Formulation of effective theories for the dark matter direct detection

Natsumi Nagata

ACP seminar
09 April, 2014

Based on [J. Hisano, K. Ishiwata, N. N., 1004. 4090, 1007. 2601, and 1210. 5985]
[J. Hisano, K. Ishiwata, N. N., M. Yamanaka, 1012. 5455]
and [J. Hisano, K. Ishiwata, N. N., T. Takesako, 1104. 0228]

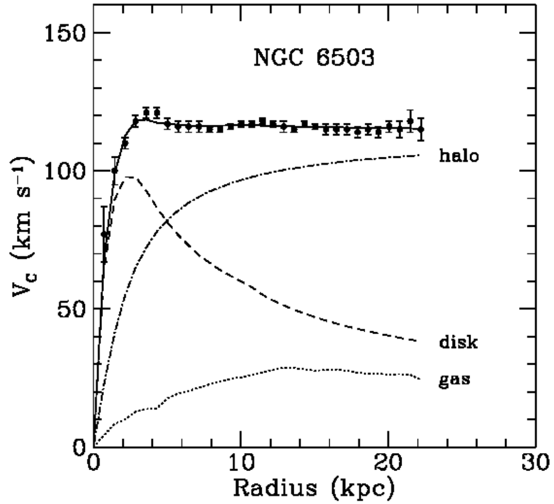
Outline

1. Introduction
2. The method of Effective theory
3. Some results
   a) Pure bino DM
   b) Pure Wino DM (high-scale SUSY scenario)
   c) Minimal DM
   d) KK photon DM in the MUED model
4. Conclusion and discussion

1. Introduction

Introduction — Evidence for dark matter (DM)

Galactic scale

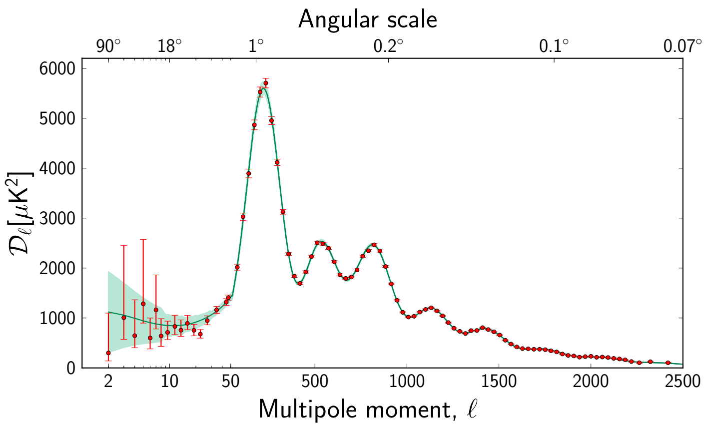


Begeman et. al. (1991)

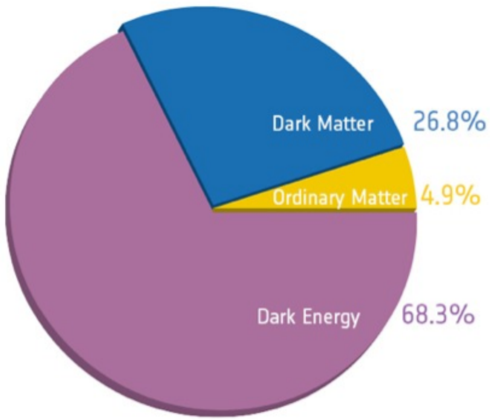
Scale of galaxy clusters

Clowe et. al. (2006)

Cosmological scale



Planck (2013)



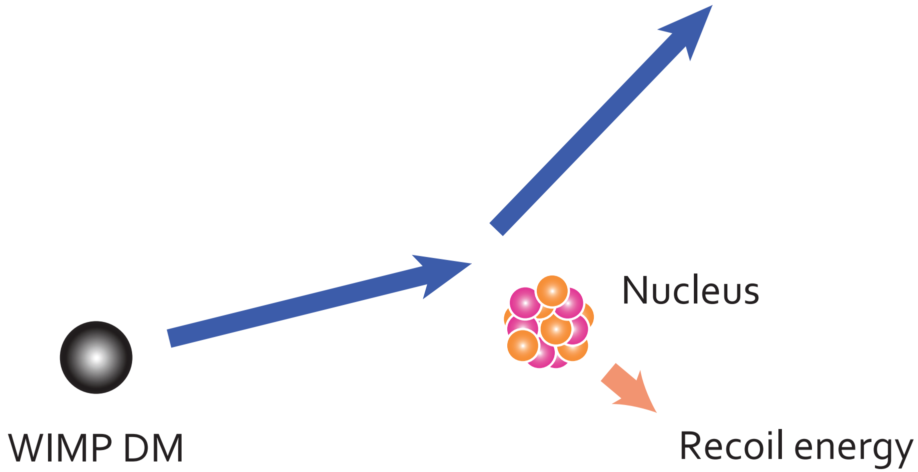
Planck (2013)

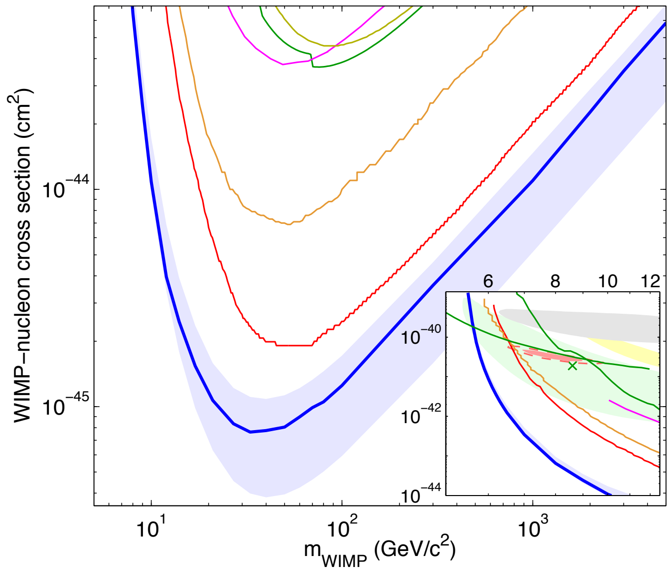
One of the most promising candidates for dark matter is

Weakly Interacting Massive Particles (WIMPs)

- have masses roughly between 10 GeV ~ a few TeV.
- interact only through weak and gravitational interactions.
- Their thermal relic abundance is naturally consistent with the cosmological observations [thermal relic scenario].
- appear in models beyond the Standard Model.

Introduction | Direct detection experiments





[Large Underground Xenon (LUX), arXiv: 1310.8214]

- LUX experiment gives a stringent constraint on spin-independent WIMP-nucleon scattering cross section.

$$\sigma_{\rm SI} < 7.6 \times 10^{-46}\ {\rm cm}^2$$ (for WIMPs of mass 33 GeV)

- Ton-scale detectors for direct detection experiments are expected to yield significantly improved sensitivities.

Motivation

To study the nature of dark matter based on direct detection experiments, the precise calculation of

the WIMP-nucleon scattering cross section

is required.

■ Previous works

- For Majorana DM
  e.g.) M. Drees and M. Nojiri, Phys. Rev. D **48** (1993) 3483.
- For vector DM
  H. C. P. Cheng, J. L. Feng and K. T. Matchev, Phys. Rev. Lett. **89**, 211301 (2002).
  G. Servant and T. M. P. Tait, New J. Phys. **4**, 99 (2002).

➢ In these works, some of the leading contributions (especially those of gluon) to the scattering cross sections are not properly taken into account.

➢ We study the way of evaluating the cross section systematically by using the method of effective field theory

2. The method of effective theory

Method of effective theories

1. By integrating out heavy particles, we obtain the effective interactions of WIMP DM with quarks and gluons.

Operator Product Expansion (OPE)

$$\mathcal{L}_{\rm eff} = \sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

C_i (μ) : Wilson coefficients

include short-distant effects

O_i (μ) : Effective operators

Higer-dimensional operators. Their nucleon matrix elements contain the effects of long-distance.

μ : factorization scale

A scale at which a high-energy theory is matched with the effective theory.

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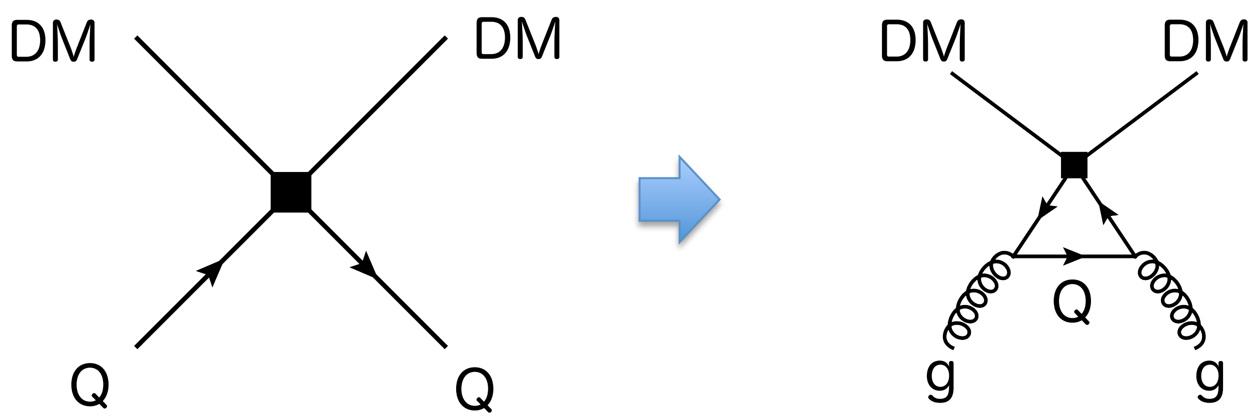
Method of effective theories

2. Evaluate the nucleon matrix elements of the effective operators (at a certain scale).

When evolving the operators down to the scale, we need to match the effective theories above/below each quark threshold.



3. By using the nucleon matrix elements, we evaluate the scattering cross section of DM with a nucleon

Effective Lagrangian for Majorana DM

Spin-independent

$$\mathcal{L}_{\rm eff} = \sum_q C_S^q \mathcal{O}_S^q + C_S^g \mathcal{O}_S^g + \sum_{i=1,2} \sum_q C_{T_i}^q \mathcal{O}_{T_i}^q + \sum_{i=1,2} C_{T_i}^g \mathcal{O}_{T_i}^g \ ,$$

$\tilde{\chi}^0$: Majorana DM

Scalar-type

$$\mathcal{O}_S^q \equiv \frac{1}{2}\overline{\tilde{\chi}^0}\tilde{\chi}^0 m_q \bar{q} q \ ,$$

$$\mathcal{O}_S^g \equiv \frac{1}{2}\overline{\tilde{\chi}^0}\tilde{\chi}^0 G^A_{\mu\nu} G^{A\mu\nu} \ ,$$

Twist-2 type

$$\mathcal{O}_{T_1}^q \equiv \frac{1}{2}\overline{\tilde{\chi}^0} i\partial^\mu \gamma^\nu \tilde{\chi}^0 \mathcal{O}_{\mu\nu}^q \ ,$$

$$\mathcal{O}_{T_2}^q \equiv \frac{1}{2}\overline{\tilde{\chi}^0} i\partial^\mu i\partial^\nu \tilde{\chi}^0 \mathcal{O}_{\mu\nu}^q \ ,$$

$$\mathcal{O}_{T_1}^g \equiv \frac{1}{2}\overline{\tilde{\chi}^0} i\partial^\mu \gamma^\nu \tilde{\chi}^0 \mathcal{O}_{\mu\nu}^g \ ,$$

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Twist-2 operator

$$\mathcal{O}_{\mu\nu}^q \equiv \frac{1}{2}\bar{q} i \left(D_\mu \gamma_\nu + D_\nu \gamma_\mu - \frac{1}{2} g_{\mu\nu} \not{D}\right) q$$

$$\mathcal{O}_{\mu\nu}^g \equiv G_\mu^{a\rho} G_{\rho\nu}^a + \frac{1}{4} g_{\mu\nu} G^a_{\alpha\beta} G^{a\alpha\beta}$$

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Induces coupling of DM with "mass of nucleon"

Twist-2 type

$$\mathcal{O}_{T_1}^q \equiv \frac{1}{2}\overline{\tilde{\chi}^0} i\partial^\mu \gamma^\nu \tilde{\chi}^0 \mathcal{O}_{\mu\nu}^q \ ,$$

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$$\mathcal{O}_S^g \equiv \frac{1}{2}\overline{\tilde{\chi}^0}\tilde{\chi}^0 G_{\mu\nu}^A G^{A\mu\nu} \ ,$$

Induces coupling of DM with "quark and gluon momenta"

Twist-2 type

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Twist-2 operator

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$$\mathcal{O}_{\mu\nu}^g \equiv G_\mu^{a\rho} G_{\rho\nu}^a + \frac{1}{4} g_{\mu\nu} G_{\alpha\beta}^a G^{a\alpha\beta}$$

Nucleon matrix elements | Quark (scalar-type)

Nucleon matrix elements of scalar-type quark operators are evaluated by using the QCD lattice simulations.

mass fractions

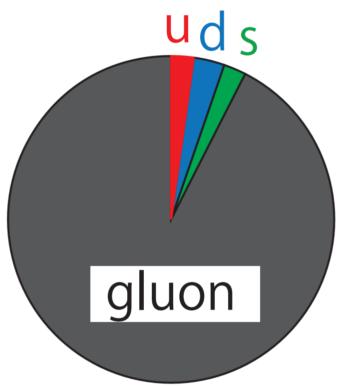
$$\langle N|m_q\bar{q}q|N\rangle/m_N \equiv f_{T_q}$$ (m_N : Nucleon mass)

For proton	
f_{Tu}	0.023
f_{Td}	0.034
f_{Ts}	0.025
For neutron	
f_{Tu}	0.019
f_{Td}	0.041
f_{Ts}	0.025

H. Ohki et al. (2008)

Gluon contribution

$$1 - \sum_{q=u,d,s} f_{Tq} \equiv f_{TG}$$



Mass fractions for proton

Remarks.

Strange quark content is much smaller than those evaluated with the chiral perturbation theory.

Nucleon matrix elements — Gluon (scalar-type)

Nucleon matrix element of scalar-type gluon operator is evaluated by using the trace anomaly of the energy-momentum tensor.

- Trace anomaly of the energy-momentum tensor in QCD (N_f = 3)

$$\Theta^{\mu}_{\mu} = \frac{\beta(\alpha_s)}{4\alpha_s} G^{A}_{\mu\nu} G^{A\mu\nu} + (1-\gamma_m) \sum_q m_q \bar{q} q$$

$\Theta^{\mu}_{\mu} \rightarrow m_N$

$$\left(\begin{array}{l} \beta(\alpha_s) = -\frac{9\alpha_s^2}{2\pi} \\ (\text{for} \quad N_F = 3) \end{array} \right)$$

$\sum_q m_q \bar{q} q \rightarrow \left(\sum_{q=u,d,s} m_N f_{Tq} \right)$

$$\Rightarrow \quad \boxed{\langle N | \alpha_s G^{A}_{\mu\nu} G^{A\mu\nu} | N \rangle = -\frac{8\pi}{9} m_N f_{TG}}$$

M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, Phys. Lett. B **78** (1978) 443.

Nucleon matrix elements | Twist-2 operators

Nucleon matrix elements of twist-2 operators are evaluated by using the parton distribution functions (PDFs).

$$\langle N(p)|\mathcal{O}^q_{\mu\nu}|N(p)\rangle = \frac{1}{m_N}(p_\mu p_\nu - \frac{1}{4}m_N^2\eta_{\mu\nu})(q(2)+\bar{q}(2))$$
$$\langle N(p)|\mathcal{O}^g_{\mu\nu}|N(p)\rangle = \frac{1}{m_N}(p_\mu p_\nu - \frac{1}{4}m_N^2\eta_{\mu\nu})\ G(2)$$

Here, q(2) and G(2) are called the second moments of PDFs, which are defined by

$$q(2)+\bar{q}(2) = \int_0^1 dx\ x\ [q(x)+\bar{q}(x)]$$
$$G(2) = \int_0^1 dx\ x\ g(x)$$

Second moment at $\mu = m_Z$			
$G(2)$	0.48		
$u(2)$	0.22	$\bar{u}(2)$	0.034
$d(2)$	0.11	$\bar{d}(2)$	0.036
$s(2)$	0.026	$\bar{s}(2)$	0.026
$c(2)$	0.019	$\bar{c}(2)$	0.019
$b(2)$	0.012	$\bar{b}(2)$	0.012

J. Pumplin et al., JHEP 0207:012

Effective coupling of Majorana DM with nucleon

The SI coupling of Majorana DM with nucleon is given as

$$\mathcal{L}_{\rm eff} = \frac{1}{2} f_N \overline{\widetilde{\chi}^0} \widetilde{\chi}^0 \overline{N} N$$

$$f_N/m_N = \sum_{q=u,d,s} C_S^q f_{T_q} + \frac{3}{4} \sum_{i=1,2} \sum_{q=u,d,s,c,b} C_{T_i}^q (q(2) + \overline{q}(2)) - \frac{8\pi}{9\alpha_s} C_s^g f_{TG} + \frac{3}{4} \sum_{i=1,2} C_{T_i}^g G(2)$$

The gluon contribution turns out to be comparable to the quark contributions even if it is induced by higher loop diagrams.

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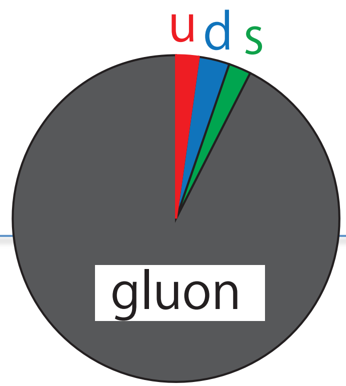

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suppressed by α_s

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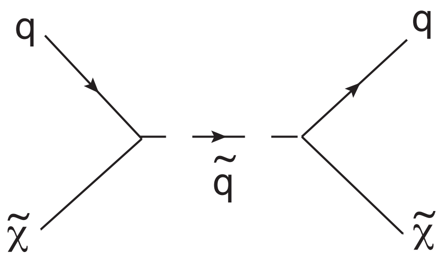
3. Some results

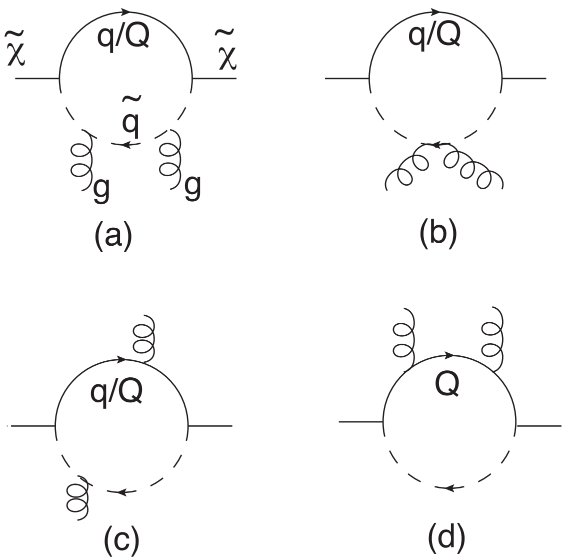
a) Pure bino DM

Pure Bino DM

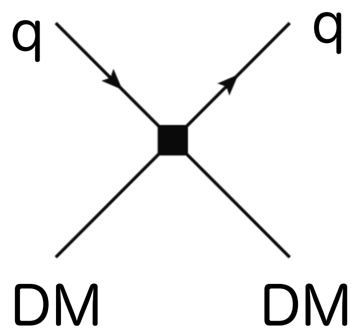
The tree-level diagram:



1-loop diagrams:



Matching

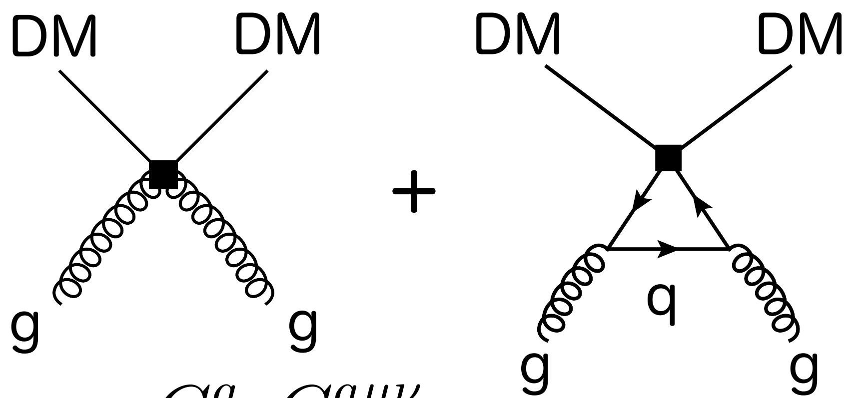


Scalar

$\propto \bar{q}q$

twist-2

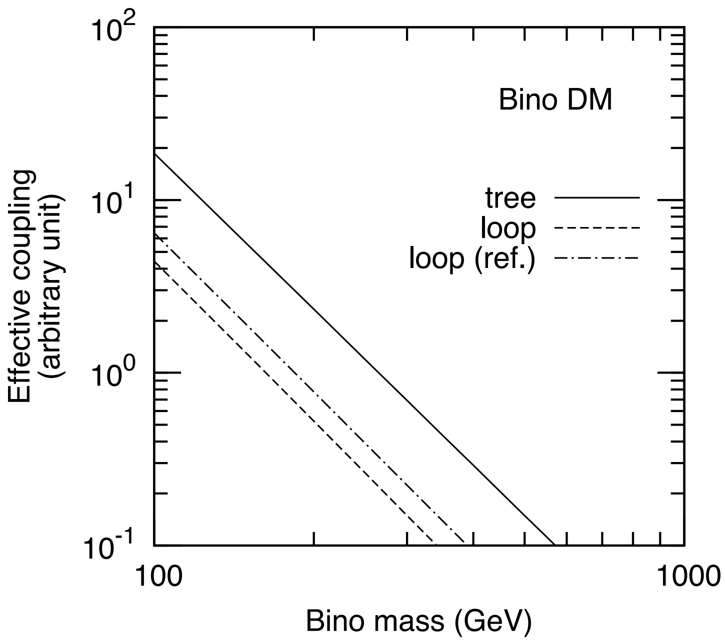
$\propto \mathcal{O}^q_{\mu\nu}$



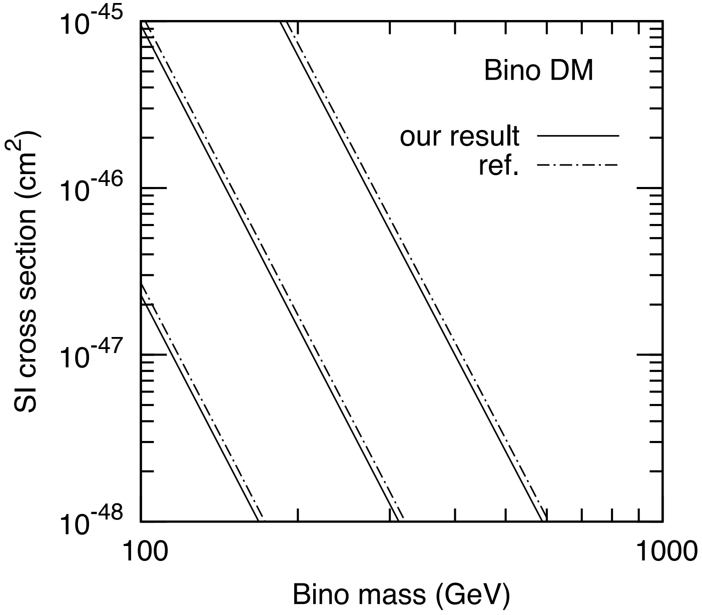
$\propto G^a_{\mu\nu}G^{a\mu\nu}$

Only the short-distance contribution should be included into the Wilson coefficients.

Pure Bino DM



Each contribution to effective coupling f_p



Bino DM-proton SI cross sections

ref.) M. Drees and M. Nojiri, Phys. Rev. **D48** (1993) 3483.

We found O(10)% alternations in the SI cross sections

Due to a lack of matching in the previous calculation…

J. Hisano, K. Ishiwata, and N. Nagata, Phys. Rev. **D82** (2010) 115007.

3. Some results

b) Wino DM (high-scale SUSY)
c) Minimal DM

Mass spectrum

On the assumption of a generic Kahler potential and no singlet field in the SUSY breaking sector

Scalar Particles　　Gravitino　　Higgsinos

Higgsinos can be light

(additional symmetries)

Gauginos　(Loop suppressed)

Gluino

Bino

Wino

Anomaly mediation

L. Randall and R. Sundrum (1998)

G.F. Giudice, M.A. Luty, H. Murayama, R. Rattazzi (1998)

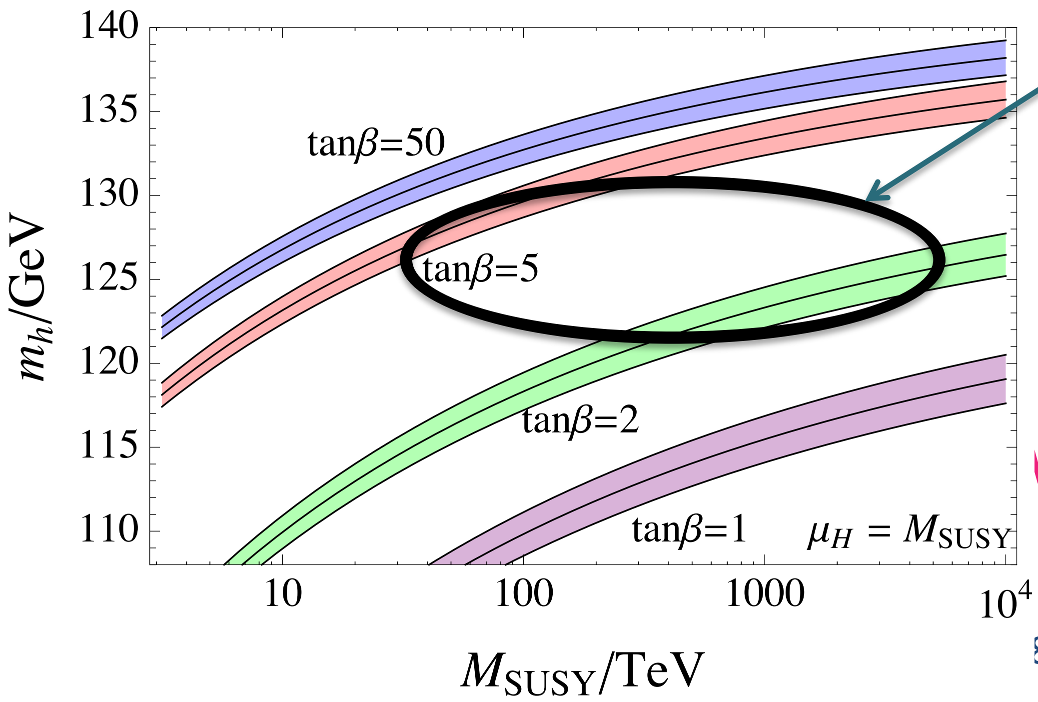
Mass spectrum

On the assumption of a generic Kahler potential and no singlet field in the SUSY breaking sector

Scalar Particles Gravitino Higgsinos

$M_S = 10^{(2\text{-}3)}$ TeV

126 GeV Higgs boson



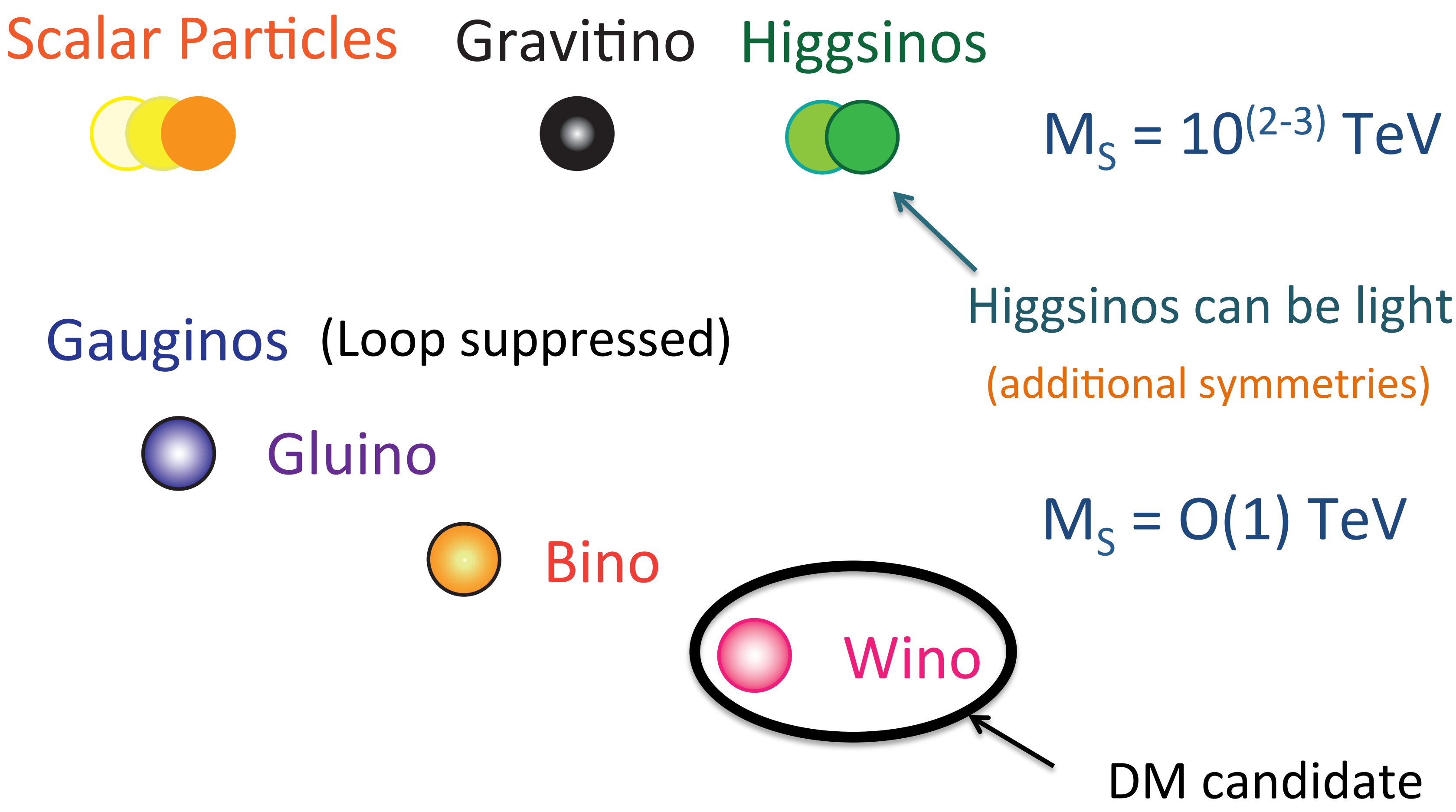
Vino

M. Ibe, T.T. Yanagida (2012).

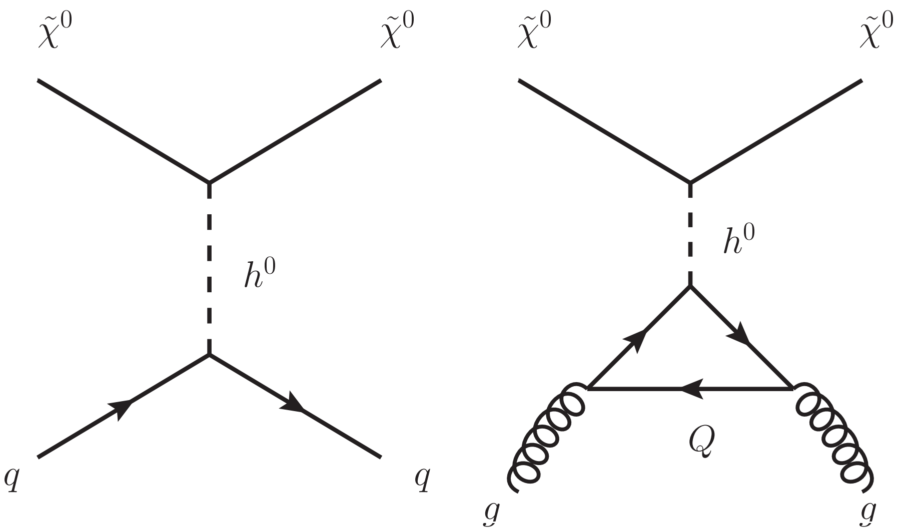
3)

Mass spectrum

On the assumption of a generic Kahler potential and no singlet field in the SUSY breaking sector



Diagrams Tree-level



``Higgs" contribution

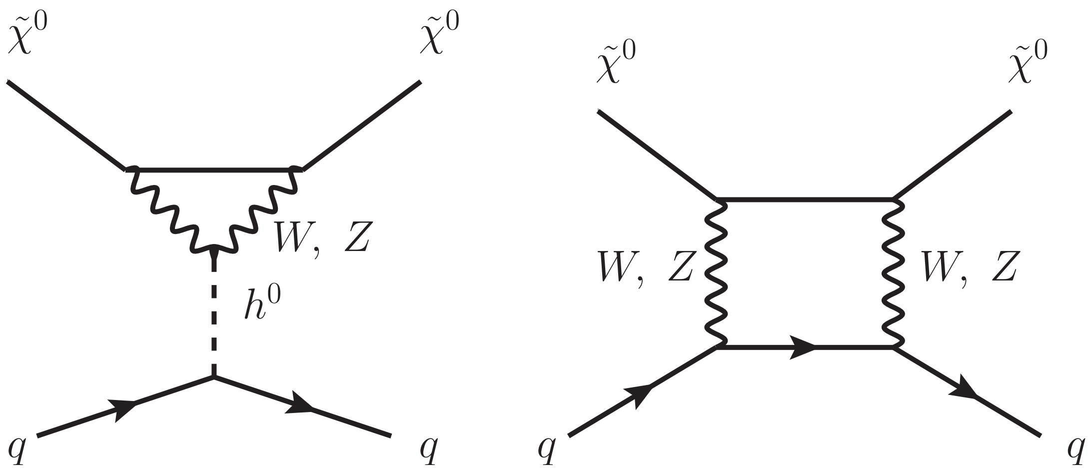
<u>Effective coupling</u>

$$C_q^H = \frac{g_2^2}{2m_W m_h^2}(Z_{12} - Z_{11}\tan\theta_W)(Z_{13}\cos\beta - Z_{14}\sin\beta)$$

(Z_{ij}: Neutralino mixing matrix)

$$\Rightarrow \quad C_q^H \simeq \frac{g_2^2(M_2 + \mu\sin 2\beta)}{2m_h^2(M_2^2 - \mu^2)} \qquad (|\mu \pm M_2| \gg m_Z)$$

Diagrams 1-loop



``Scalar"

$\propto \bar{q}q$

``twist-2"

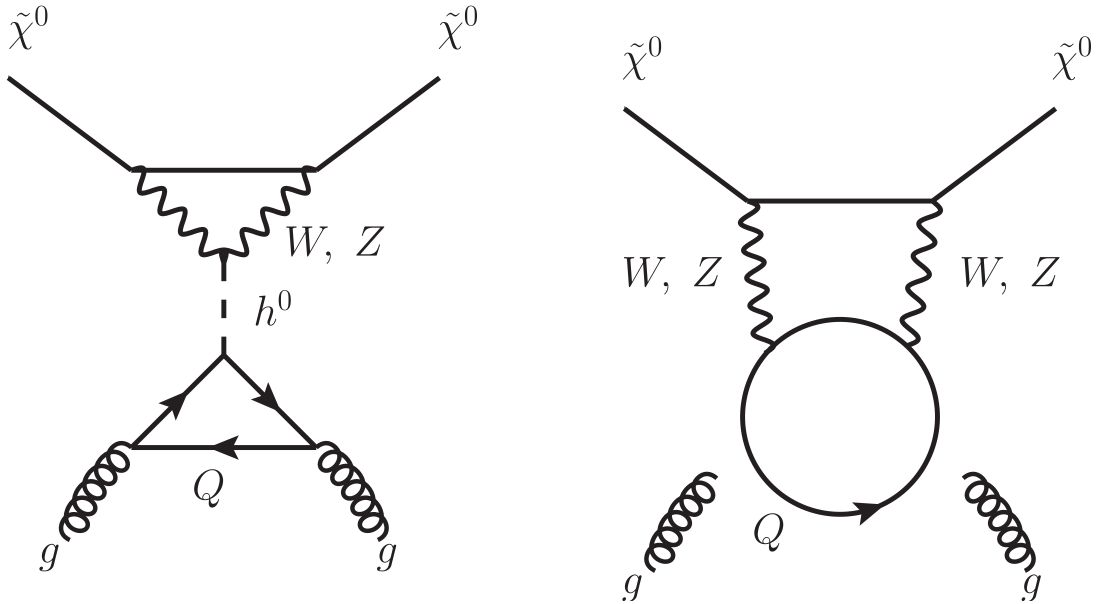
$\propto \mathcal{O}^q_{\mu\nu}$

These interactions are not suppressed even if the DM mass is much larger than the W boson mass.

Non-decoupling effects

J. Hisano, S. Matsumoto, M. Nojiri, O. Saito, Phys. Rev. D **71** (2005) 015007.

Diagrams 2-loop



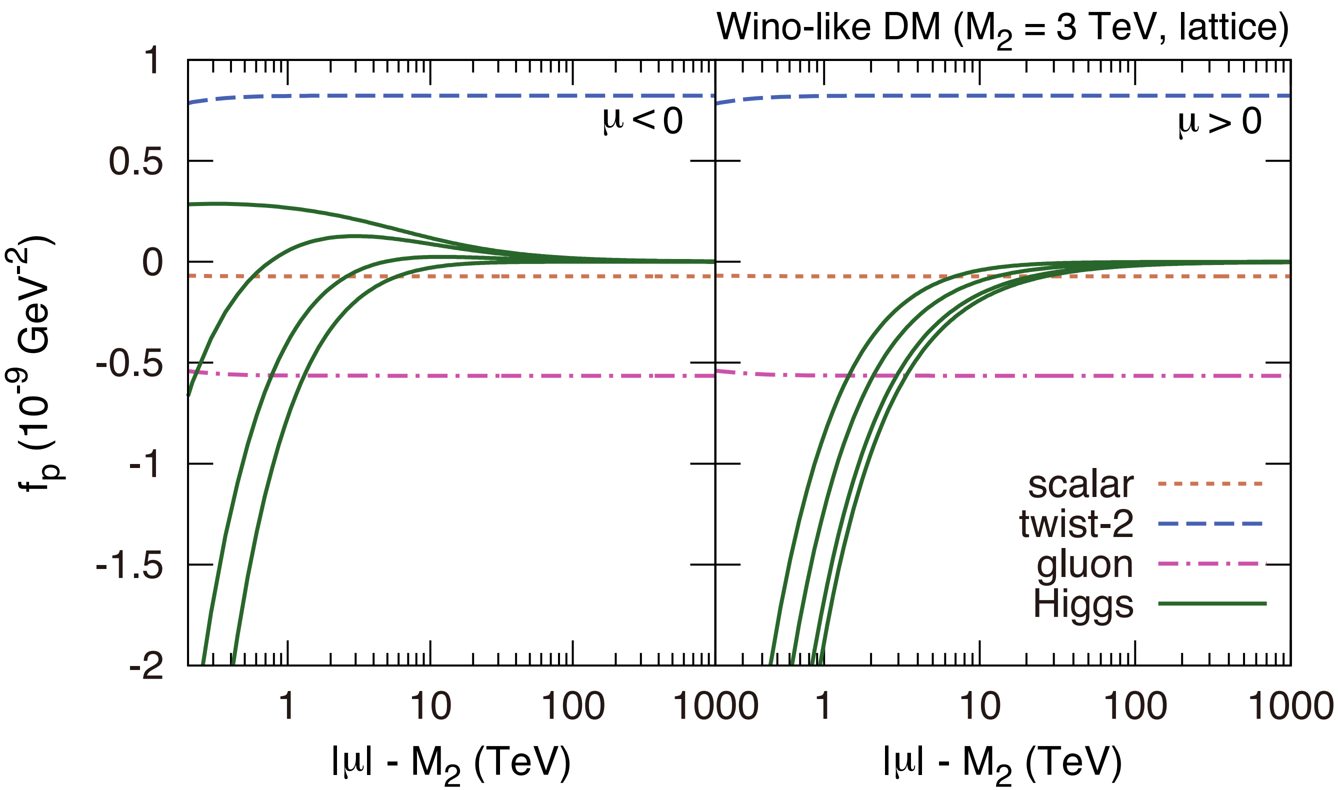
Gluon contribution

$$\propto G^a_{\mu\nu} G^{a\mu\nu}$$

- Neglected in previous calculations
- 2-loop gluon contribution can be comparable to 1-loop quark contribution
- non-decoupling

J. Hisano, K. Ishiwata, and N. Nagata, Phys. Lett. B **690** (2010) 311.

Wino-like DM | Effective coupling with a proton



$\tan\beta$ = 1, 2, 5, 50

(from top to bottom)

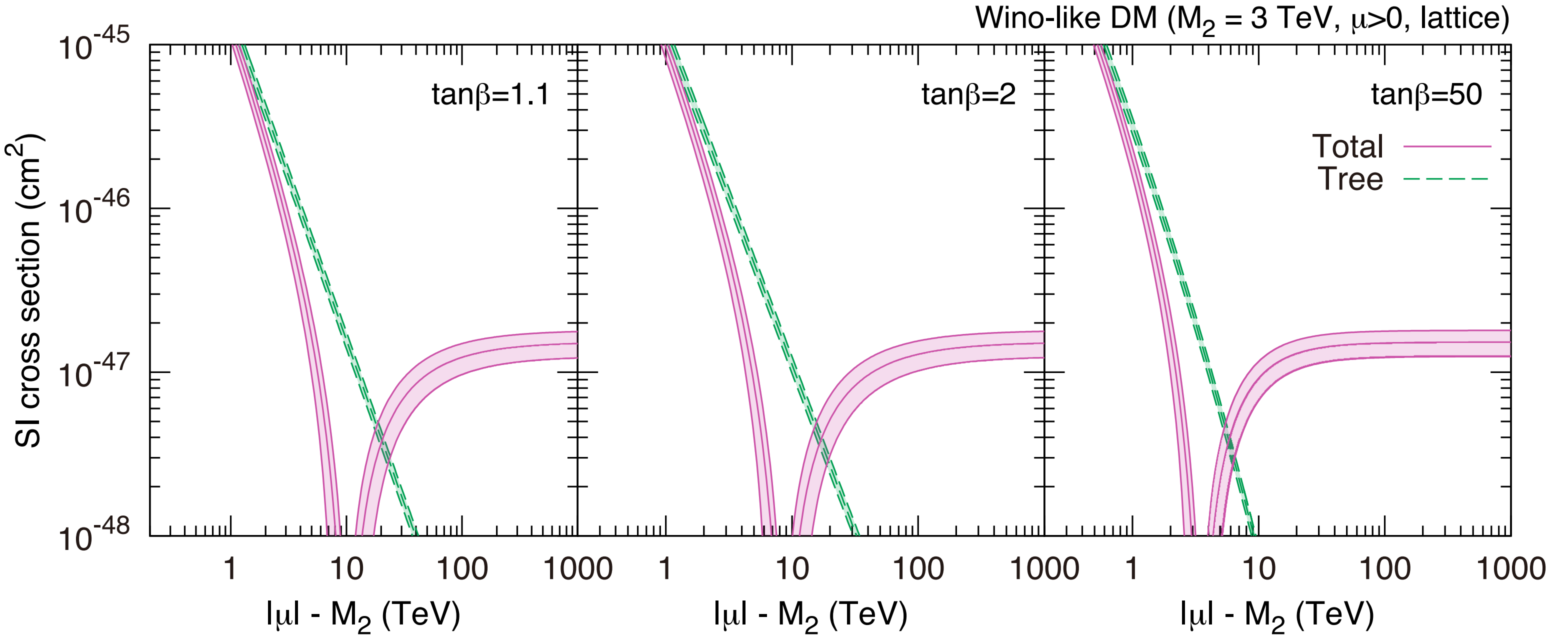
$\tan\beta$ = 1, 2, 5, 50

(from bottom to top)

There is a cancellation among these contributions

J. Hisano, K. Ishiwata, and N. Nagata, Phys. Rev. **D87** (2013) 035020.

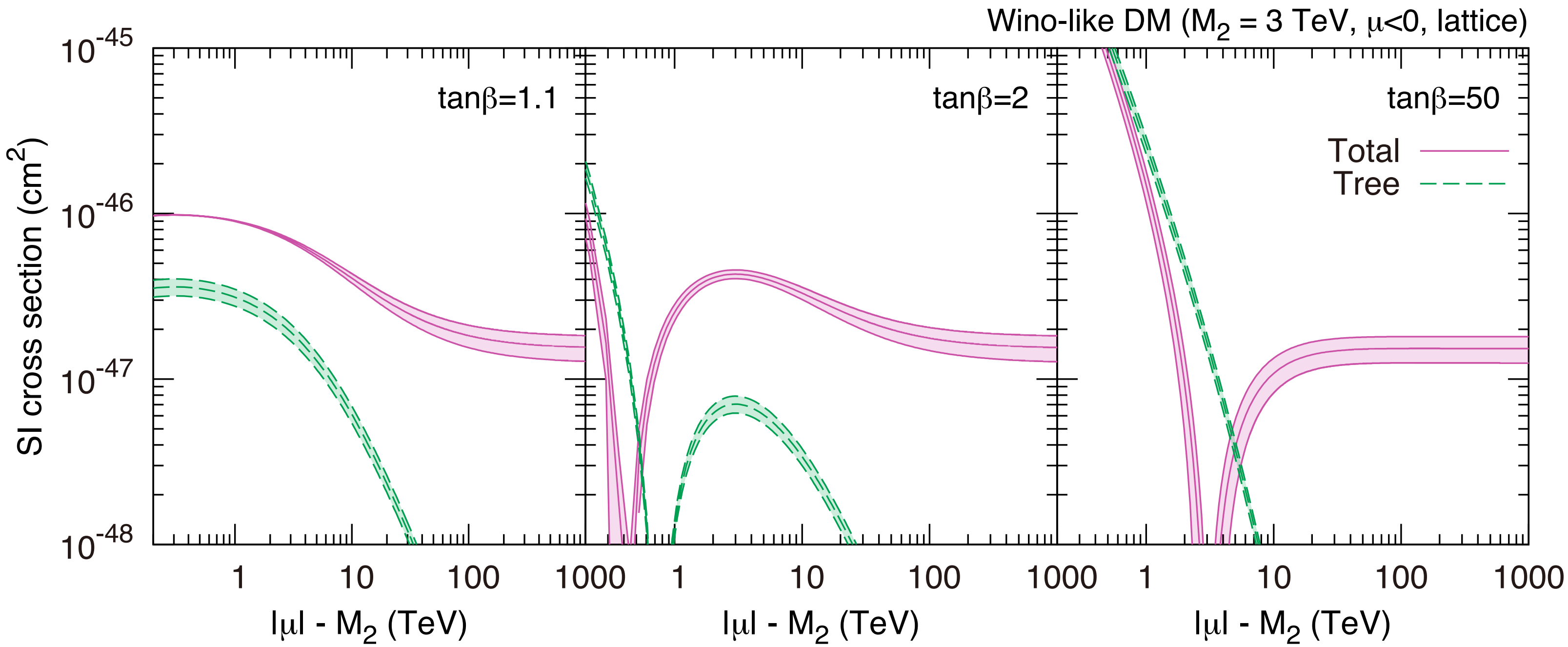
Wino-like DM | Scattering cross sections with a proton



- Cancellations between tree- and loop-level contributions occur at a certain value of μ
- Loop contribution is dominant in a wide range of parameter region

J. Hisano, K. Ishiwata, and N. Nagata, Phys. Rev. **D87** (2013) 035020.

Wino-like DM | Scattering cross sections with a proton



Tree-level contribution interferes constructively to the loop contribution in the case of low tanβ

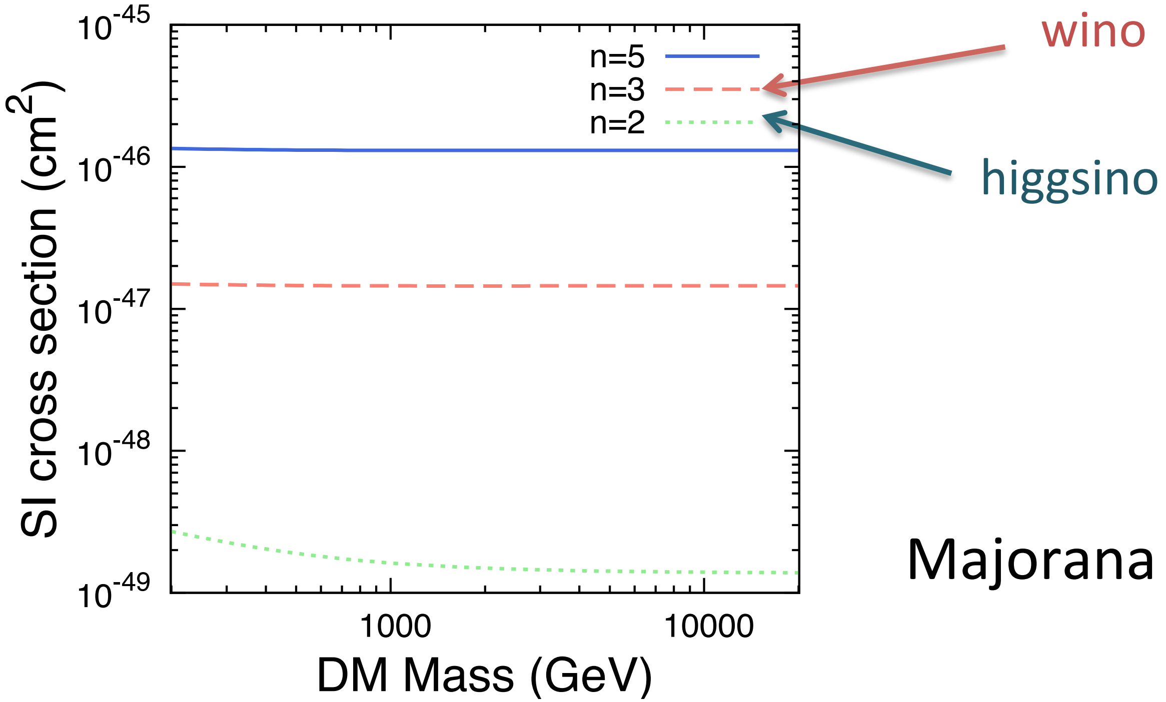
J. Hisano, K. Ishiwata, and N. Nagata, Phys. Rev. **D87** (2013) 035020.

Minimal DM

Minimal dark matter

M. Cirelli, N. Fornengo, A. Strumia (2005)

The neutral component of an $SU(2)_L$ *n*-tuplet is assumed to be DM in the Universe.



Majorana DM

We again find cancellations among the contributions.

J. Hisano, K. Ishiwata, N. Nagata, and T. Takesako, JHEP **1107** (2011) 005.

3. Some results

d) KK-photon DM (Minimal UED)

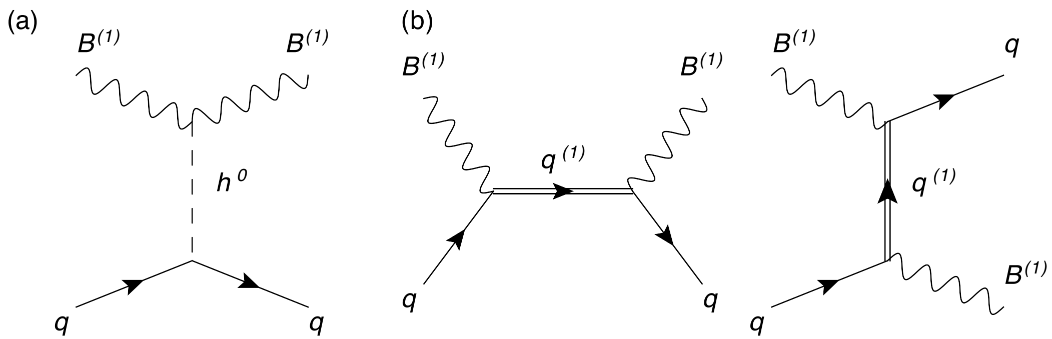
Vector DM | KK photon DM (MUED)

T. Appelquist, H. C. Cheng, B. A. Dobrescu (2001)
H. C. Cheng, K. T. Matchev, M. Schmaltz (2002)

Minimal Universal Extra Dimension (MUED) model

The first KK photon becomes the lightest Kaluza-Klein particle (LKP).

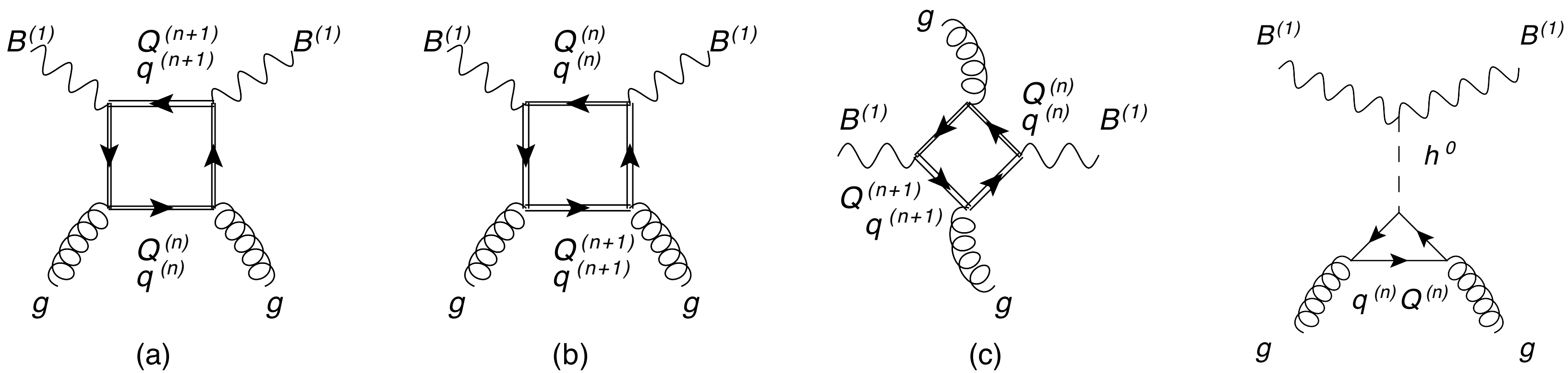
Tree-level diagrams: → **Vector DM**



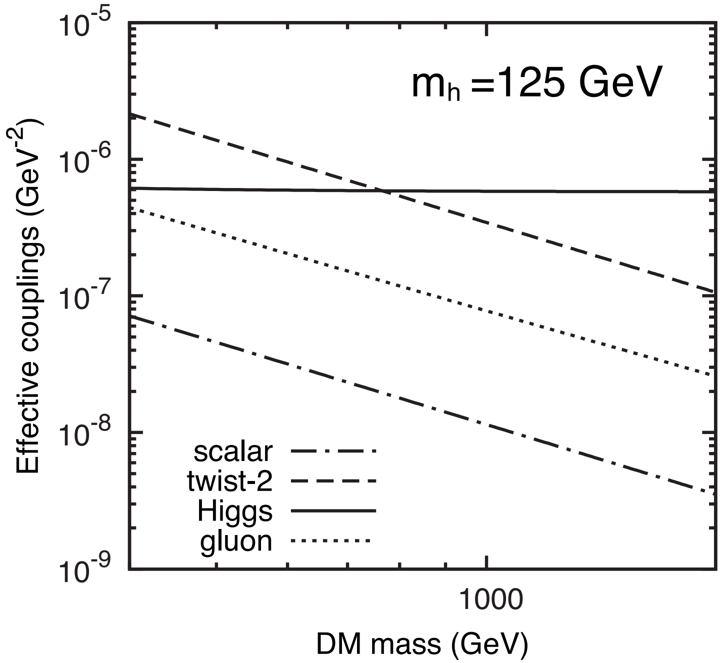
$B^{(1)}$: KK photon DM $\quad q^{(1)}$: the first KK quark

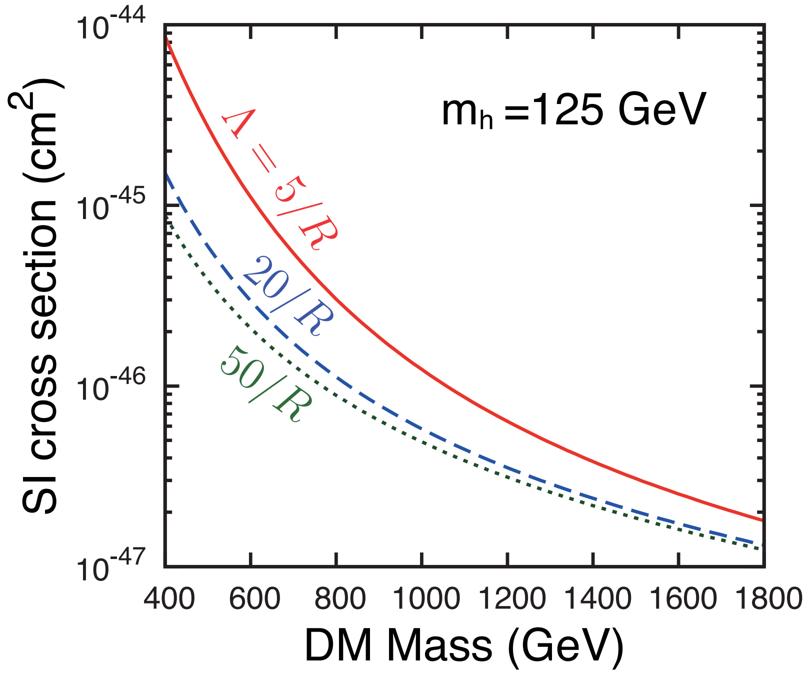
Neglected in previous calculations

1-loop diagrams:



Vector DM | KK photon DM (MUED)





<u>Each contribution in the effective coupling</u>

<u>The SI scattering cross sections</u>

- All of the contributions have the same sign (constructive).
- Resultant scattering cross sections are larger than those in previous work by about an order of magnitude in some parameter region.

J. Hisano, K. Ishiwata, NN, and M. Yamanaka, Prog. Theor. Phys. Vol. 126, No. **3** (2011) 435.

4. Conclusion and discussion

Summary

- We evaluate the elastic scattering cross sections of WIMP DM with nucleon based on the method of effective theory.

- The interaction of DM with gluon as well as quarks yields sizable contribution to the cross section, though the gluon contribution is induced at loop level.

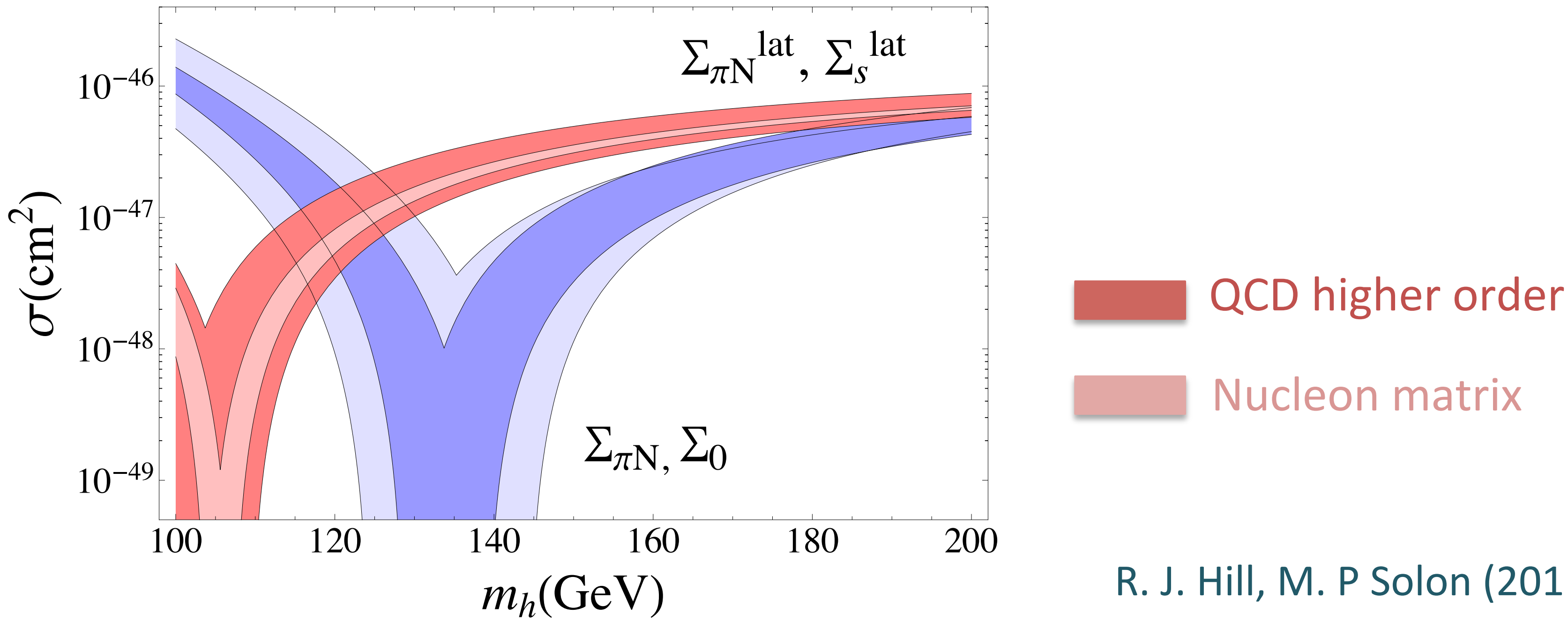
- In the wino dark matter scenario we find the cross section is smaller than the previous results by more than an order of magnitude

- The cross section of the first Kaluza-Klein photon dark matter turns out to be larger.

Backup

Prospects

Wino-proton scattering cross sections

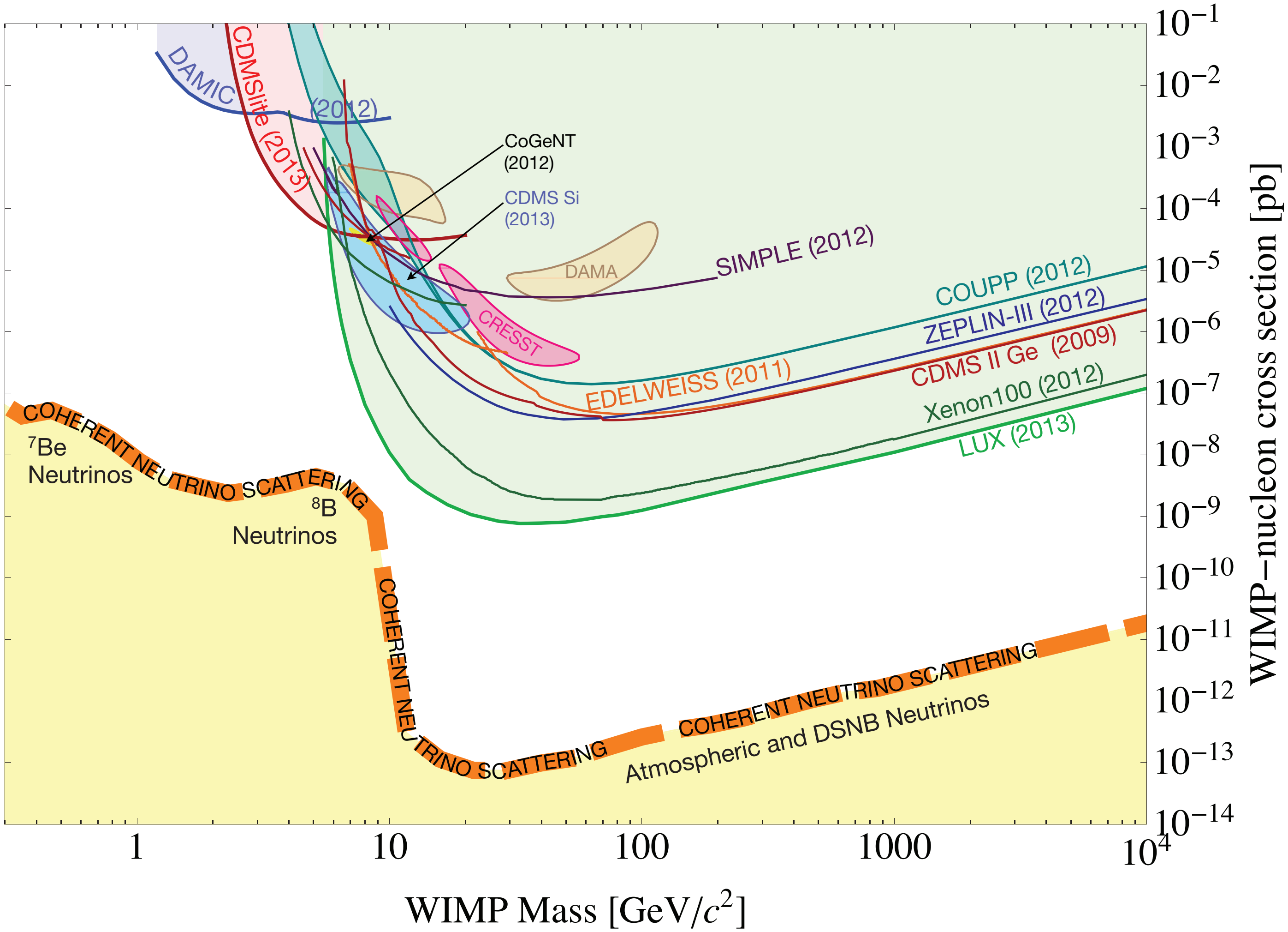


R. J. Hill, M. P Solon (2011)

- Uncertainty mainly comes from the perturbative QCD.
- Need for higher order calculation.

J. Hisano, K. Ishiwata, N. Nagata, in progress.

Neutrino BG



J. Billard, E. Figueroa-Feliciano, L. Strigari [arXiv: 1307.5458].

Higgs-nucleon coupling

$$\mathcal{L}_{NNh} = -g_{NNh}\bar{N}Nh$$

$$g_{NNh} = \frac{\sqrt{2}}{v}\sum_q \langle N|m_q\bar{q}q|N\rangle$$
$$= \frac{\sqrt{2}}{v}\left[m_N(f_{Tu}+f_{Td}+f_{Ts}) - \frac{\alpha_s}{4\pi}\langle N|G^a_{\mu\nu}G^{a\mu\nu}|N\rangle\right]$$
$$= \frac{\sqrt{2}}{v}m_N\left[\frac{2}{9}+\frac{7}{9}(f_{Tu}+f_{Td}+f_{Ts})\right]$$

Large mass fractions (f_Tq → large)

→ Higgs-nucleon couplings are enhanced

Input parameters

$$\sigma_{\pi N} = \frac{m_u + m_d}{2}\langle p|\bar{u}u + \bar{d}d|p\rangle$$

$$y = \frac{2\langle p|\bar{s}s|p\rangle}{\langle p|\bar{u}u + \bar{d}d|p\rangle}$$

$$\xi = \frac{\langle p|\bar{u}u - \bar{d}d|p\rangle}{\langle p|\bar{u}u + \bar{d}d|p\rangle}$$

$$\xi = 0.135 \pm 0.035$$

H. Y. Cheng (1989)

Lattice results (ours)

$$\sigma_{\pi N} = 53 \pm 2(\mathrm{stat})^{+21}_{-7}(\mathrm{syst})\ \mathrm{MeV}$$

$$y = 0.030 \pm 0.016(\mathrm{stat})^{+0.006}_{-0.008}(\mathrm{syst})$$

H. Ohki et al. (2008)

Chiral perturbation (traditional)

$$\sigma_{\pi N} = 64 \pm 7\ \mathrm{MeV}$$

M. M. Pavan et al. (2002)

$$y = 0.44 \pm 0.13$$

B. Borasoy and U. G. Meissner (1997)