QCD Effects on Direct Detection of Wino Dark Matter

Junji Hisano
(KMI, Nagoya Univ.)

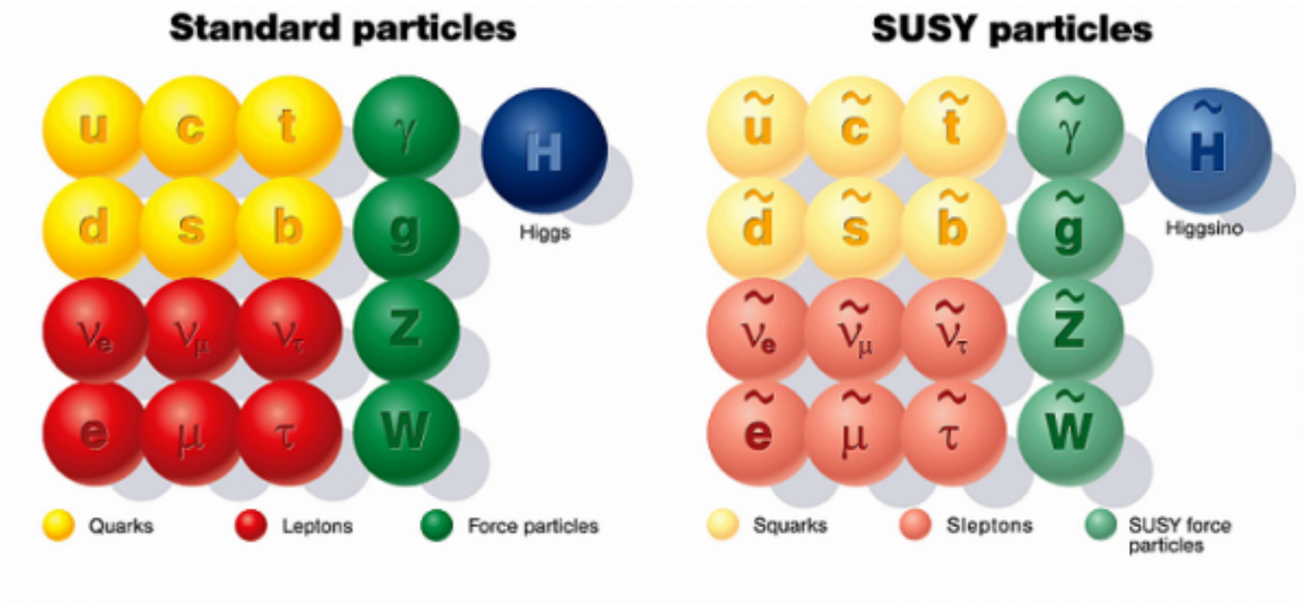
Based on a collaboration with
K. Ishiwata (Kanazawa) and N. Nagata (Minesota)
Arxiv:1504.00915

Portorož 2015
Particle Phenomenology From the Early Universe to High Energy Colliders
April 7 - 10 2015, Portorož, Slovenia

Contents of my talk

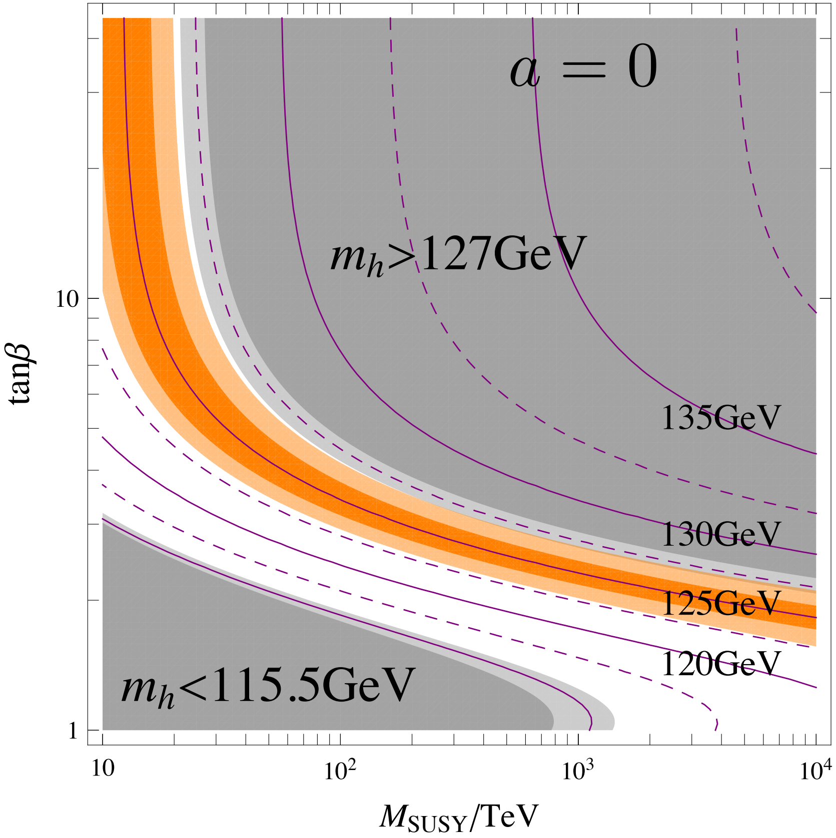
1. Motivation of Wino dark matter
2. Wino dark matter direct detection
3. QCD correction to direct detection rate of wino dark matter
4. Summary

What is wino?



- Superpartner of $SU(2)_L$ gauge bosons in SUSY SM.
- $SU(2)_L$ triplet fermions.
- Neutral component of Winos is a candidate of WIMP DM.

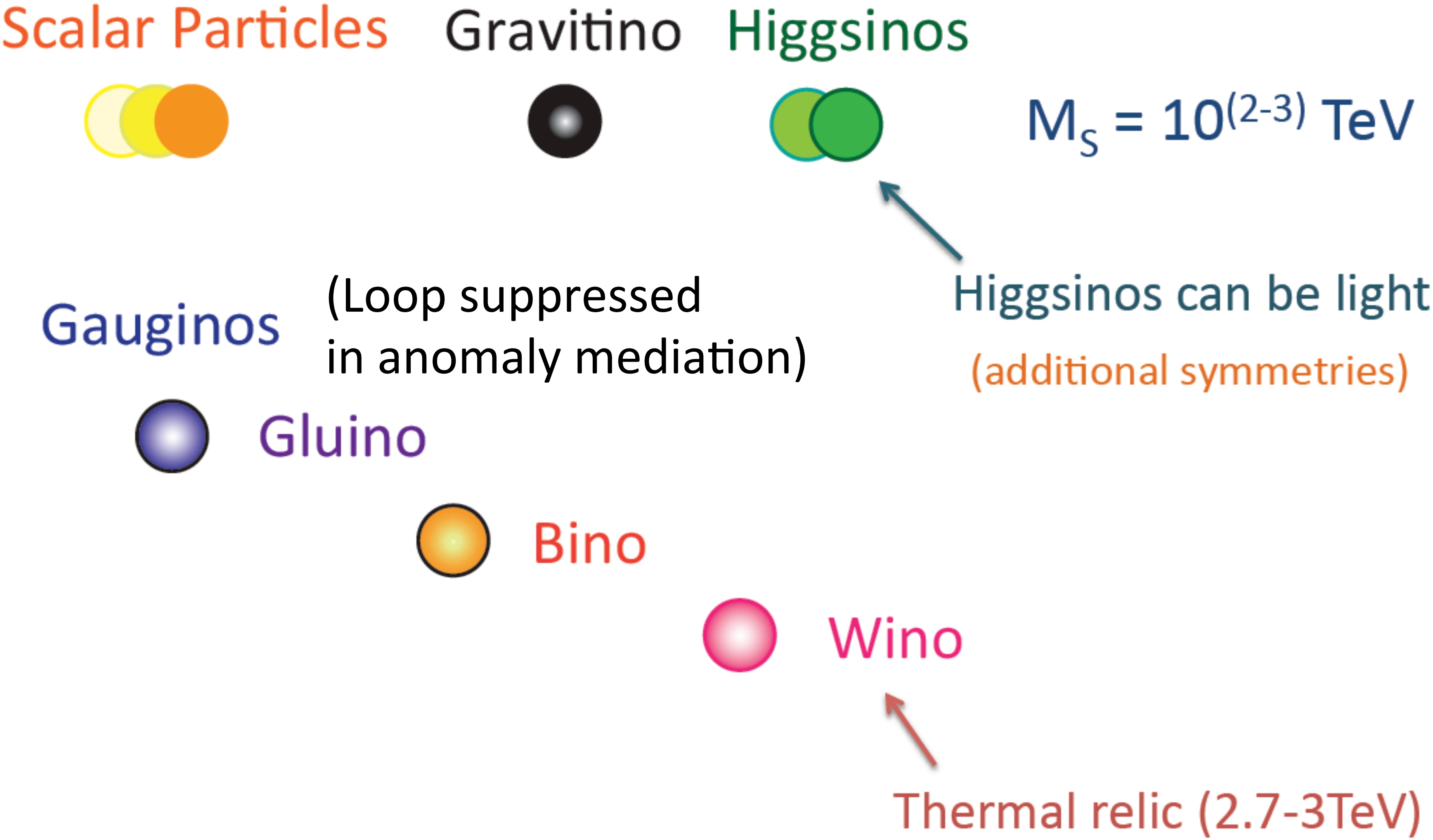
Higgs mass in High-scale SUSY



(Ibe, Matsumoto, Yanagida (12))

For tanβ~2-5, 125 GeV Higgs mass is well-explained in High-scale SUSY (~O($10^{2\text{-}3}$) TeV). This is consistent with various problems in SUSY SM (flavor, CP, gravitino, proton decay…)

Mass spectrum in High-scale SUSY



Scalar Particles

Gravitino

Higgsinos

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

Higgsinos can be light

(additional symmetries)

Gauginos

(Loop suppressed
in anomaly mediation)

Gluino

Bino

Wino

Thermal relic (2.7-3TeV)

J. Hisano, S. Matsumoto, M. Nagai, O. Saito, M. Senami (2006).

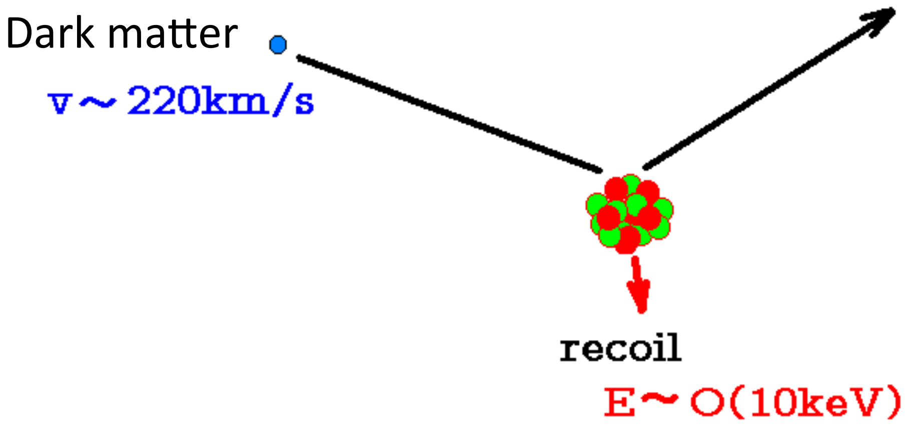
Strategy to find High-scale SUSY

Lightest SUSY particle (LSP):wino

- If wino mass is lighter than ~1TeV, it might be discovered at LHC.
- Indirect detection of wino dark matter. Wino pair annihilation is enhanced by the Sommerfeld effect. Line gamma rays from galactic center will be searched for at CTA.
- EDM induced by Barr-Zee diagrams. Even if Higgsino mass is 100TeV, electron EDM reach to ~ 10^{-30} ecm.
- Direct detection of wino dark matter. The spin-independent cross section is ~ 10^{-47} cm^2, which is not sensitive to wino mass itself.

Wino dark matter direct detection

Dark matter direct detection experiments



$$\mathcal{L} = \sum_{N=p,n} f_N \overline{\chi^0}\chi^0\overline{N}N + a_N \overline{\chi^0}\sigma_a\chi^0\overline{N}\sigma_a N$$

Spin-independent (SI) interaction

Spin-dependent (SD) interaction

Elastic scattering cross section with nucleus (m_T: nucleus mass, $n_{p/n}$:# of proton and neutron)

$$\sigma = \frac{4}{\pi}\left(\frac{m_{\tilde{\chi}^0}m_T}{m_{\tilde{\chi}^0}+m_T}\right)^2\left[\underbrace{(n_pf_p+n_nf_n)^2}_{\text{SI}}+4\frac{J+1}{J}\underbrace{(a_p\langle S_p\rangle+a_n\langle S_n\rangle)^2}_{\text{SD}}\right]$$

The SI cross section is enhanced for large atomic number nucleus.

Effective SI interaction at parton level

Effective SI interactions of Majorana fermion χ^0 at parton level up to D=7:

$$\mathcal{L}_{\rm eff} = \sum_{i=q,G} C^i_{\rm S}\mathcal{O}^i_{\rm S} + \sum_{i=q,G}\left(C^i_{{\rm T}_1}\mathcal{O}^i_{{\rm T}_1} + C^i_{{\rm T}_2}\mathcal{O}^i_{{\rm T}_2}\right)$$

- Scalar operators:

$$\mathcal{O}^q_{\rm S} \equiv \boxed{m_q}\,\bar{\chi}^0\chi^0\bar{q}q \qquad \mathcal{O}^G_{\rm S} \equiv \boxed{\frac{\alpha_s}{\pi}}\,\bar{\chi}^0\chi^0 G^a_{\mu\nu}G^{a\mu\nu}$$

M : WIMP mass
m_q: quark mass

- Twist-2 operators:

$$\mathcal{O}^i_{{\rm T}_1} \equiv \frac{1}{M}\bar{\chi}^0 i\partial^\mu\gamma^\nu\chi^0\mathcal{O}^i_{\mu\nu} \qquad \mathcal{O}^i_{{\rm T}_2} \equiv \frac{1}{M^2}\bar{\chi}^0(i\partial^\mu)(i\partial^\nu)\chi^0\mathcal{O}^i_{\mu\nu}$$

Twist-2 operators for quarks and gluon:

$$\mathcal{O}^q_{\mu\nu} \equiv \frac{1}{2}\bar{q}i\left(D_\mu\gamma_\nu + D_\nu\gamma_\mu - \frac{1}{2}g_{\mu\nu}\not{D}\right)q \qquad \mathcal{O}^G_{\mu\nu} \equiv G^{a\rho}_{\mu}G^a_{\nu\rho} - \frac{1}{4}g_{\mu\nu}G^a_{\rho\sigma}G^{a\rho\sigma}$$

Nuclear matrix elements

- Twist-2 operators:

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

$$\langle N(p)|\mathcal{O}^G_{\mu\nu}|N(p)\rangle = -m_N\left(\frac{p_\mu p_\nu}{m_N^2} - \frac{1}{4}g_{\mu\nu}\right)g^{(N)}(2;\mu)$$

The 2nd moments of parton-distribution functions (PDFs)

$$q^{(N)}(2;\mu) = \int_0^1 dx\ x\ q^{(N)}(x,\mu) \qquad g^{(N)}(2;\mu) = \int_0^1 dx\ x\ g^{(N)}(x,\mu)$$

1. The 2nd moments of PDFs at $\mu = m_Z$ comes from CTEQ PDFs.

$g(2)$	$0.464(2)$		
$u(2)$	$0.223(3)$	$\bar{u}(2)$	$0.036(2)$
$d(2)$	$0.118(3)$	$\bar{d}(2)$	$0.037(3)$
$s(2)$	$0.0258(4)$	$\bar{s}(2)$	$0.0258(4)$
$c(2)$	$0.0187(2)$	$\bar{c}(2)$	$0.0187(2)$
$b(2)$	$0.0117(1)$	$\bar{b}(2)$	$0.0117(1)$

2. Matrix elements in our operator definition are $\mathcal{O}(m_N)$.

Nuclear matrix elements

- Scalar operators :

$$\langle N|\enclose{circle}{m_q}\bar{q}q|N\rangle \equiv m_N f_{T_q}^{(N)}$$ ($f_{T_q}^{(N)}$: mass fraction)

$$\langle N|\enclose{circle}{\frac{\alpha_s}{\pi}}G^a_{\mu\nu}G^{a\mu\nu}|N\rangle = m_N \frac{4\alpha_s^2}{\pi\beta(\alpha_s; N_f=3)}\left[1-(1-\gamma_m)\sum_q f_{Tq}^{(N)}\right]$$

(From trace anomaly)

1. Mass fractions $f_{T_q}^{(N)}$ come from Lattice QCD outputs.

Proton		Neutron	
$f_{T_u}^{(p)}$	0.019(5)	$f_{T_u}^{(n)}$	0.013(3)
$f_{T_d}^{(p)}$	0.027(6)	$f_{T_d}^{(n)}$	0.040(9)
$f_{T_s}^{(p)}$	0.009(22)	$f_{T_s}^{(n)}$	0.009(22)

2. Matrix elements in our operator definition are $\mathcal{O}(m_N)$. This imply that we have to evaluate one-loop higher diagrams for gluon than those for quarks
3. Quark operator and gluon operator are RG-inv at least at $\mathcal{O}(\alpha_s)$.

Strategy to evaluate SI coupling of nucleon

Evaluate the Wilson coefficients at $\mu_W \simeq m_Z$ with Nf=5 active quarks by integrating out heavy particles.

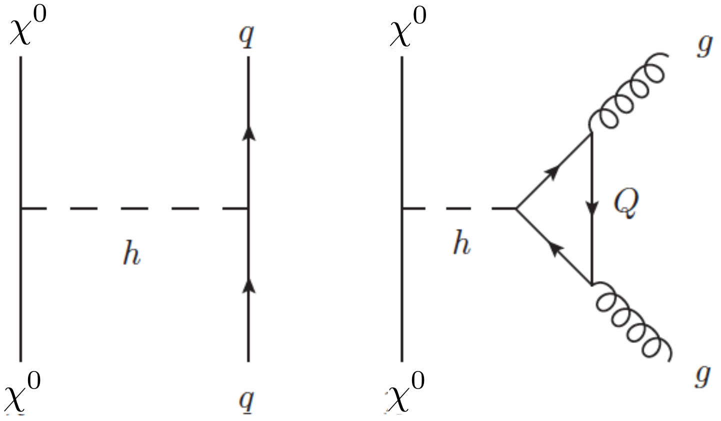
Evolve the the Wilson coefficients down to the scale at which the nucleon matrix elements are evaluated.

Express the SI coupling with nucleon.

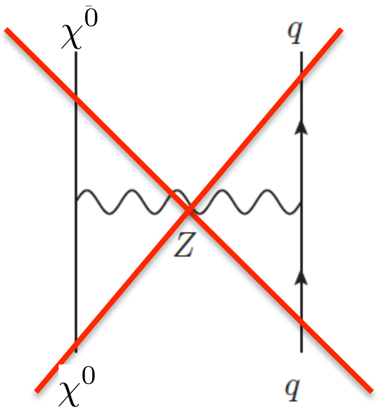
Scalar operators and twist-2 operators are not mixed with each other in RG flow so that we can evaluate those contributions to the SI coupling with nucleon separately.

Tree-level contribution to SI interaction of wino

Higgsino-Wino mixing induces to tree-level coupling with Higgs boson, though it is suppressed by m_W/μ (μ:Higgsino mass).



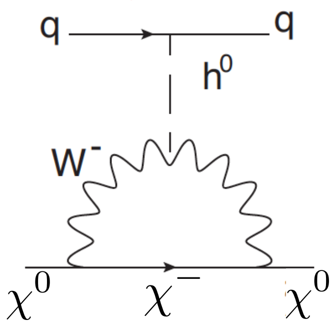
q : light quarks (u,d,s)
Q: heavy quarks (c,b,t)



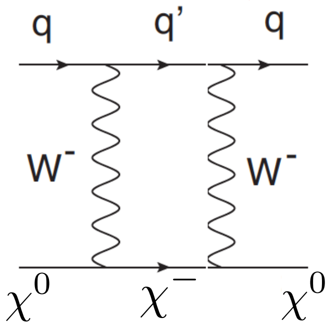
Contribution to SD interaction.

Loop-level contribution to SI interaction

Quark scalar op.



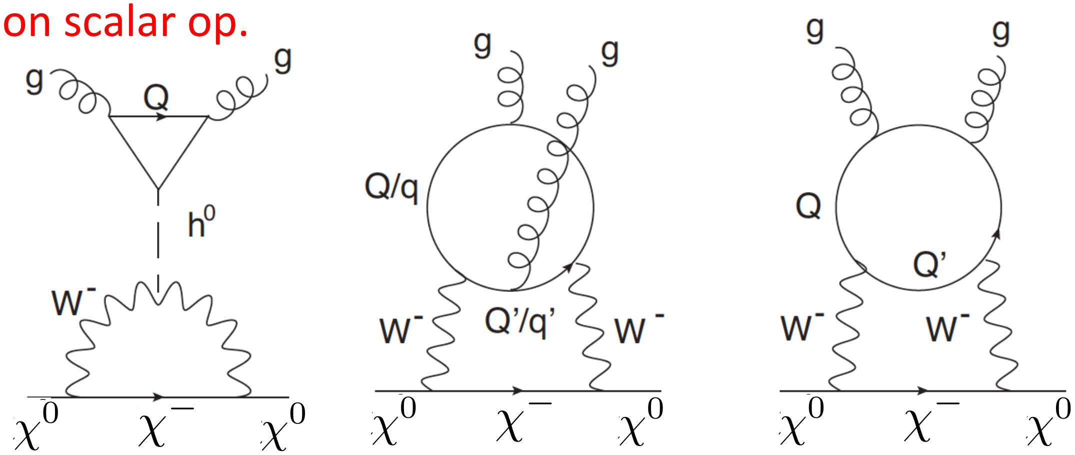
Quark twist-2 op.



q : light quarks (u,d,s)

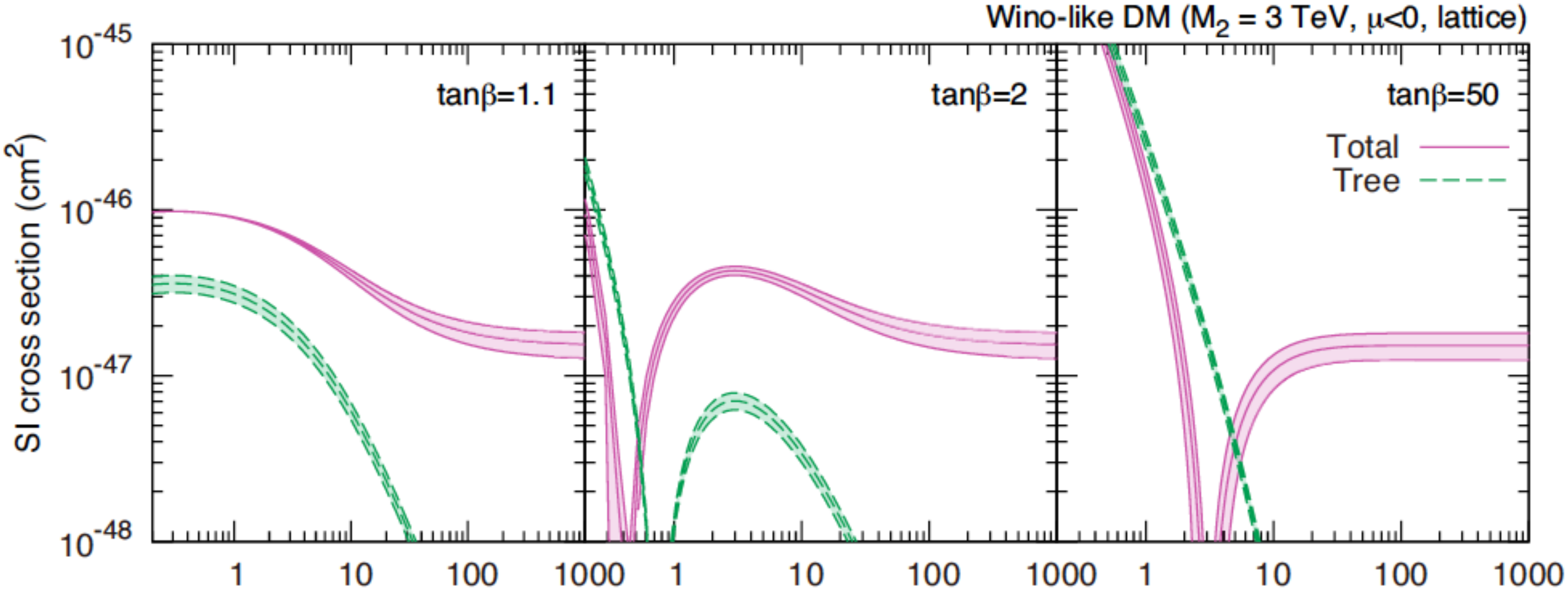
Q: heavy quarks (c,b,t)

Gluon scalar op.



These contributions are not suppressed by power of of wino mass. When Higgsino mass is much heavier than wino one, loop-level contribution dominates over tree-level one. (JH, Matsumoto, Nojiri, Saito)

SI cross section of Wino DM (3TeV)



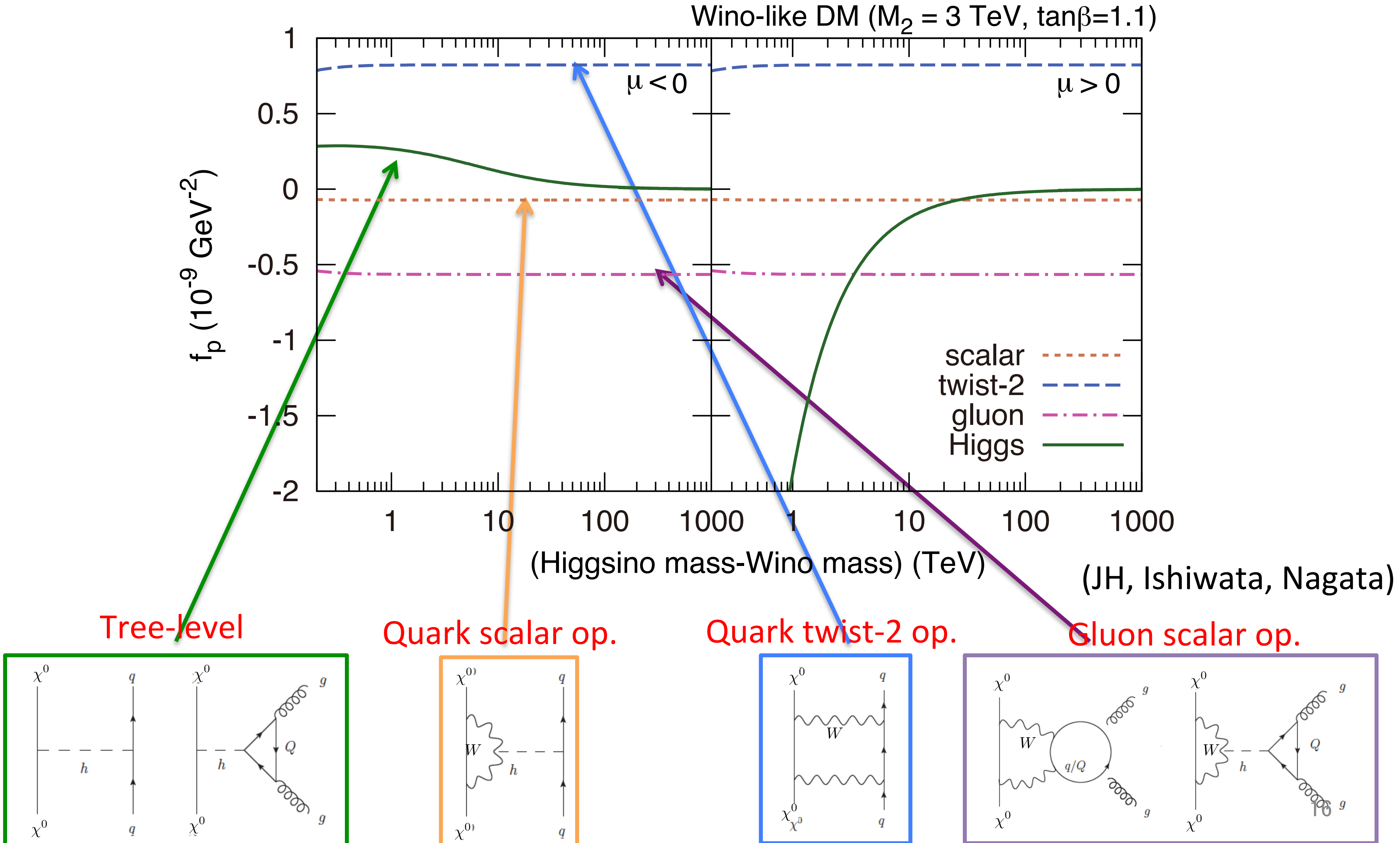
(Higgsino mass – Wino mass) (TeV)

(JH, Ishiwata, Nagata)

Even if wino is much heavier than weak scale, SI cross section is insensitive to the wino mass.

Accidental cancelation

SI coupling of wino with nucleon has various contributions :



(JH, Ishiwata, Nagata)

Tree-level

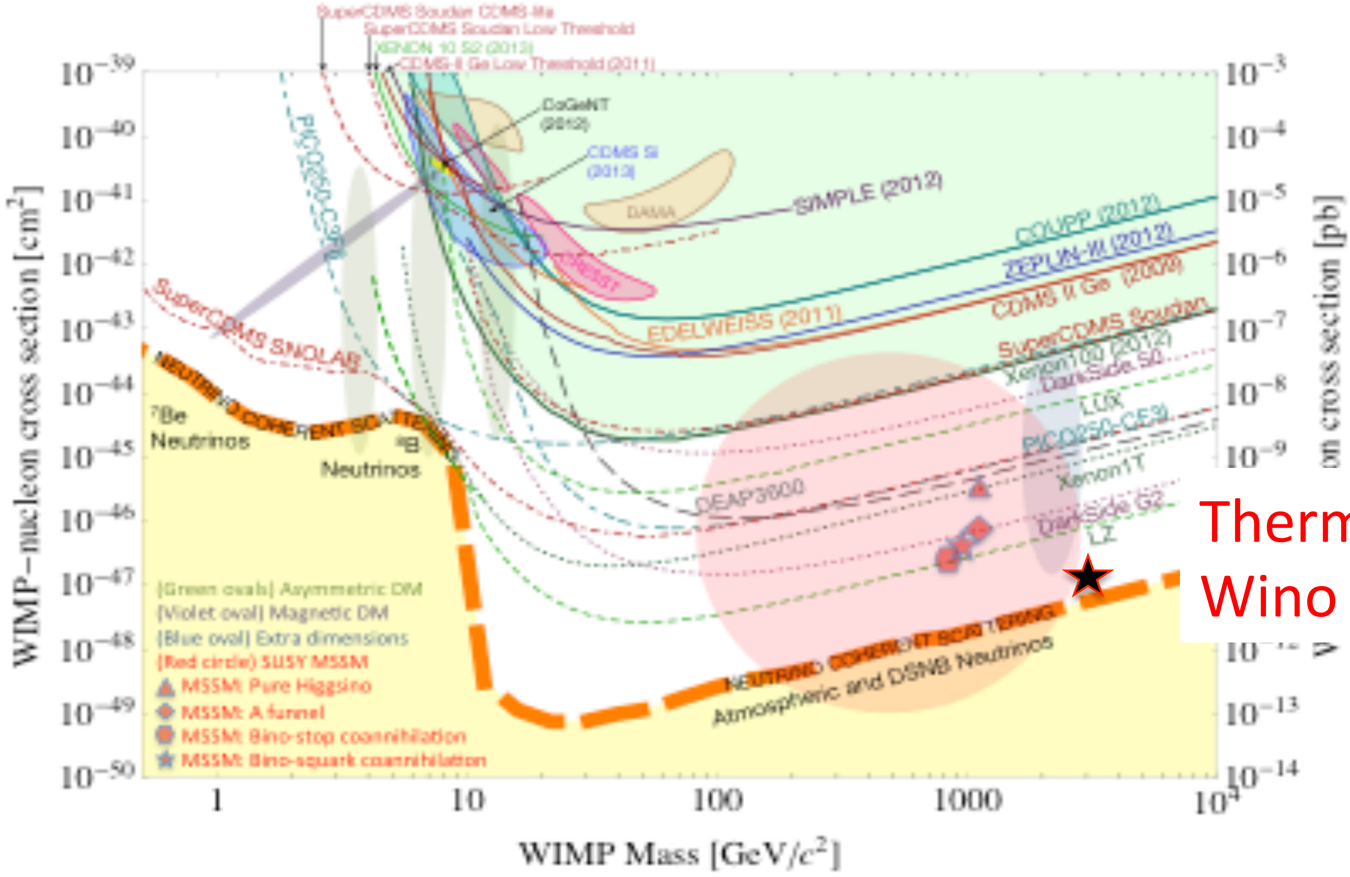
Quark scalar op.

Quark twist-2 op.

Gluon scalar op.

Future prospects

Accidental cancellation reduces the SI cross section. NLO QCD correction may change it by a factor 2 (Hill & Solon).
The cross section is larger than neutrino BG?



Thermal Wino DM

(From snowmass report)

QCD Correction to Direct Detection of Wino Dark Matter

Strategy to evaluate SI coupling of nucleon

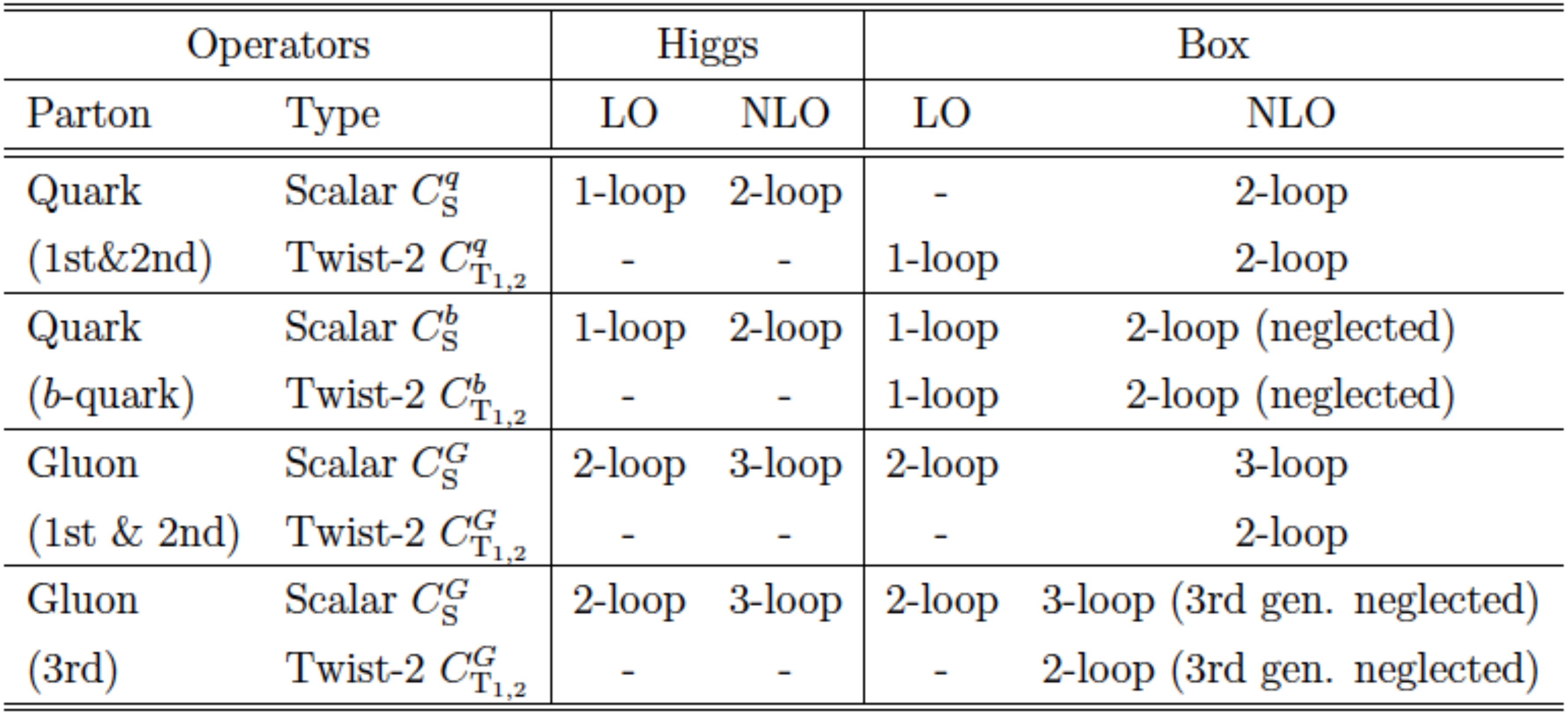
Evaluate the Wilson coefficients up to the NLO in the strong coupling constant α_s at $\mu_W \simeq m_Z$ with Nf=5 active quarks by integrating out heavy particles.

Evolve the the Wilson coefficients down to the scale at which the nucleon matrix elements are evaluated.

- Two-loop RGEs
- One-loop threshold corrections at quark masses

Express the SI coupling with nucleon.

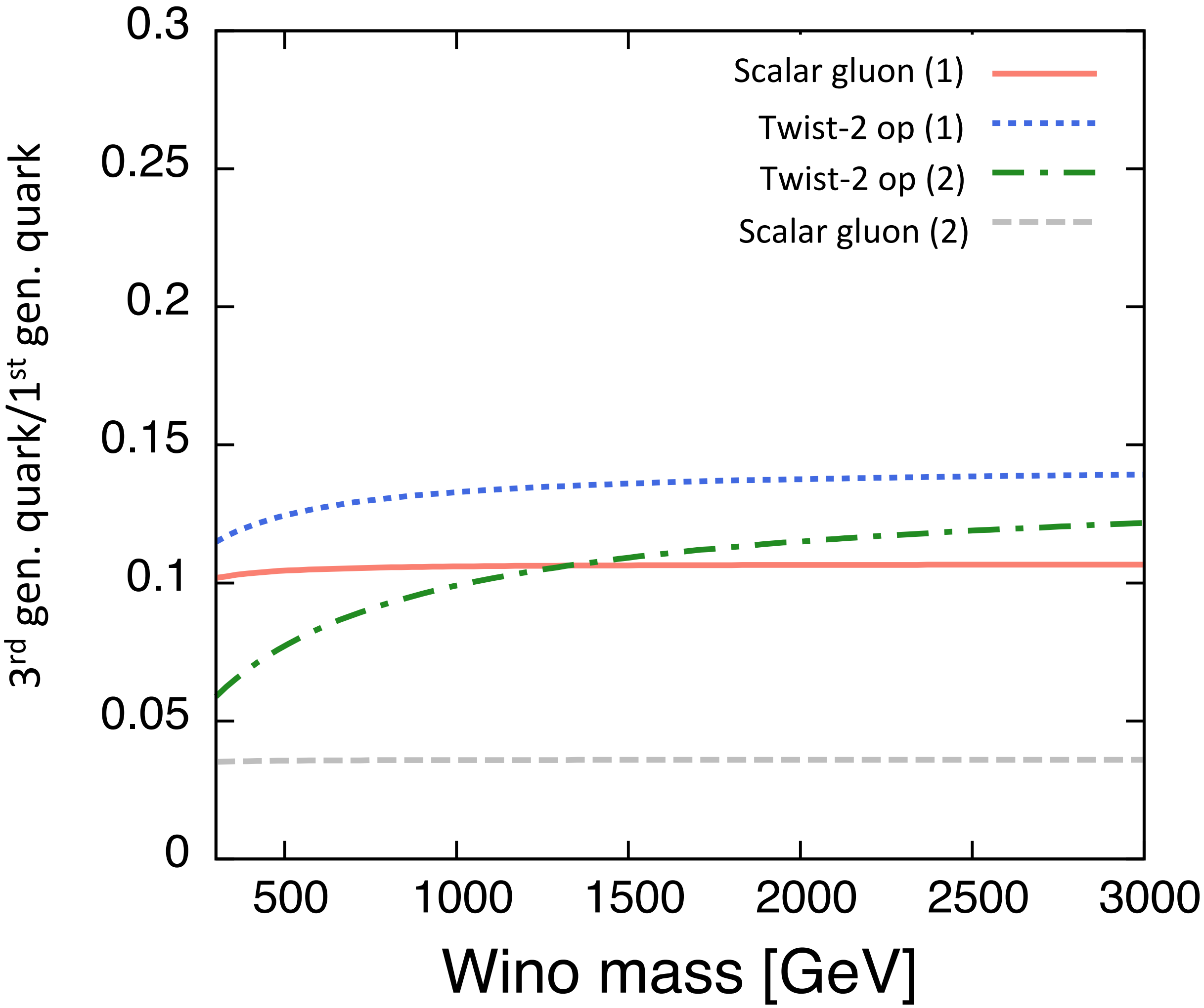
What are included in our NLO calculation



Operators		Higgs		Box	
Parton	Type	LO	NLO	LO	NLO
Quark	Scalar C^q_{S}	1-loop	2-loop	-	2-loop
(1st&2nd)	Twist-2 $C^q_{\mathrm{T}_{1,2}}$	-	-	1-loop	2-loop
Quark	Scalar C^b_{S}	1-loop	2-loop	1-loop	2-loop (neglected)
(*b*-quark)	Twist-2 $C^b_{\mathrm{T}_{1,2}}$	-	-	1-loop	2-loop (neglected)
Gluon	Scalar C^G_{S}	2-loop	3-loop	2-loop	3-loop
(1st & 2nd)	Twist-2 $C^G_{\mathrm{T}_{1,2}}$	-	-	-	2-loop
Gluon	Scalar C^G_{S}	2-loop	3-loop	2-loop	3-loop (3rd gen. neglected)
(3rd)	Twist-2 $C^G_{\mathrm{T}_{1,2}}$	-	-	-	2-loop (3rd gen. neglected)

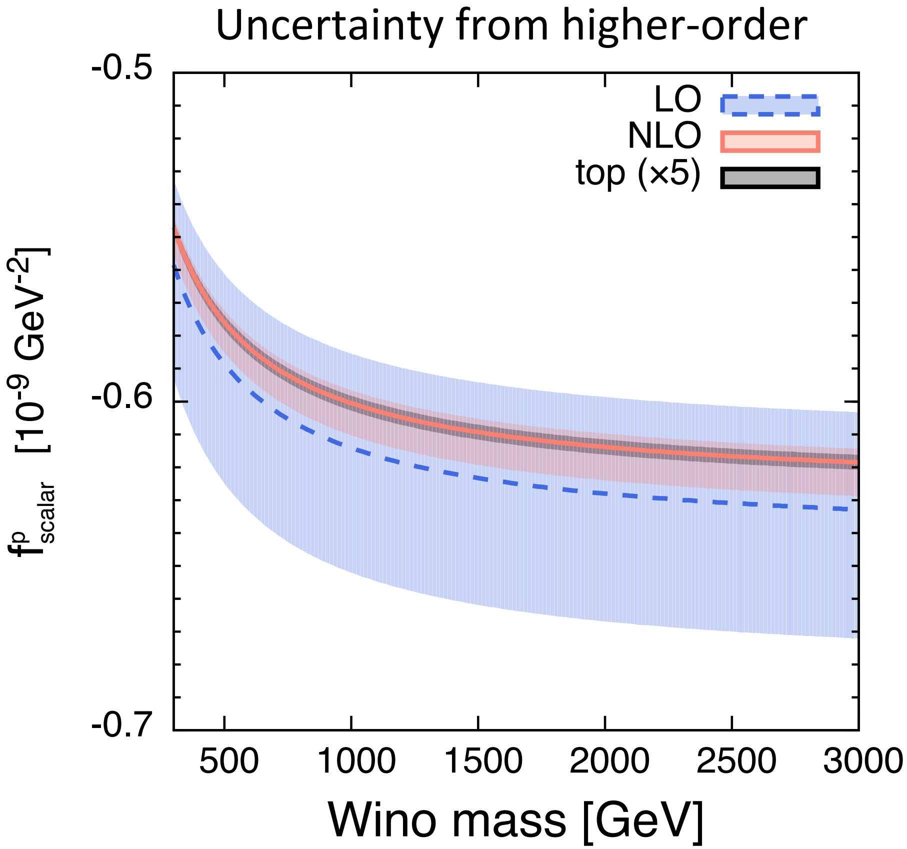
- The NLO contributions form the 3rd gen. quarks are neglected.
- OPEs of correlation function of charged current are evaluated by Broadhurst et al (94) (scalar operators up to NNLO) and Bardeen, Buras et al (78) (twist-2 operator up to NLO) for massless quarks.

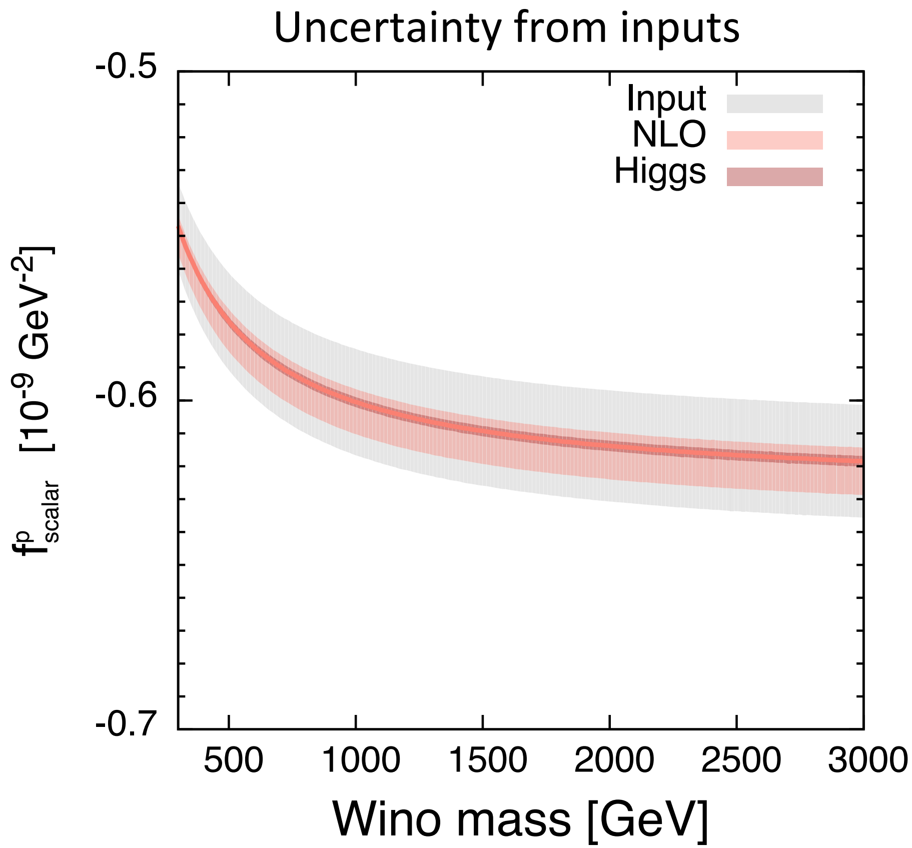
LO contribution from 3rd generation quarks



Even the LO contributions form the 3rd gen. quarks are subdominant.

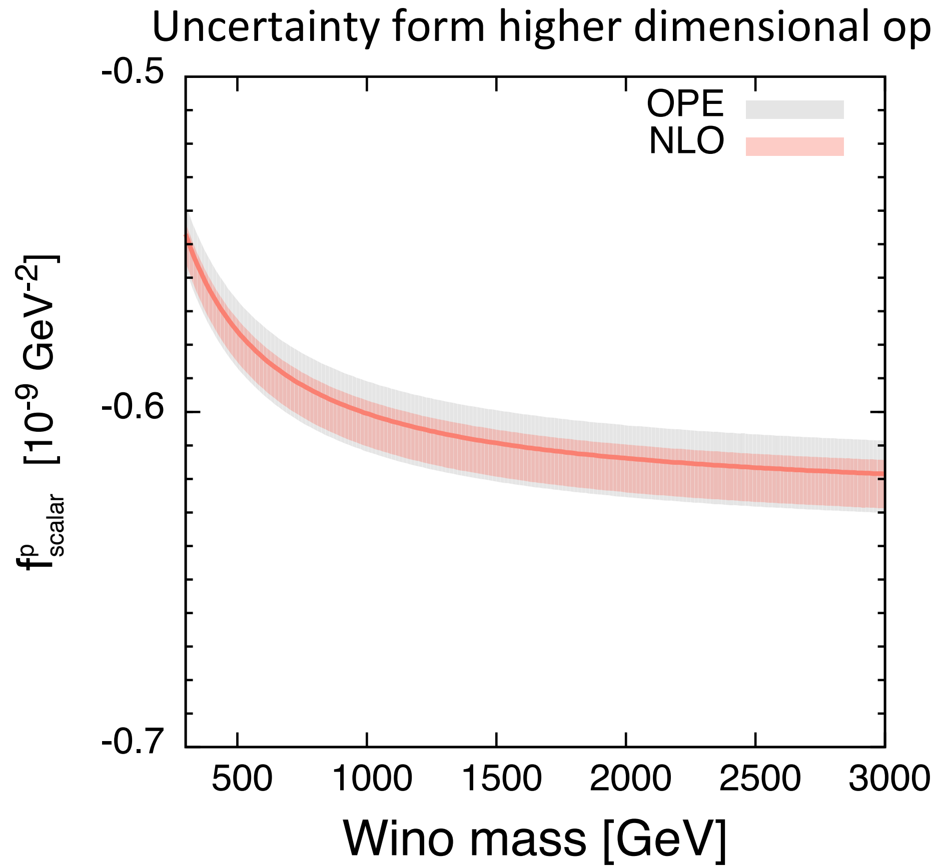
SI coupling from scalar operators


Uncertainty from higher-order


Uncertainty from inputs

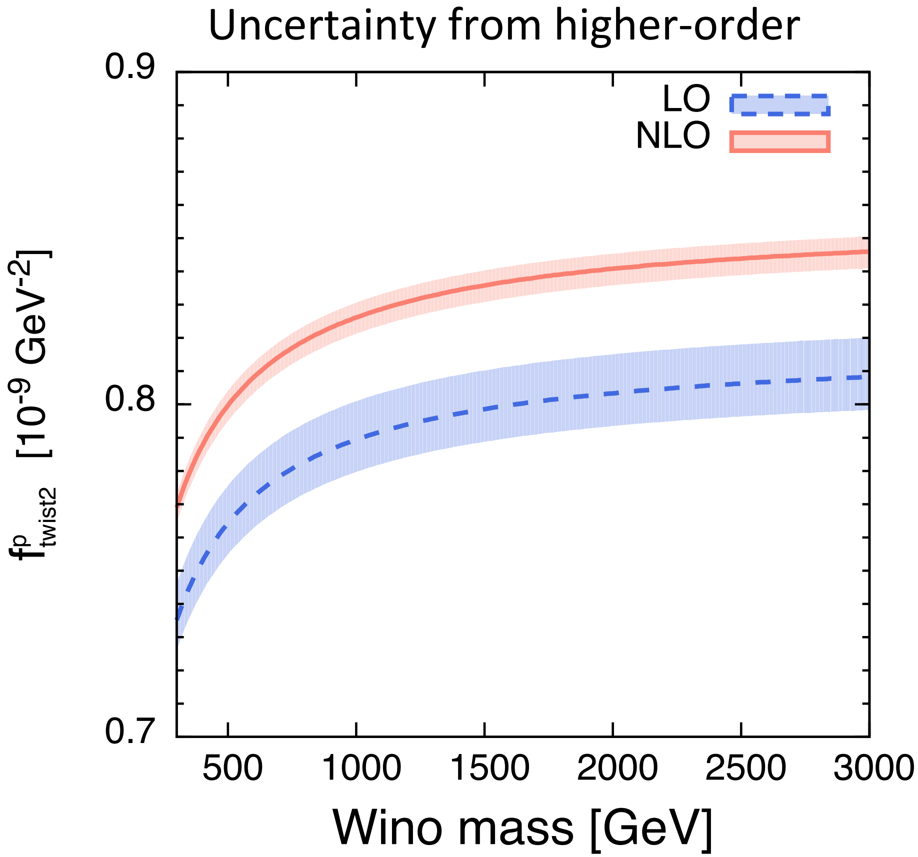
- Uncertainty at NLO is 5 times smaller than in LO.
- Third generation NLO contribution is negligible.
- Uncertainty at NLO is smaller than that in matrix elements.

SI coupling from scalar operators

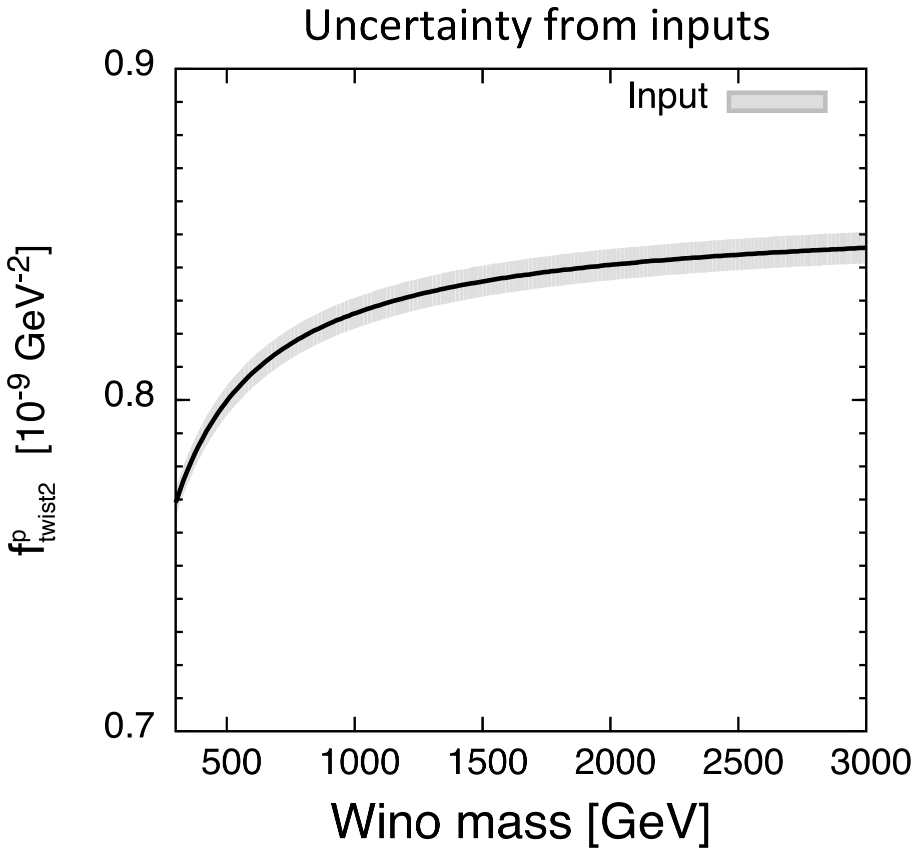


- Higher dimensional op by integrating our charm leads uncertainty. It is about 2 % from NDA. If $f_{T_c}^{(N)} \equiv \langle N | m_c \bar{c} c | N \rangle / m_N$ is evaluated with Lattice QCD, the uncertainty may be reduced.

SI coupling from twist-2 operators



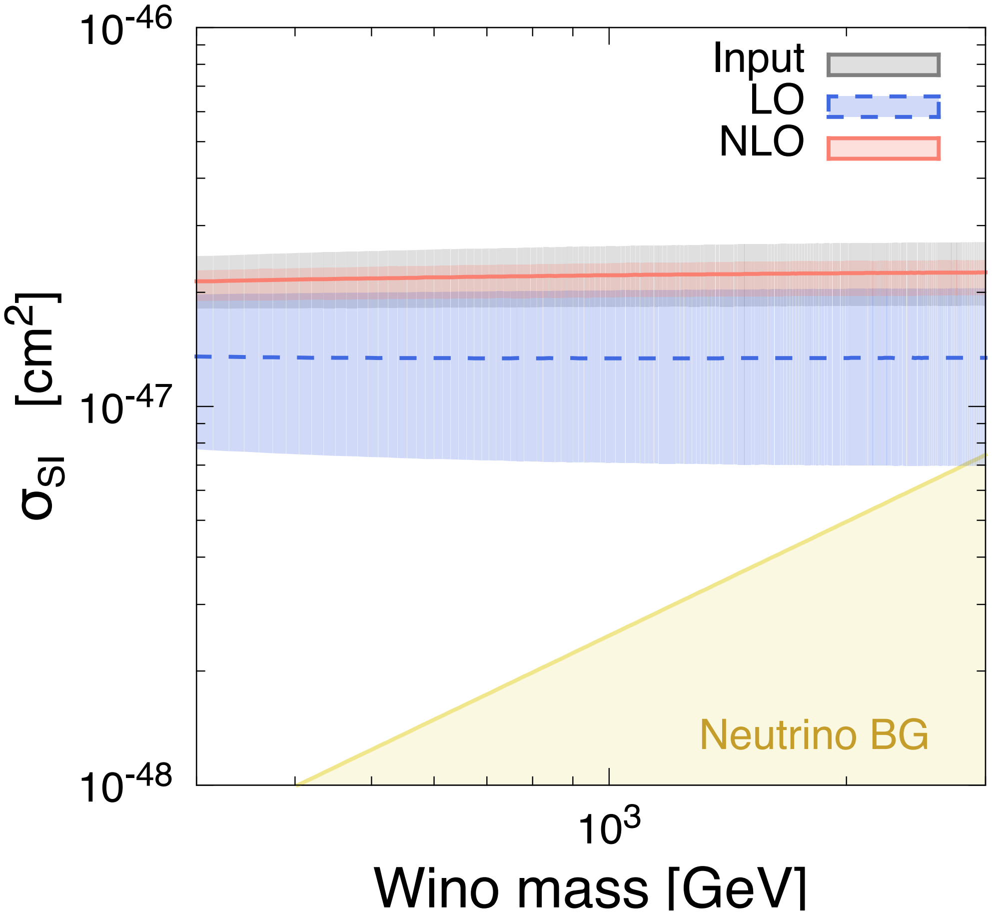
Uncertainty from higher-order



Uncertainty from inputs

- Quark and gluon NLO contribution is +10% and -5 % of the quark LO one.
- Uncertainty from input are negligible.

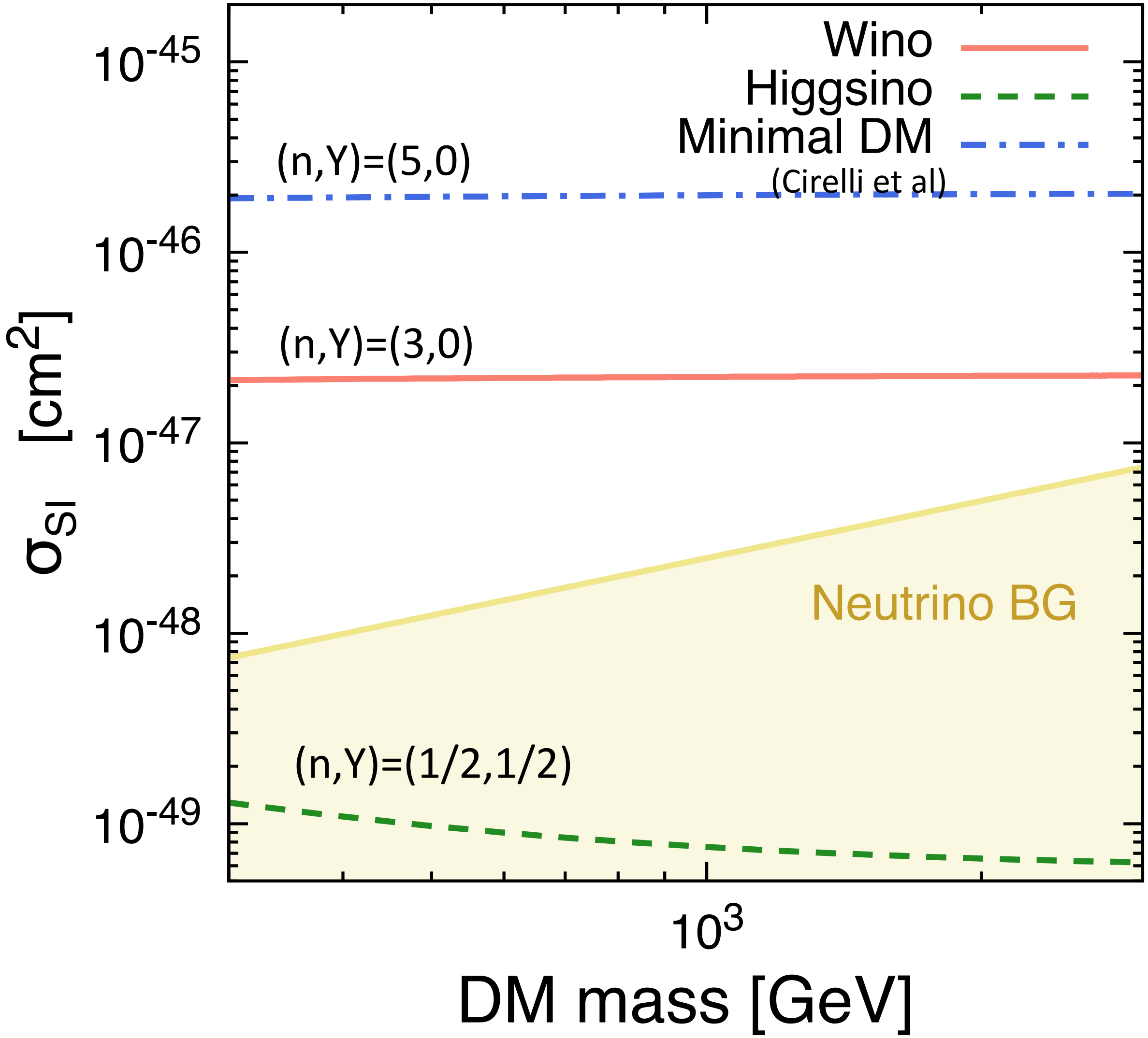
SI cross section of wino with nucleon at NLO



- In a heavy wino mass limit, $\sigma^p_{\rm SI} = 2.3\,^{+0.2}_{-0.3}\,^{+0.5}_{-0.4} \times 10^{-47}\ {\rm cm}^2$ (first error: higher order, second one: input)
- Thermal wino DM (M~3TeV) has larger cross section than neutrino BG.

Electroweakly-interacting dark matter

Neutral fermions with only weak interactions are DM candidates.



Conclusion

In High-scale SUSY, wino is the DM candidate. We evaluate the spin-independent cross section of wino DM at NLO.

$$\sigma_{\rm SI}^{p} = 2.3 \ {}^{+0.2}_{-0.3} \ {}^{+0.5}_{-0.4} \times 10^{-47} \ {\rm cm}^2$$

This is larger than the neutrino BGs even if the wino mass is ~3 TeV (favored from the thermal relic abundance).

We also derive the spin-independent cross section of electroweakly-interacting DM.