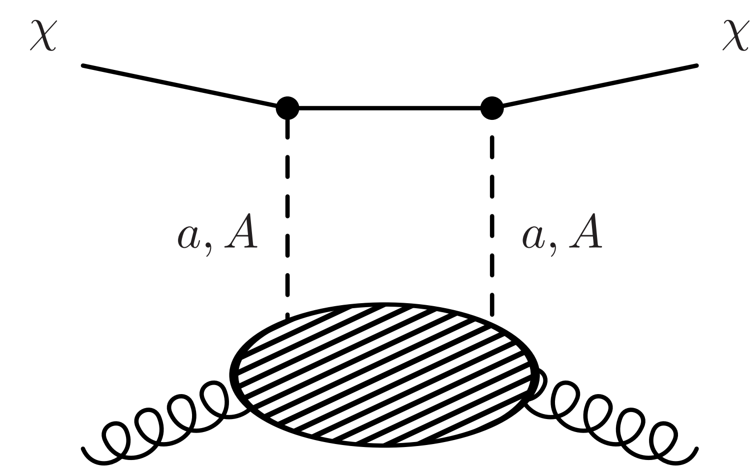
> This procedure is justified if the loop that generates the four-fermion interaction and the loop that relates the quarks to the gluon-condensate factorize. While this assumption is reasonable for heavy new physics which can be integrated out at energies above the top mass, it is not fully appropriate 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.

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

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



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



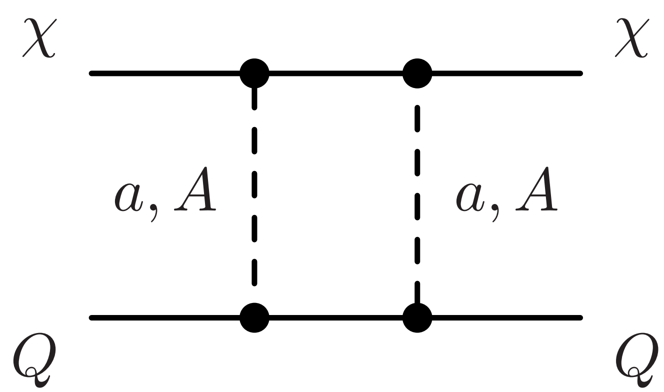
2-loop diagrams should be calculated! [Arcadi et. al (2018)]

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.

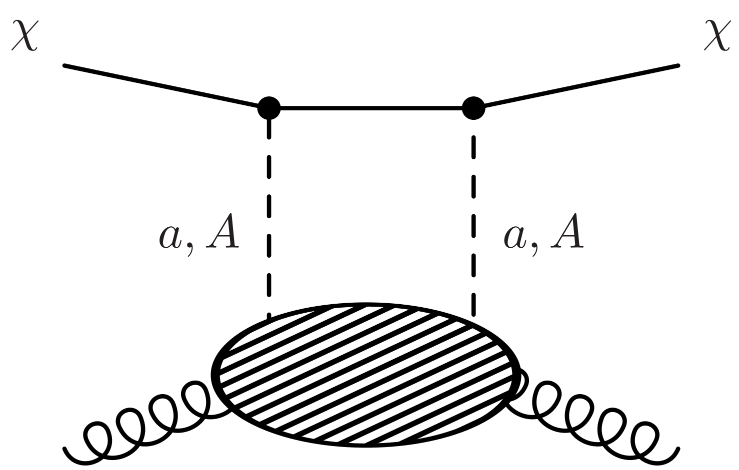
two-loop computation is the scope of our work

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

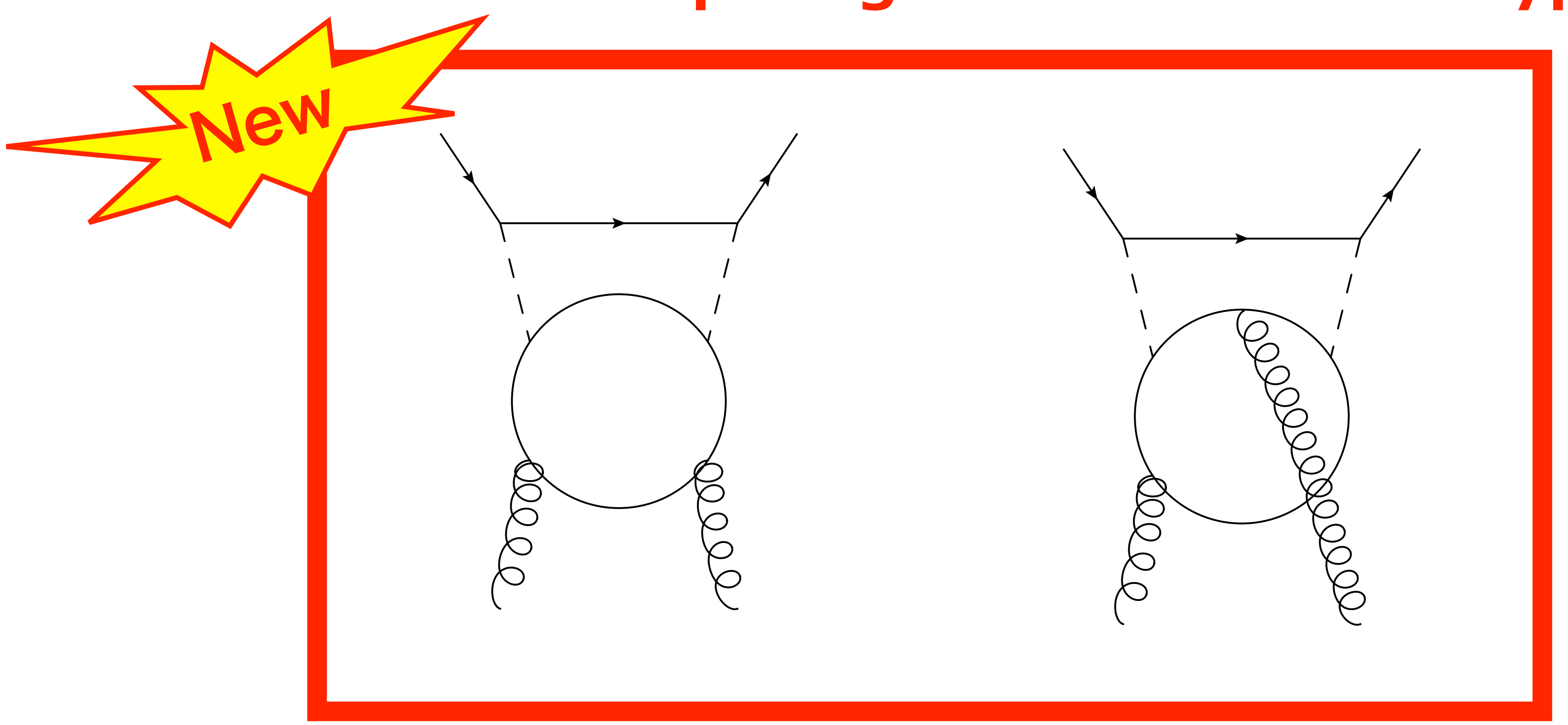
this replacement cannot be justified but used in [Arcadi et. al (2018)]



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

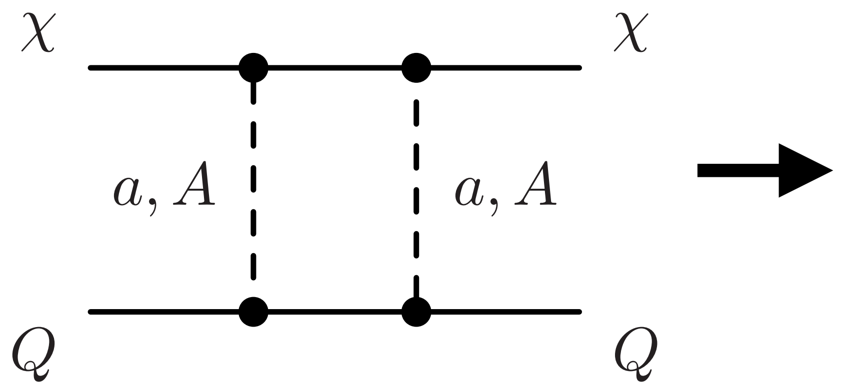


We calculate full two-loop diagrams for the box type diagrams



a reason why it is not justified

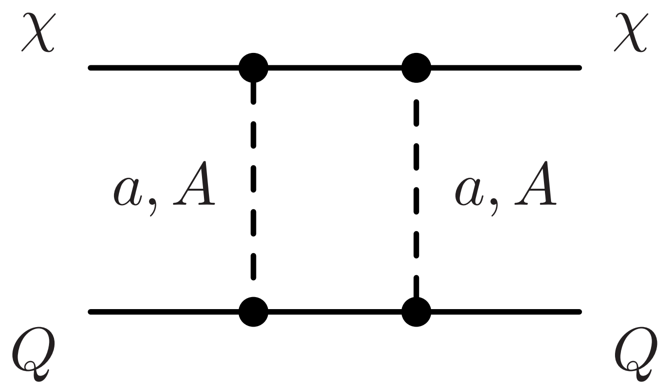
we need to obtain the effective interaction



$$(\bar{\chi}\chi)\left(m_Q\bar{Q}Q\right),\ (\bar{\chi}\partial_\mu\partial_\nu\chi)\left(\bar{Q}D^\mu\gamma^\nu Q\right),\cdots$$

a reason why it is not justified

we need to obtain the effective interaction

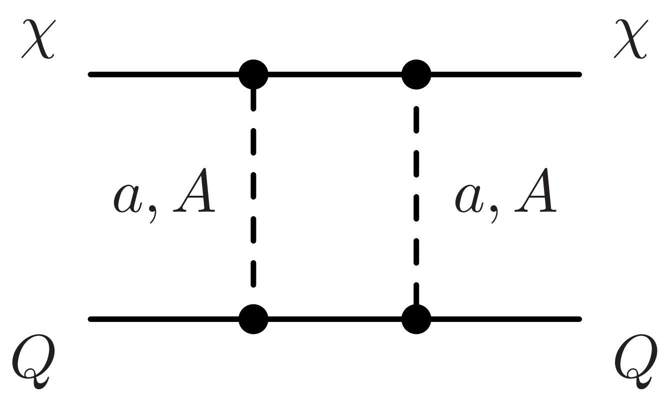


$$\to \quad (\bar{\chi}\chi)\left(m_Q \bar{Q} Q\right),\ (\bar{\chi}\partial_\mu\partial_\nu\chi)\left(\bar{Q} D^\mu \gamma^\nu Q\right),\cdots$$

$$\bar{Q}\frac{i}{2}\left(D^\mu\gamma^\nu + D^\nu\gamma^\mu - g^{\mu\nu}\frac{\not{D}}{2}\right)Q + \bar{Q}\frac{i}{2}\left(D^\mu\gamma^\nu - D^\nu\gamma^\mu\right)Q + \frac{m_Q}{4}g^{\mu\nu}\bar{Q}Q$$

a reason why it is not justified

we need to obtain the effective interaction



$$\rightarrow \quad (\bar{\chi}\chi)\left(m_Q\bar{Q}Q\right),\ (\bar{\chi}\partial_\mu\partial_\nu\chi)\left(\bar{Q}D^\mu\gamma^\nu Q\right),\cdots$$

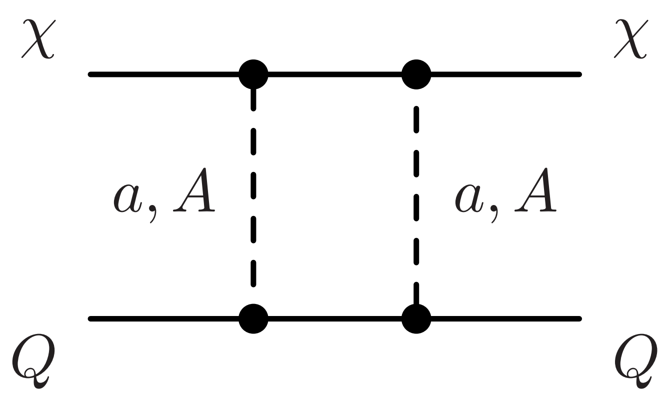
$$\bar{Q}\frac{i}{2}\left(D^\mu\gamma^\nu + D^\nu\gamma^\mu - g^{\mu\nu}\frac{\not{D}}{2}\right)Q + \bar{Q}\frac{i}{2}\left(D^\mu\gamma^\nu - D^\nu\gamma^\mu\right)Q + \frac{m_Q}{4}g^{\mu\nu}\bar{Q}Q$$

$$\supset \overline{u}(p)\frac{\gamma^5(\not{\ell}+\not{p}+m_Q)\gamma^5}{(\ell+p)^2-m_Q^2}u(p)$$

$$= u(\bar{p})\frac{\not{\ell}}{\ell^2+2\ell p}u(p) = u(\bar{p})\frac{\not{\ell}}{\ell^2}\left(1-\frac{2\ell p}{\ell^2}+\cdots\right)u(p)$$

a reason why it is not justified

we need to obtain the effective interaction



$$(\bar{\chi}\chi)\left(m_Q \bar{Q}Q\right), \ (\bar{\chi}\partial_\mu\partial_\nu\chi)\left(\bar{Q}D^\mu\gamma^\nu Q\right), \cdots$$

$$\bar{Q}\frac{i}{2}\left(D^\mu\gamma^\nu + D^\nu\gamma^\mu - g^{\mu\nu}\frac{\not{D}}{2}\right)Q + \bar{Q}\frac{i}{2}\left(D^\mu\gamma^\nu - D^\nu\gamma^\mu\right)Q + \frac{m_Q}{4}g^{\mu\nu}\bar{Q}Q$$

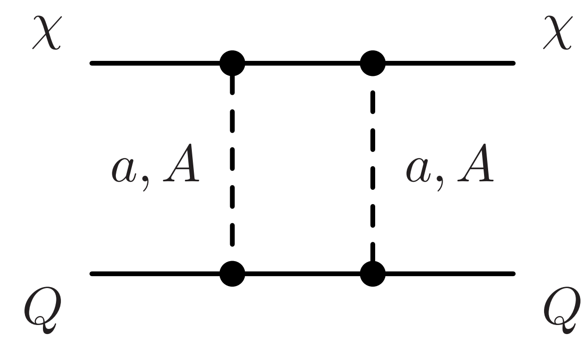
$$\supset \overline{u}(p)\frac{\gamma^5(\not{\ell} + \not{p} + m_Q)\gamma^5}{(\ell + p)^2 - m_Q^2}u(p)$$

$$= \bar{u}(p)\frac{\not{\ell}}{\ell^2 + 2\ell p}u(p) = \bar{u}(p)\frac{\not{\ell}}{\ell^2}\left(1 - \frac{2\ell p}{\ell^2} + \cdots\right)u(p)$$

- this expansion is justified if $p \ll \ell \sim \mathcal{O}(m_a)$ or $\mathcal{O}(m_\chi)$
- $m_t < m_a$ is not always true (m_a = *100* GeV in a benchmark)

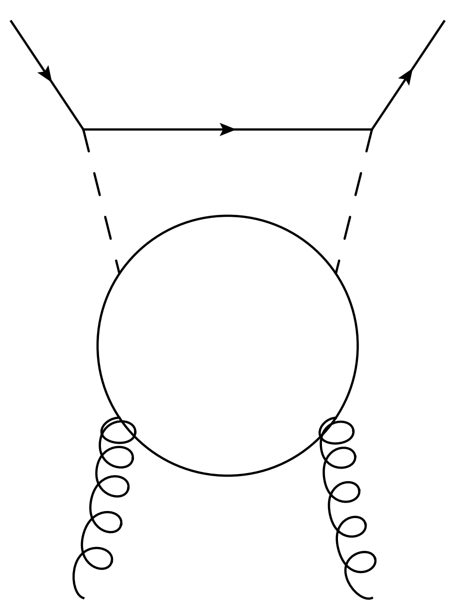
yet another reason why it is not justified

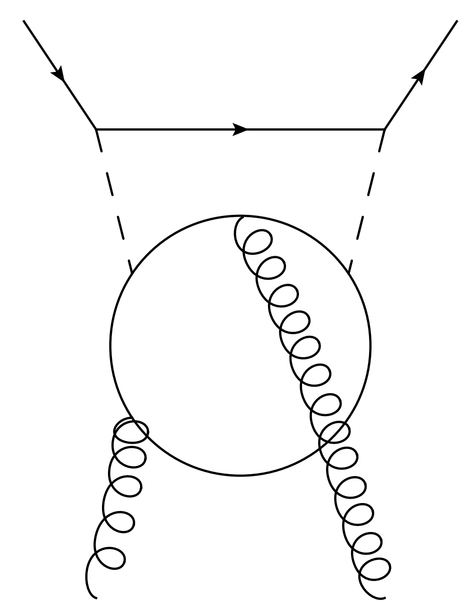
even if $m_Q < m_a$, we miss some two-loop diagrams



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

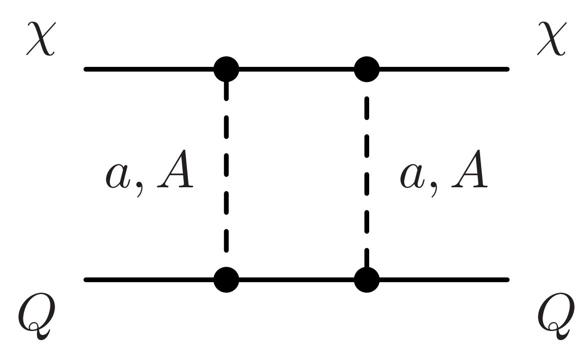
We cannot obtain





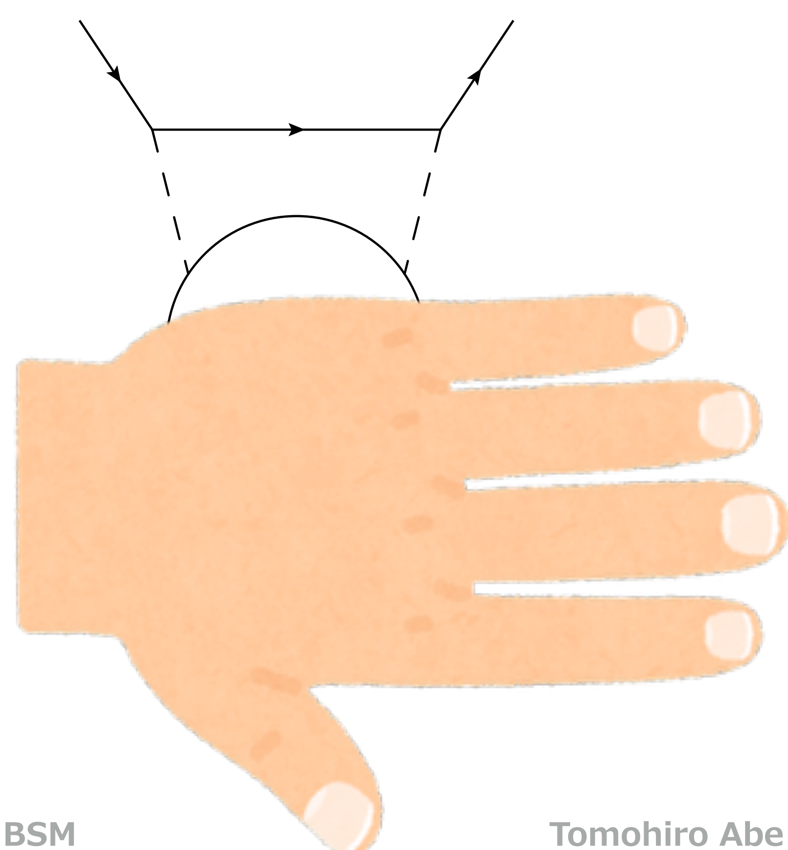
yet another reason why it is not justified

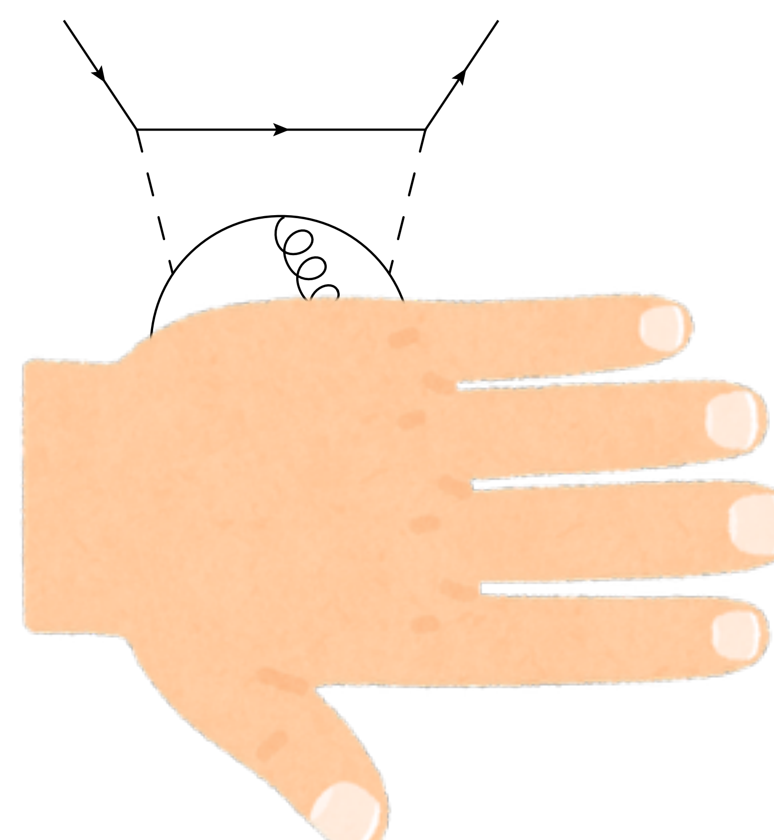
even if $m_Q < m_a$, we miss some two-loop diagrams



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

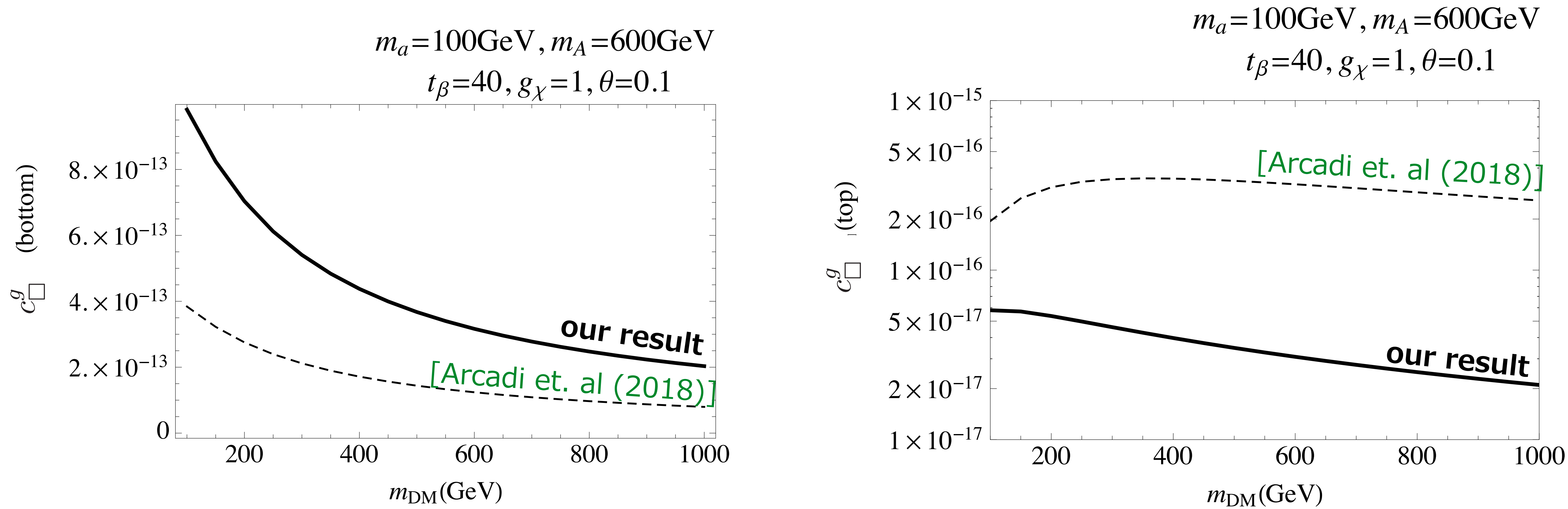
We cannot obtain





Comparison with the previous work

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



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)

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

this term was used in the literatures

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

but they were not used!

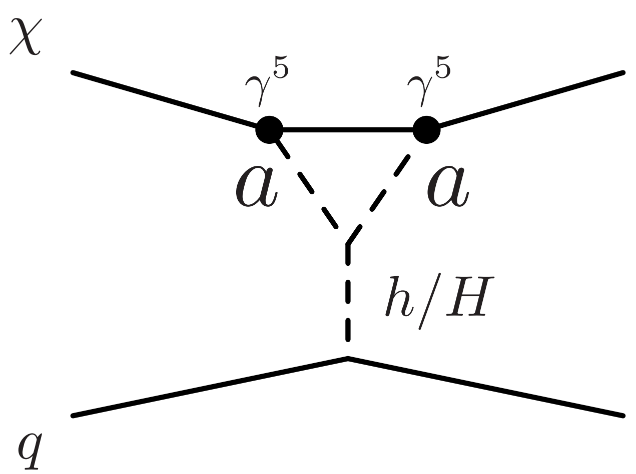
sinθ suppression for the aah coupling
(θ is the mixing angle btw CP-odd states)

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

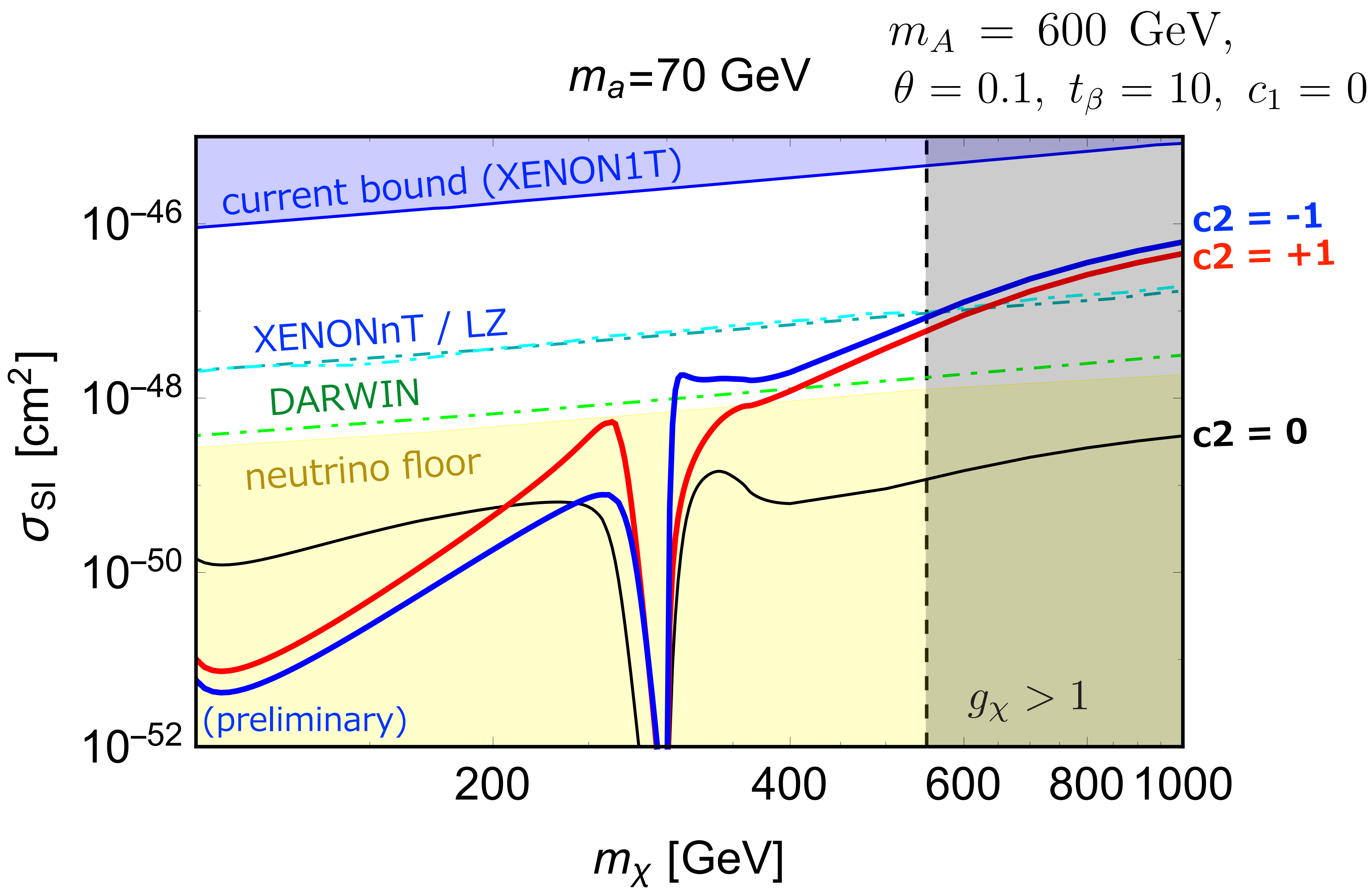
No suppression by sinθ !

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

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 than 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

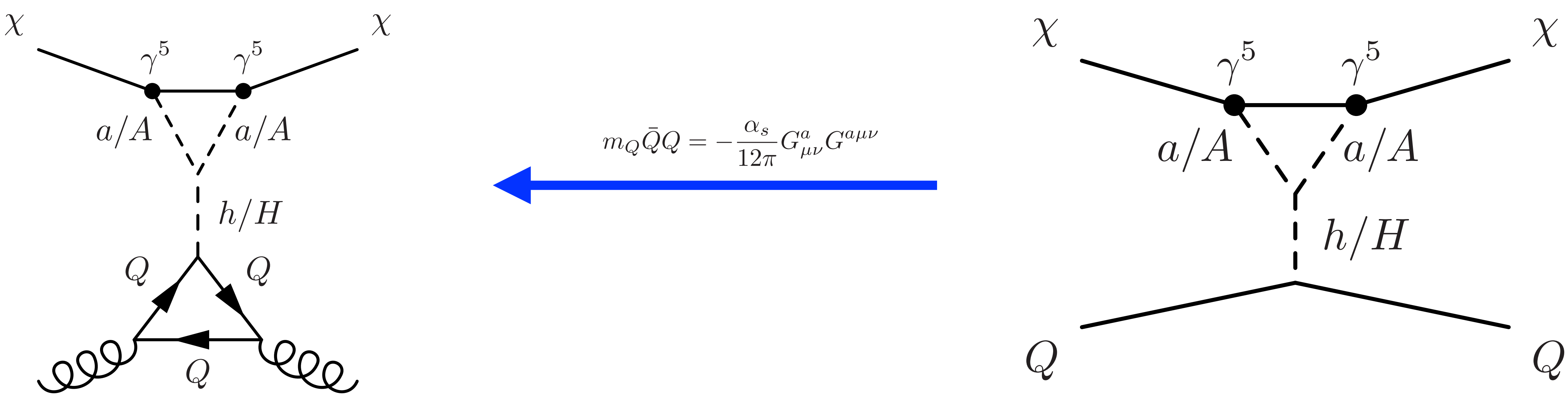
triangle diagrams with gluons

triangle diagram with gluons

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

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

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



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

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

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

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