Theoretical Developments in Dark Matter-Nucleon Scattering

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LAPTh, Annecy, France

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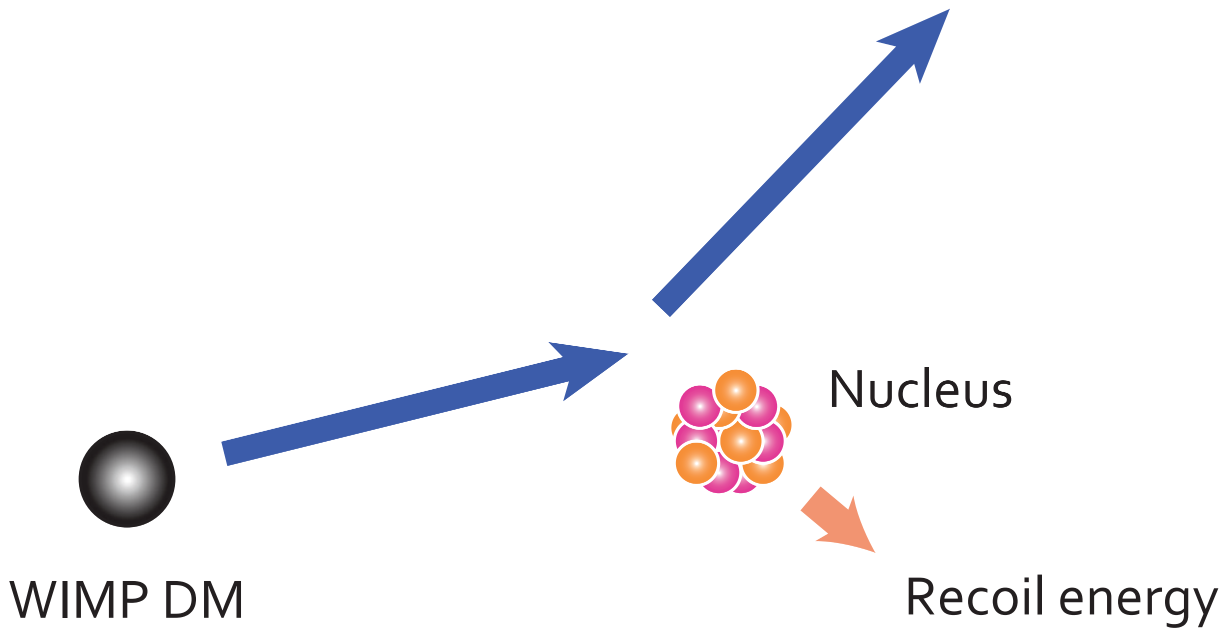
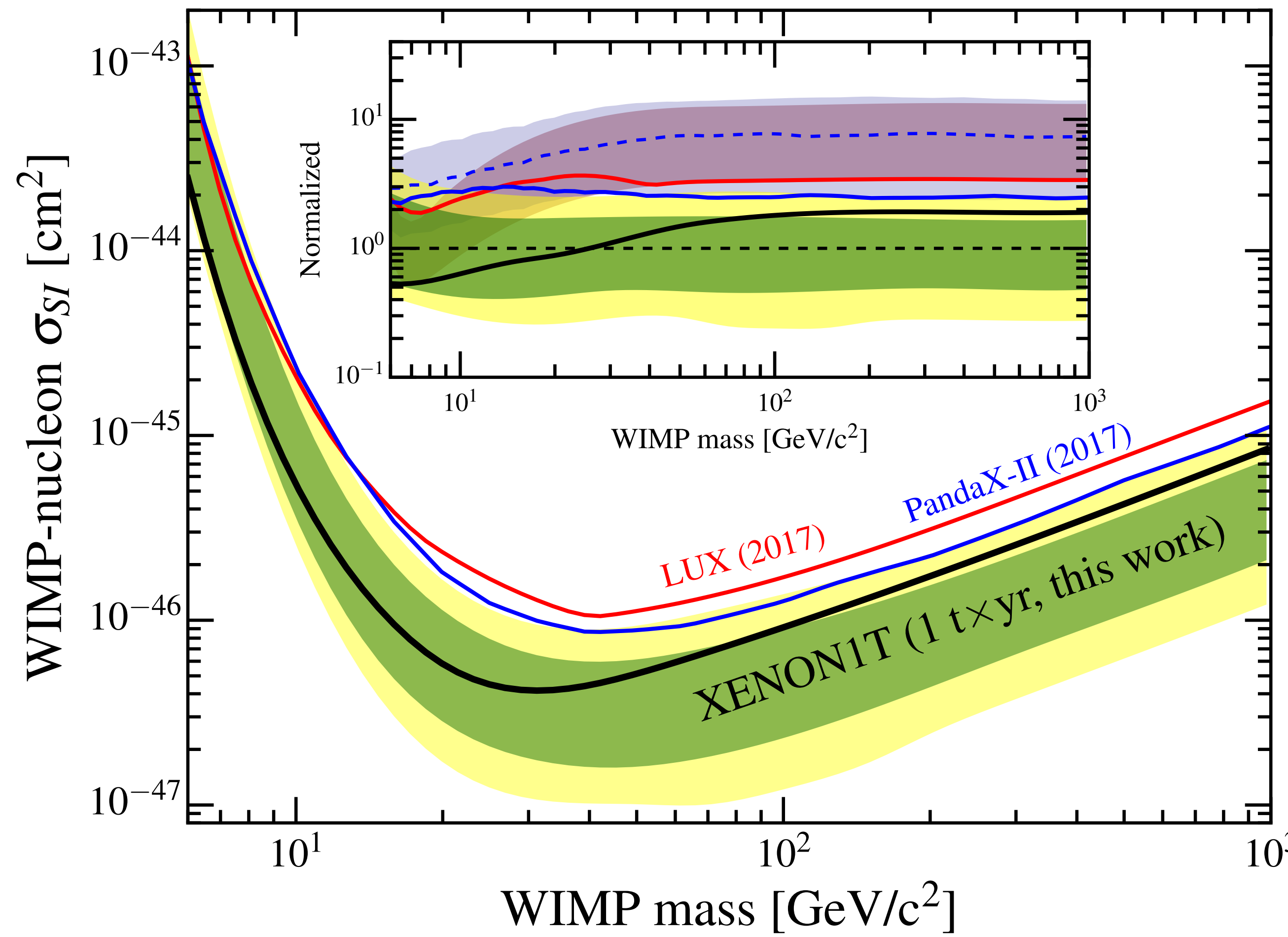
DM Direct Detection experiments





XENON Collaboration, arXiv: 1805.12562.

Ranny Budnik's talk.

Detect recoil energy of DM-nucleus scattering.

Experimental sensitivity has been significantly improving.

Theory side

On the theoretical side, we calculate

DM-nucleon scattering cross section

Challenges

- Nucleon matrix elements.
- Appropriate treatment for perturbation.
  - Effective theoretical approach.
  - Separation of short/long-distance effects.
  - Renormalization group equations (RGEs).

NREFT: Bradley J Kavanagh's talk.

Nucleon matrix elements

Nucleon matrix elements of quark scalar operators are defined by

Mass fractions

$$\langle N | m_q \bar{q}q | N \rangle / m_N \equiv f_{T_q}$$

(m_N : nucleon mass)

We extract these values from

$$\Sigma_{\pi N} \equiv \frac{1}{2}(m_u + m_d)\langle N | \bar{u}u + \bar{d}d | N \rangle$$

$$\sigma_s \equiv \langle N | m_s \bar{s}s | N \rangle$$

- Lattice simulation
- Chiral perturbation
- Low-energy *πN* scattering

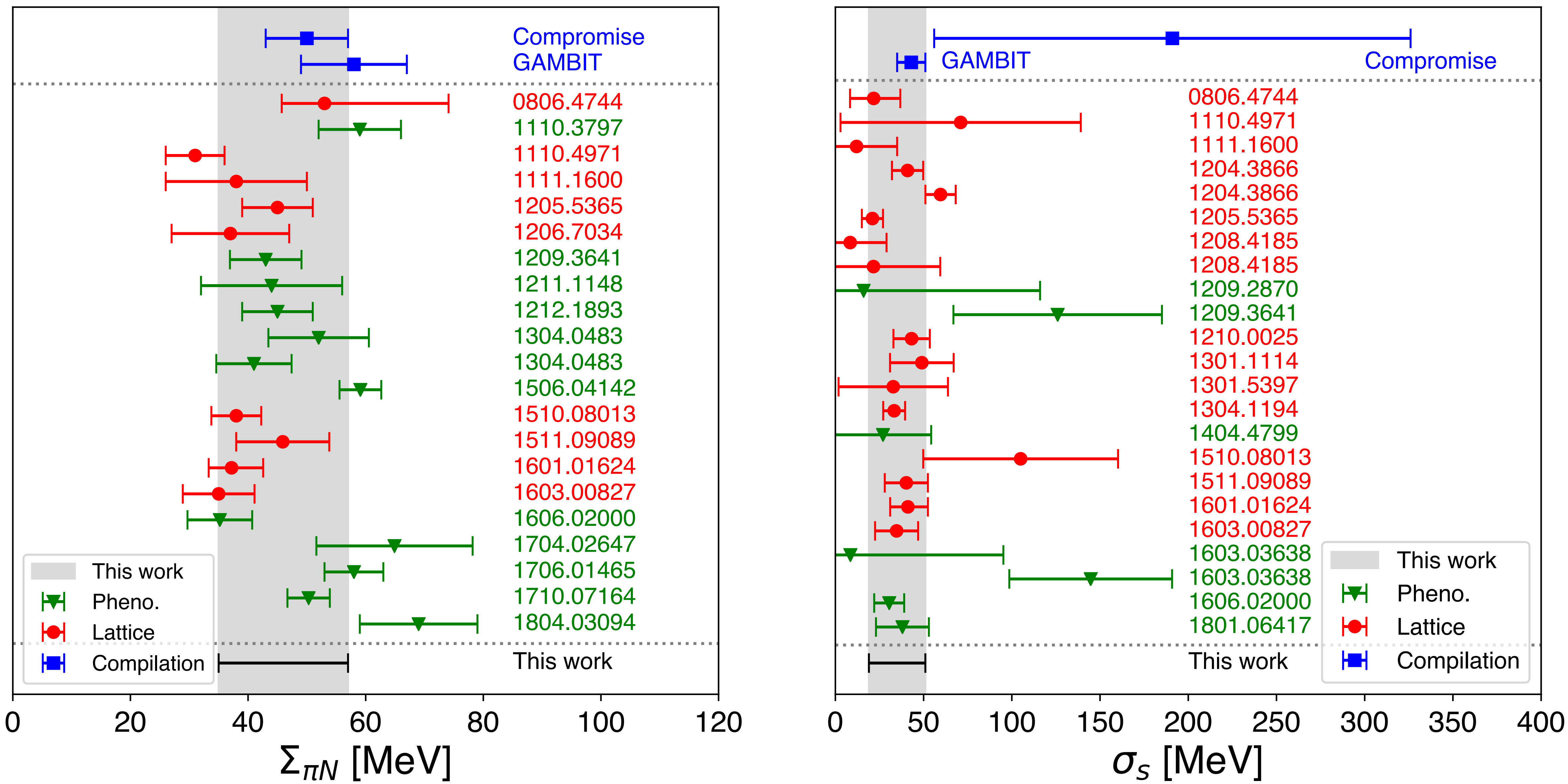
etc.

Cf.)

$$\sigma_0 = \frac{1}{2}(m_u + m_d)\langle N | \bar{u}u + \bar{d}d - 2\bar{s}s | N \rangle$$

Yields large uncertainty.

Recent computations



$$\Sigma_{\pi N} = 46 \pm 11 \text{ MeV}$$

$$\sigma_s = 35 \pm 16 \text{ MeV}$$

J. Ellis, N. Nagata, K. A. Olive, arXiv: 1805.09795.

Heavy quark/gluon contribution

Heavy quark/gluon contributions are evaluated with

Trace anomaly of the energy-momentum tensor

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

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

$G^{A}_{\mu\nu} G^{A\mu\nu} \rightarrow \langle N | G^{A}_{\mu\nu} G^{A\mu\nu} | N \rangle$

$m_q \bar{q} q \rightarrow m_N f_{T_q}$

- At leading order

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

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

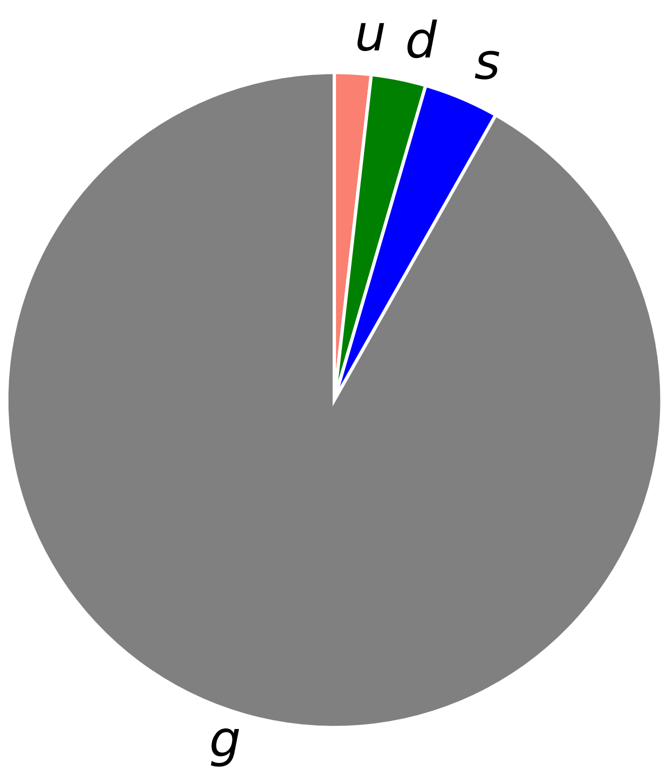
- Perturbative QCD corrections

$\mathcal{O}(\alpha_s^3)$ corrections available.

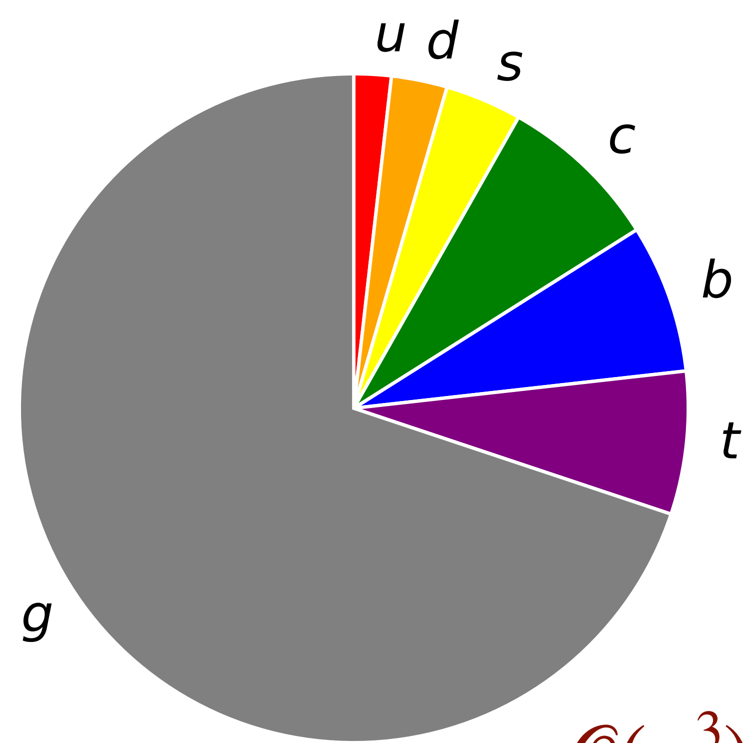
e.g.) L. Vecchi, arXiv: 1312.5695.

Our compilation for mass fractions

<u>Three quarks</u>



<u>Six quarks</u>



$\mathcal{O}(\alpha_s^3)$ pQCD

Proton		Neutron	
$f_{T_u}^{(p)}$	0.017(4)	$f_{T_u}^{(n)}$	0.014(3)
$f_{T_d}^{(p)}$	0.030(7)	$f_{T_d}^{(n)}$	0.037(9)
$f_{T_s}^{(p)}$	0.037(17)	$f_{T_s}^{(n)}$	0.037(17)
$f_{T_G}^{(p)}$	0.916(19)	$f_{T_G}^{(n)}$	0.912(20)

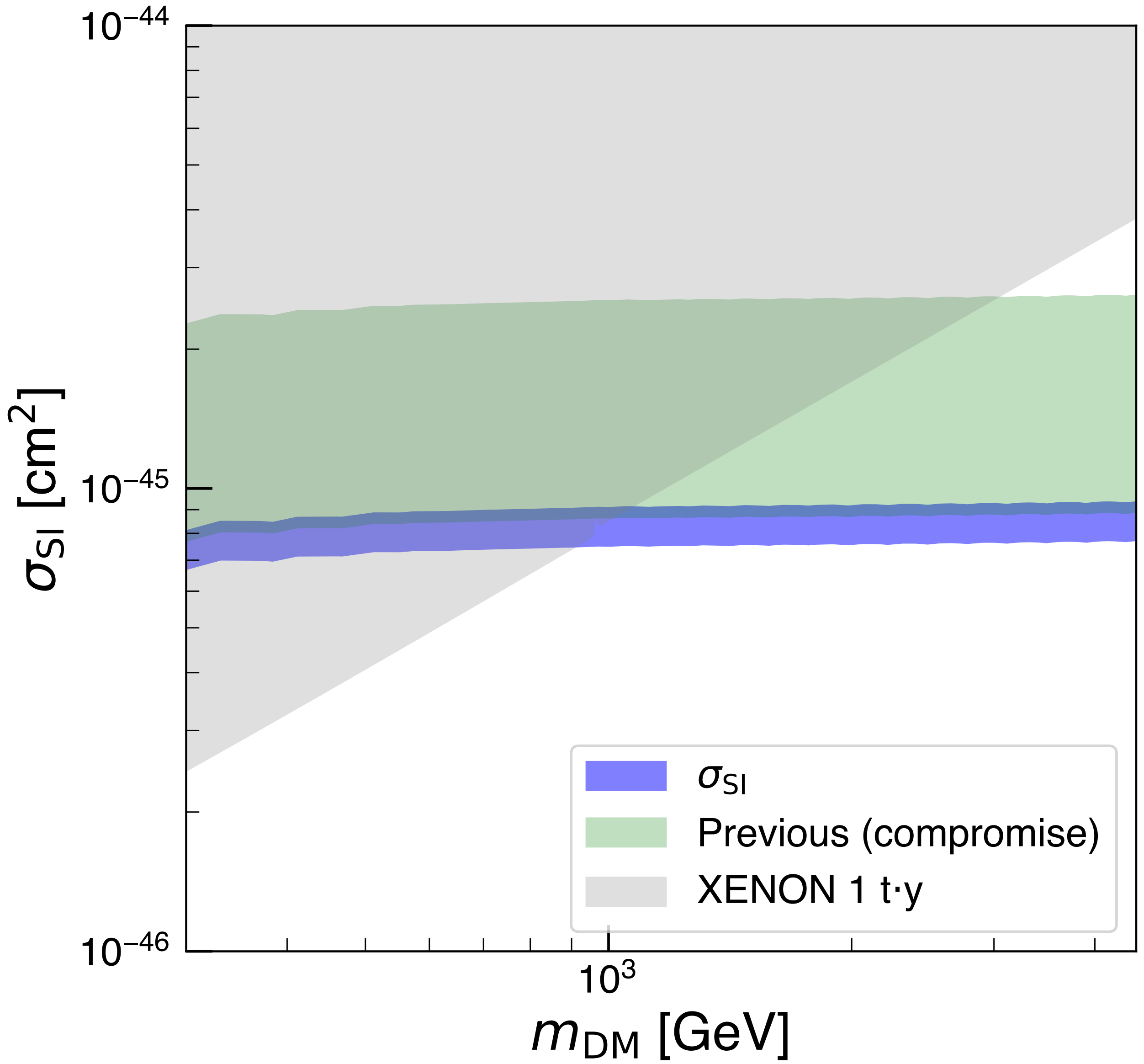
$f_{T_c}^{(p)} = 0.078(2)$ $\quad f_{T_c}^{(n)} = 0.078(2)$

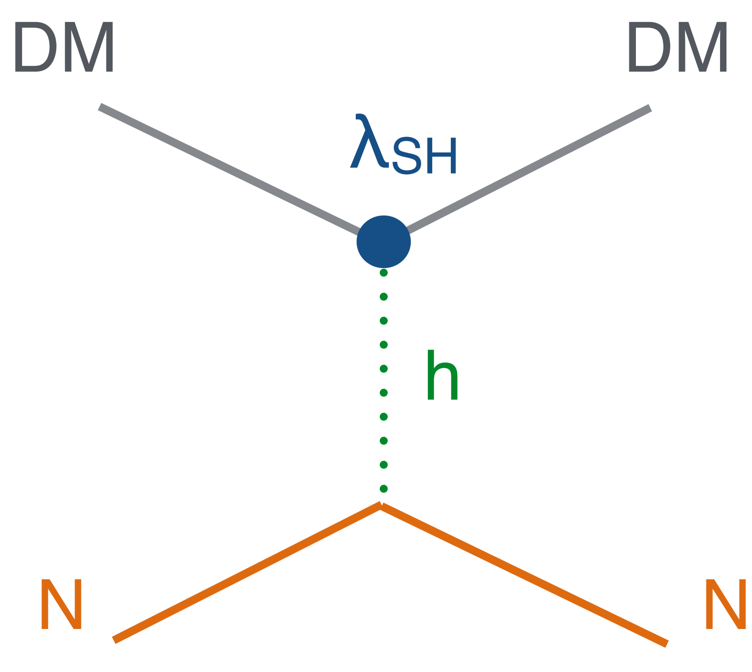
$f_{T_b}^{(p)} = 0.072(2)$ $\quad f_{T_b}^{(n)} = 0.071(2)$

$f_{T_t}^{(p)} = 0.069(2)$ $\quad f_{T_t}^{(n)} = 0.068(2)$

J. Ellis, N. Nagata, K. A. Olive, arXiv: 1805.09795.

Singlet real scalar DM

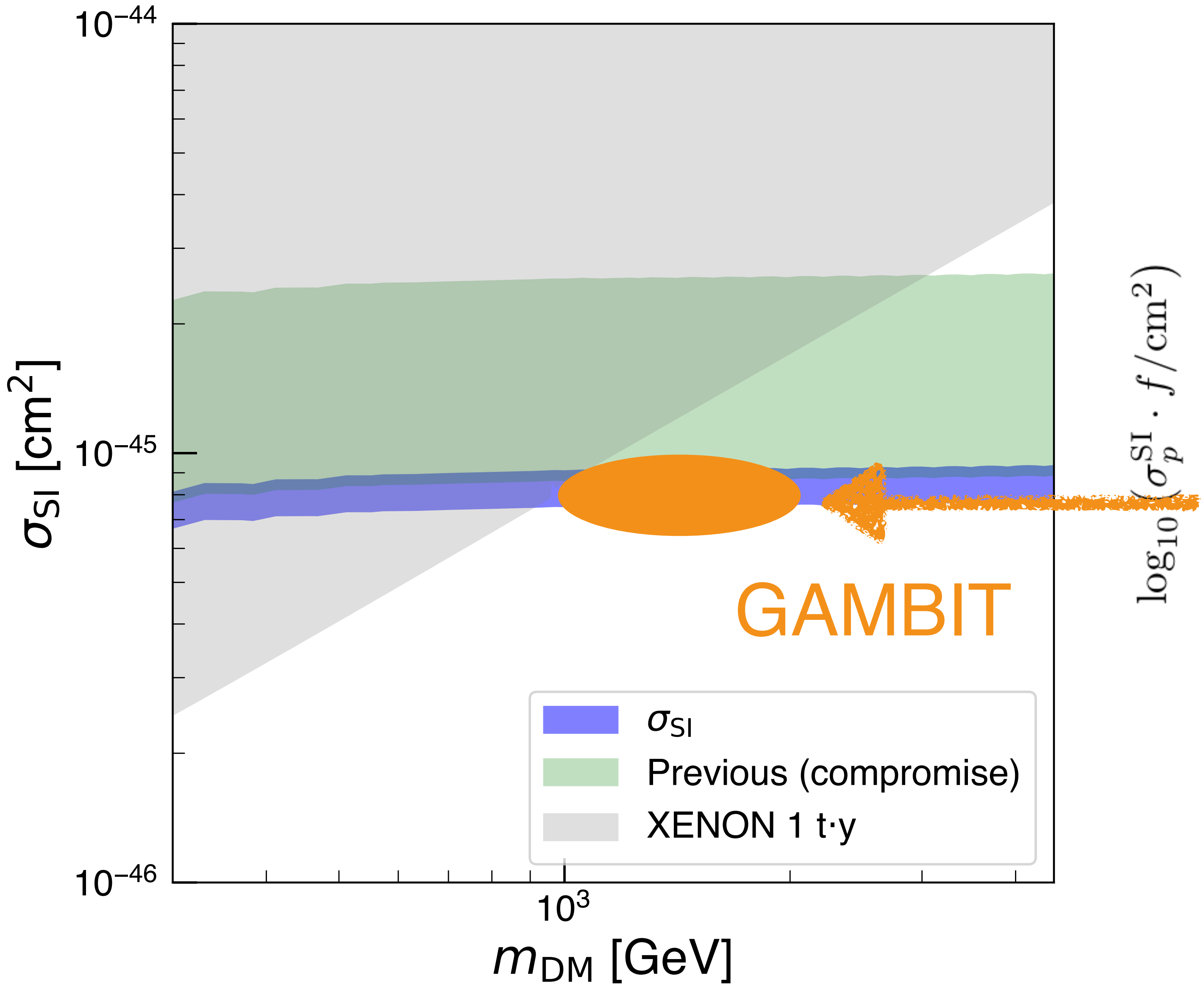


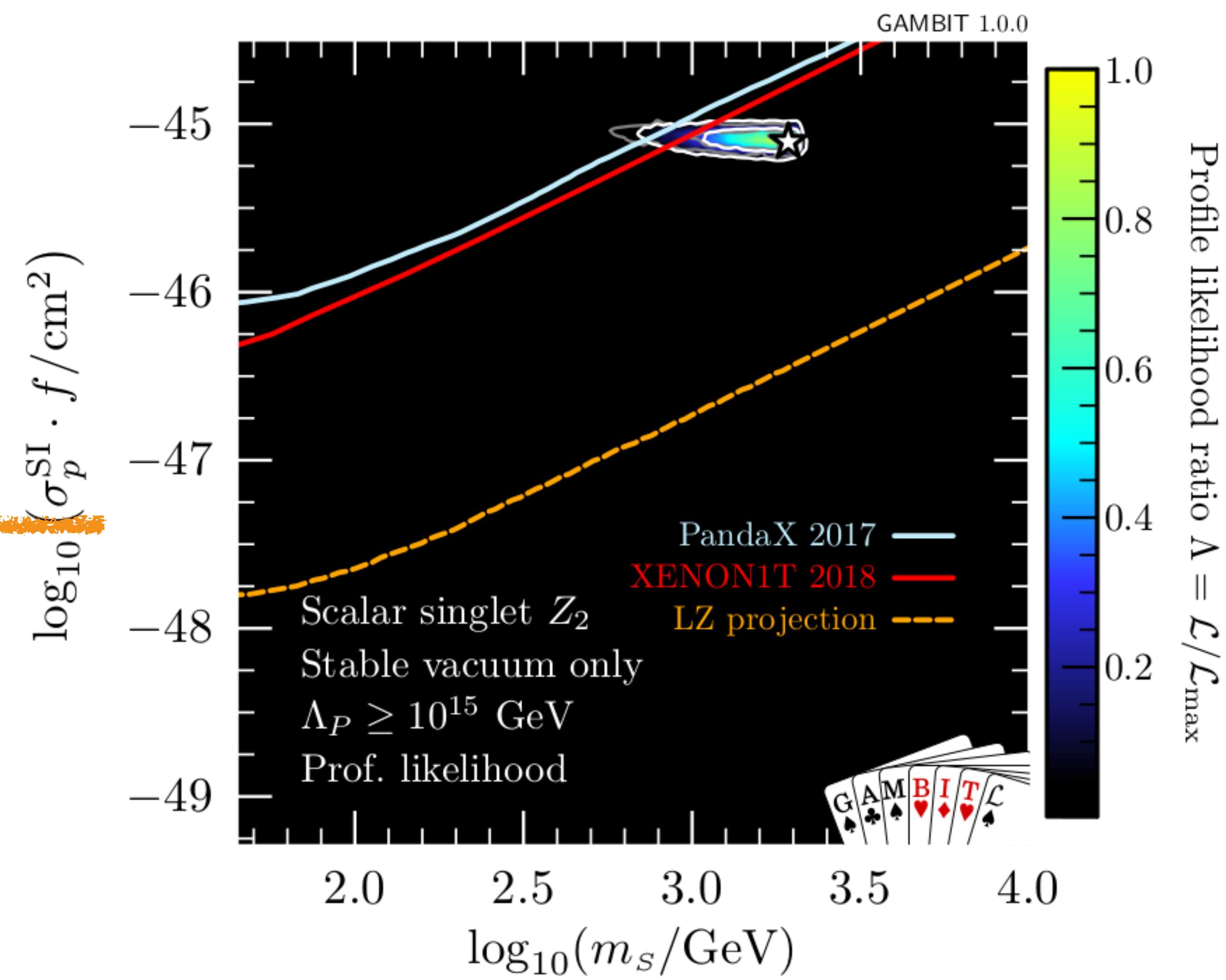


λ_{sH} is taken so that DM abundance agrees to the observed value.

Uncertainty from nucleon matrix elements reduced to O(10)% level.

Singlet real scalar DM





Felix Kahlhoefer's talk.

In good agreement with the GAMBIT result.

Perturbative calculation

To perform perturbative calculation at O(10)% accuracy

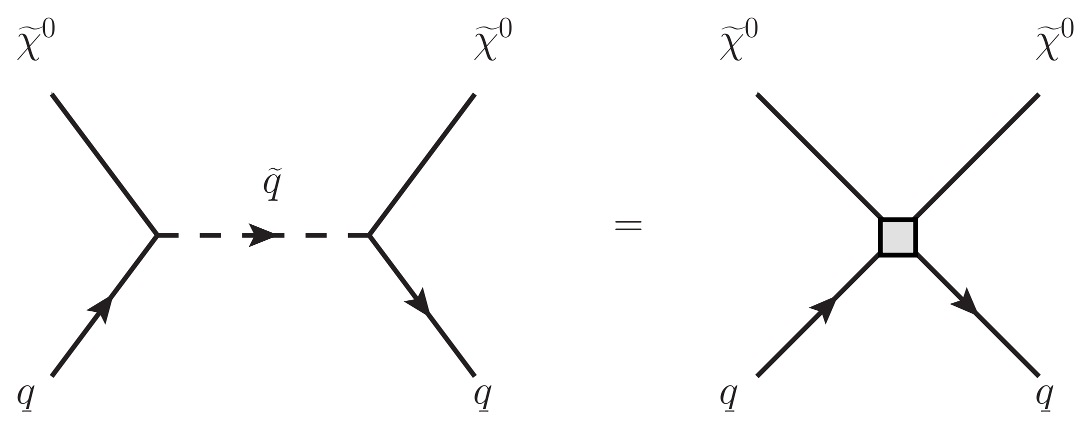
- RGE/threshold corrections in QCD
  - Effective theoretical approach.
  - Separation of short/long-distance effects.
- Electroweak-loop corrections

  Can be important when
  - DM has electroweak charge.
  - Tree-level contribution is suppressed.

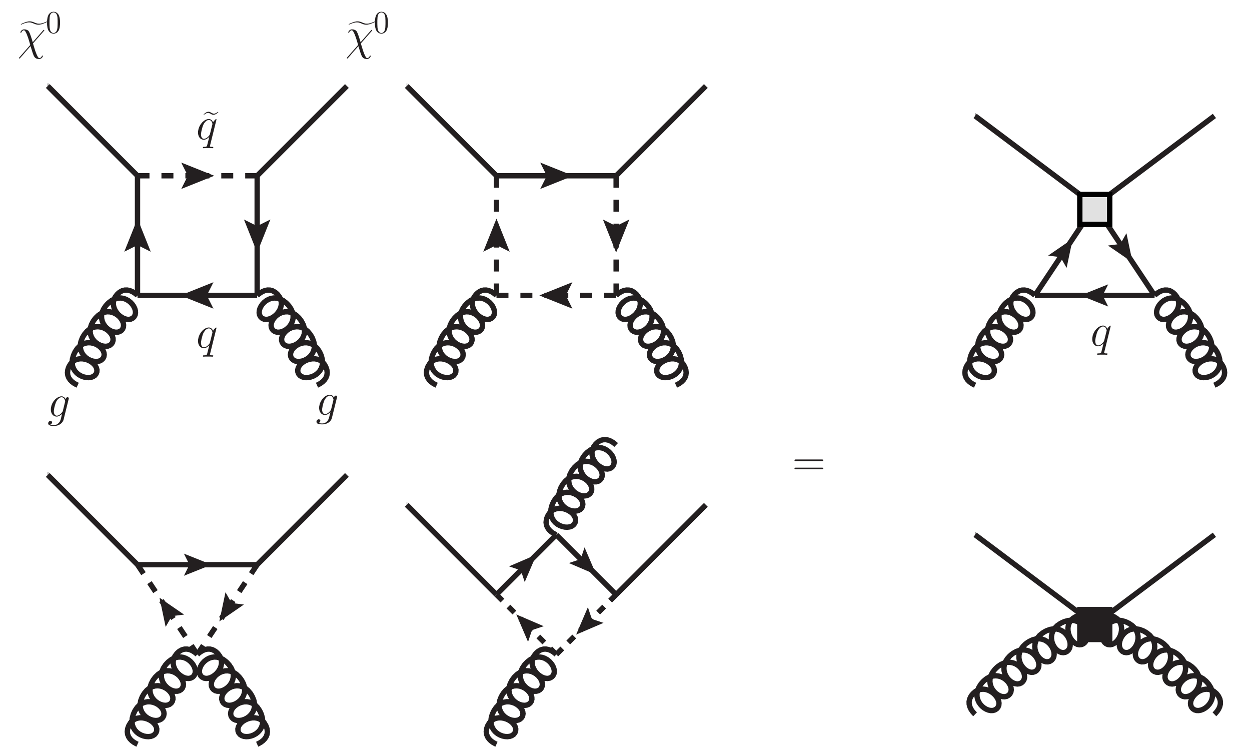
Wino in MSSM, Minimal DM, etc.

Colored mediators

Tree-level matching



One-loop matching



Only the short-distance contribution included into Wilson coefficients.

Operators are evolved according to RGEs.

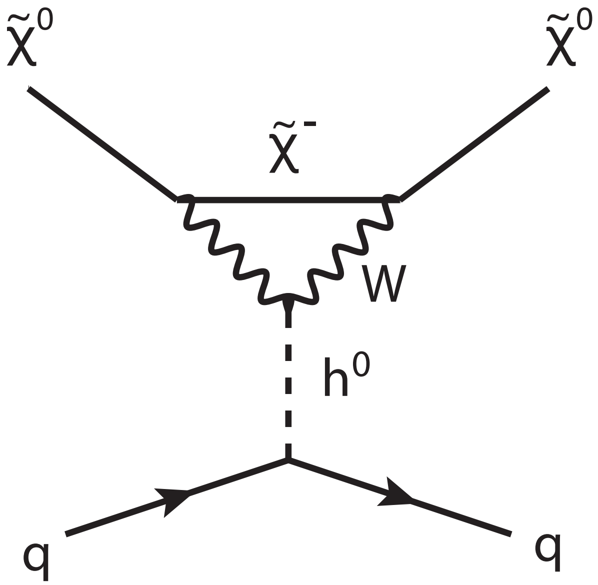
Important especially when mediators are heavy.

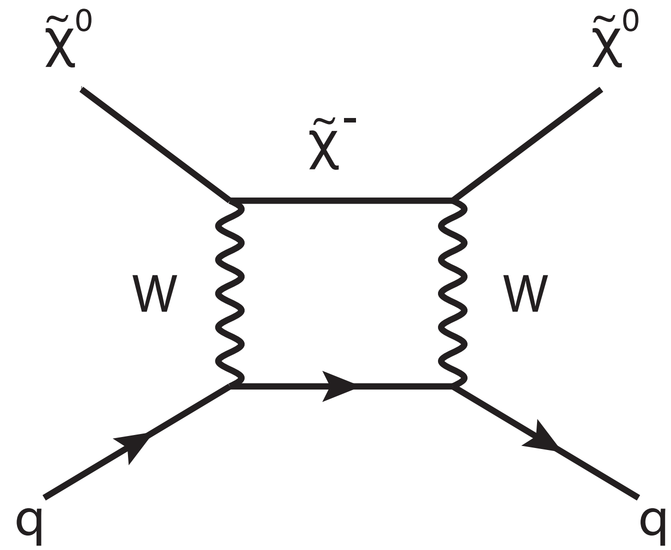
➡ O(10)% improvement.

J. Hisano, R. Nagai, N. Nagata, JHEP **1505**, 037 (2015).

Electroweak loop corrections (**n** = 3, Y = 0)

1-loop (quark)



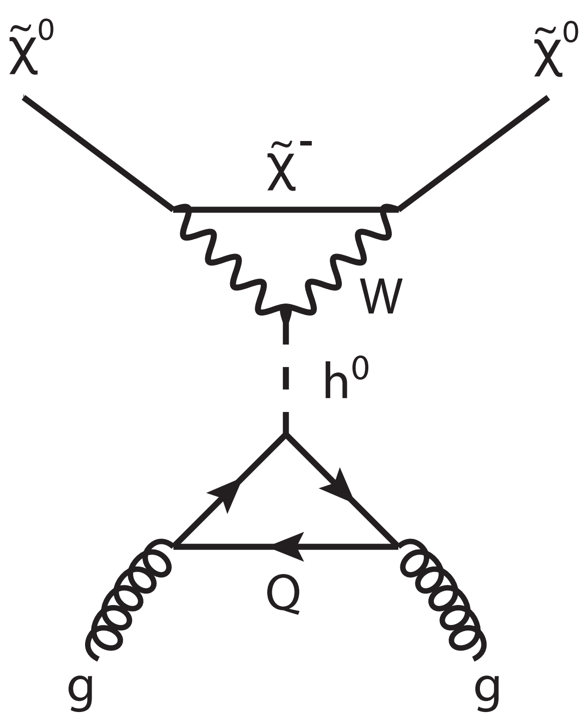


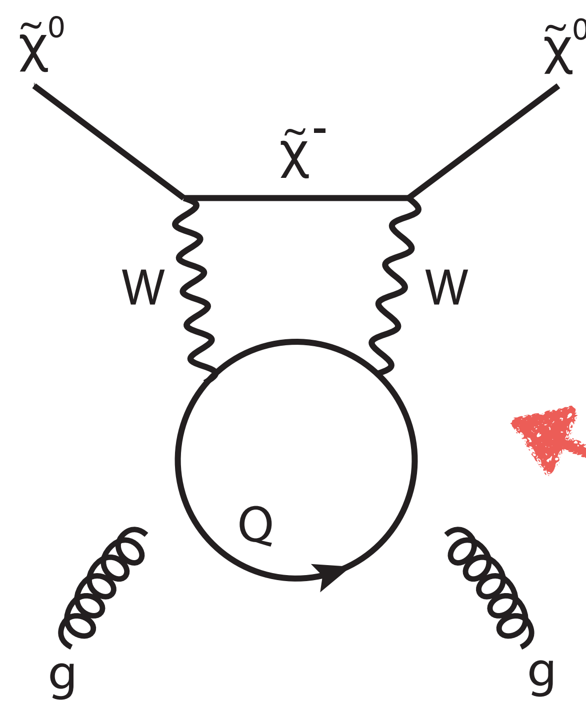
Non-decoupling effects

$$\mathcal{O}\left(\frac{\alpha_2^2}{m_W m_h^2}\right) \quad \mathcal{O}\left(\frac{\alpha_2^2}{m_W^3}\right)$$

J. Hisano, S. Matsumoto, M. Nojiri, O. Saito (2005)

2-loop (gluon)

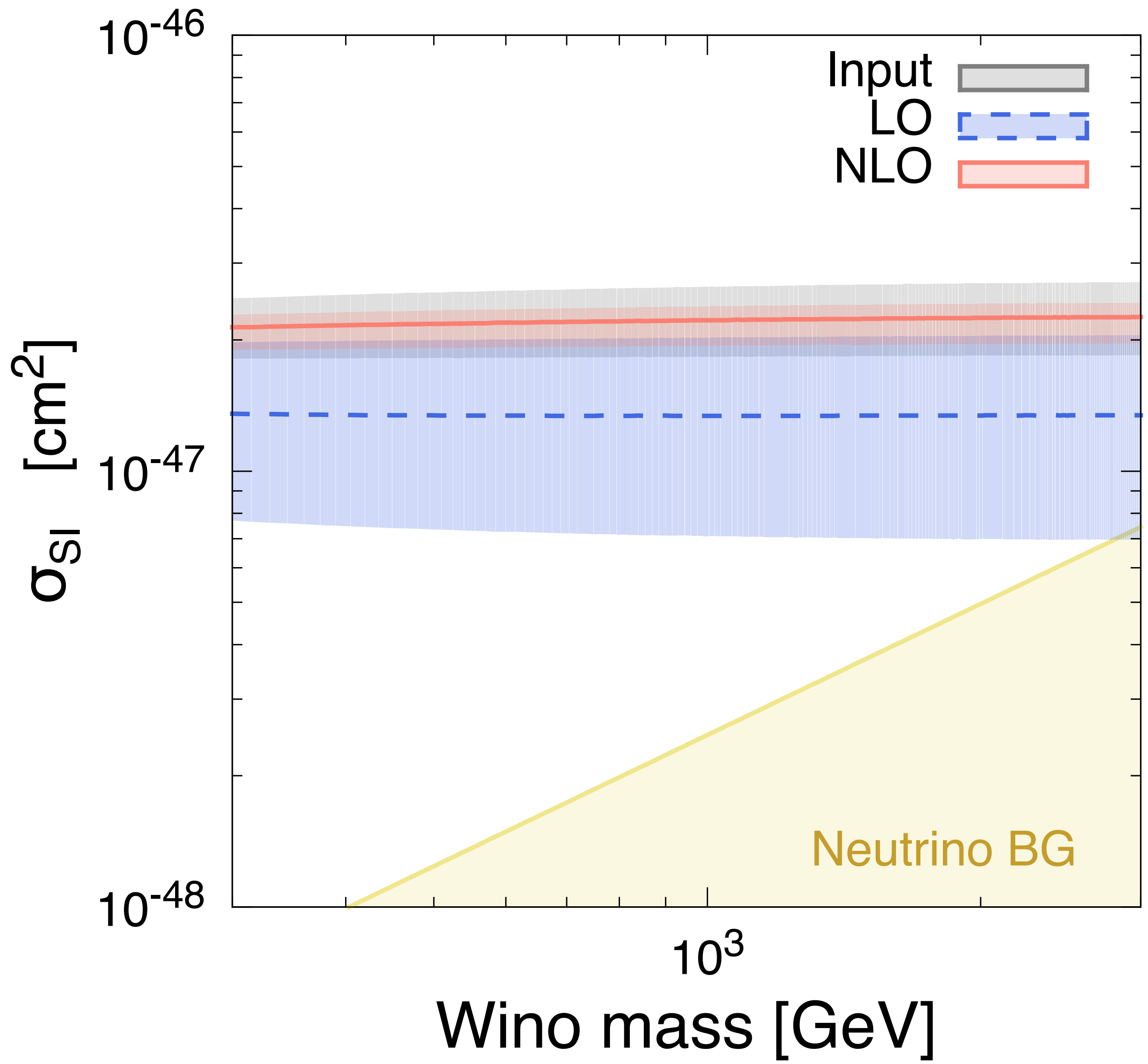




Comparable to the 1-loop contributions

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

NLO results

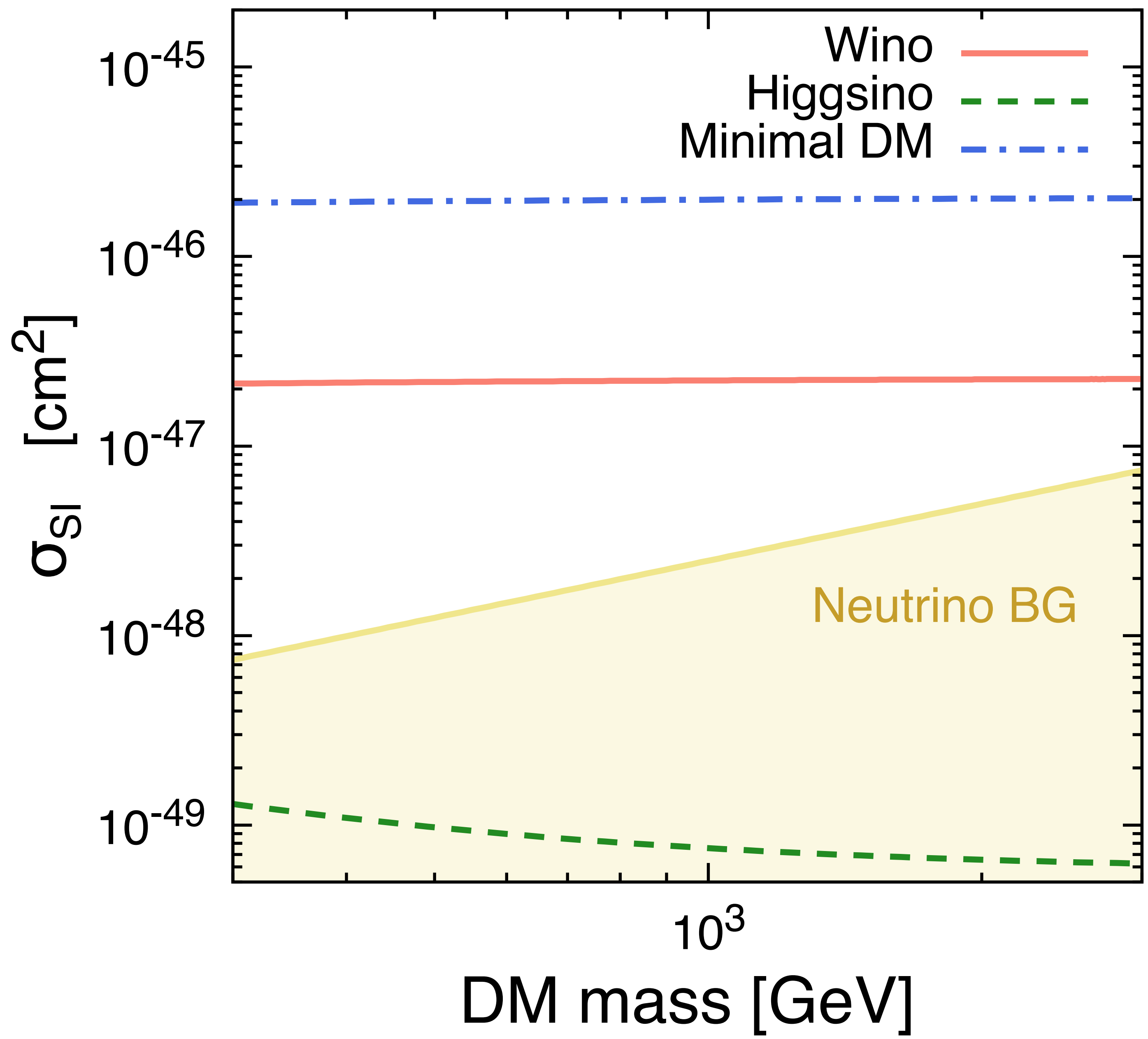


Error was large due to cancellation among various contributions.

With NLO QCD corrections included, uncertainty reduced to O(10)% level.

J. Hisano, K. Ishiwata, N. Nagata, JHEP **1506**, 097 (2015).

NLO results



- Triplet and quintuplet cases can be probed.
- Doublet case is below the neutrino floor.

J. Hisano, K. Ishiwata, N. Nagata, JHEP **1506**, 097 (2015).

Conclusion

- Direct DM searches are proceeding apace.
- To make the most of these experiments, theoretical uncertainties should be minimized.
- Uncertainties in nucleon matrix elements are controlled within O(10)% level.
- Higher-loop corrections can be important.

Backup

Recent computations

Reference	$\Sigma_{\pi N}$	Uncertainties	σ_s	Uncertainties	Method
[22]	50	7	191	135	Compilation
[33]	58	9	43	8	Compilation
[36]	53	2^{+21}_{-7}	21.7	$^{+15.1}_{-13.4}$	Lattice
[37]	59	7			BχPT, π atoms
[38]	31	3 ± 4	71	34 ± 59	Lattice
[39]	38	12	12	$^{+23}_{-16}$	Lattice
[40]			40.9	7.5 ± 4.7	Lattice
			59.6	5.1 ± 6.9	Lattice
[41]	45	6	21	6	Lattice
[42]	37	8 ± 6			Lattice
[43]			8.4	14.1 ± 15.0	Lattice
			21.6	27.2 ± 26.3	Lattice
[11]			16	80 ± 60	BχPT
[44]	43	1 ± 6	126	24 ± 54	Lattice/BχPT
[45]			43.2	10.3	Lattice
[46]	44	12			πN scattering
[47]	45	6			πN scattering
[48]			49	10 ± 15	Lattice
[49]			32.8	31.0	Lattice
[50]	52	3 ± 8			Lattice/BχPT
	41	5 ± 4			Lattice/BχPT
[51]			33.3	6.2	Lattice/BχPT
[52]			27	27 ± 4	Lattice/BχPT
[53]	59.1	1.9 ± 3			π atoms
[54]	38	3 ± 3	105	41 ± 37	Lattice
[55]	45.9	7.4 ± 2.8	40.2	11.7 ± 3.5	Lattice
[56]	37.2	$2.6^{+4.7}_{-2.9}$	41.1	$8.2^{+7.8}_{-5.8}$	Lattice
[26]	35	6.1	34.7	12.2	Lattice
[57]			8.5	4.4 ± 86.6	π atoms, πN scattering
			144.7	4.6 ± 45.9	π atoms, πN scattering
[58]	35.2	5.5	30.5	8.5	BχPT
[59]	64.9	1.5 ± 13.2			Lattice/BχPT
[60]	58	5			πN scattering
[61]	50.3	1.2 ± 3.4			Lattice/BχPT
[62]	48		38	15	Lattice/BχPT
[63]	69	10			BχPT
This work	**46**	**11**	**35**	**16**	**New compilation**

J. Ellis, N. Nagata, K. A. Olive, arXiv: 1805.09795.

PDG method

We use the method adopted by PDG to obtain average and error.

Wighted average and error

$$\bar{x} + \delta\bar{x} = \frac{\sum_i w_i x_i}{\sum_i w_i} \pm \left(\frac{\chi^2}{(N-1)\sum_i w_i} \right)^{1/2}$$

with weights defined by $w_i = 1/(\delta x_i)^2$ and χ^2

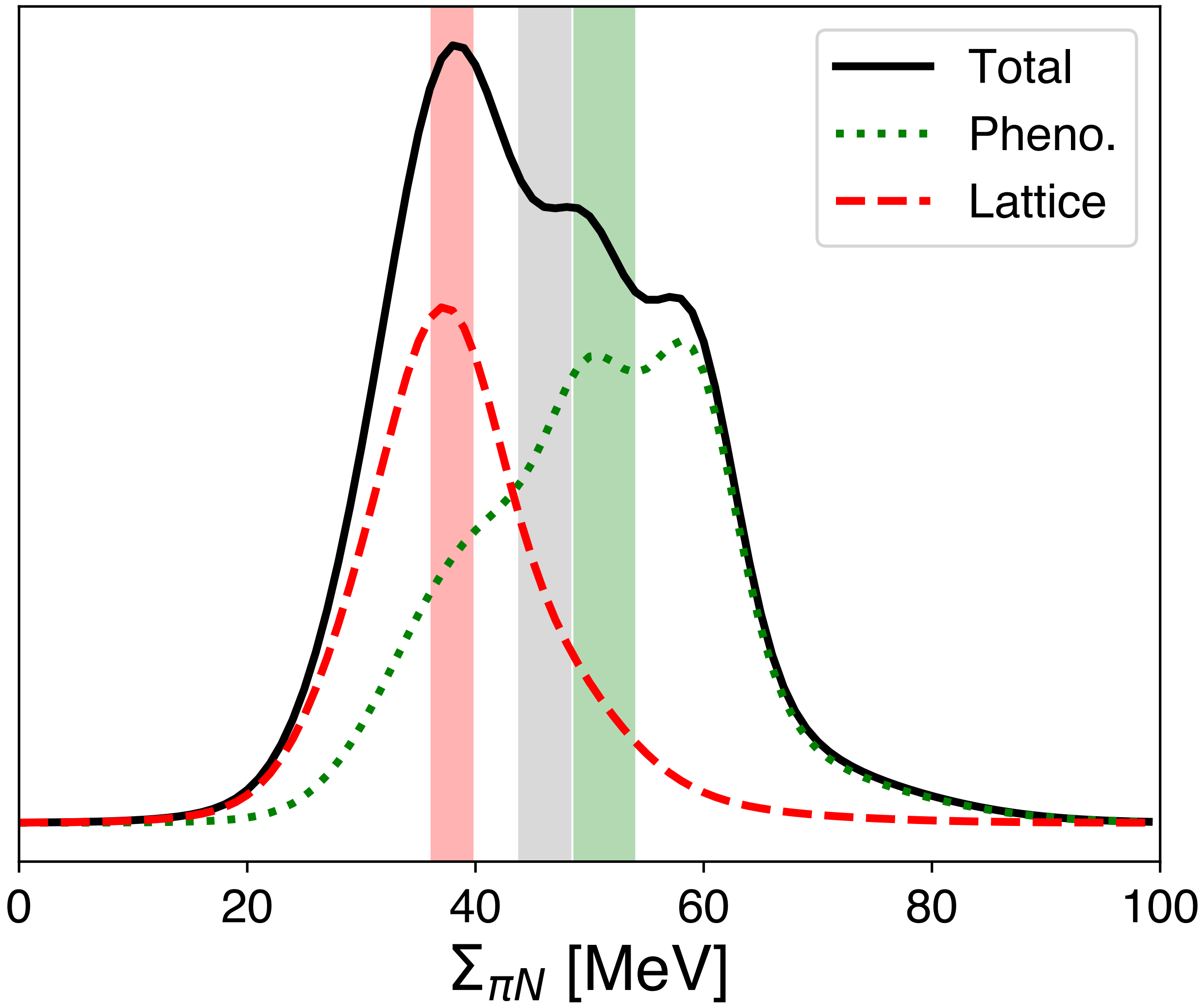
$$\chi^2 = \sum_i w_i (x_i - \bar{x})^2$$

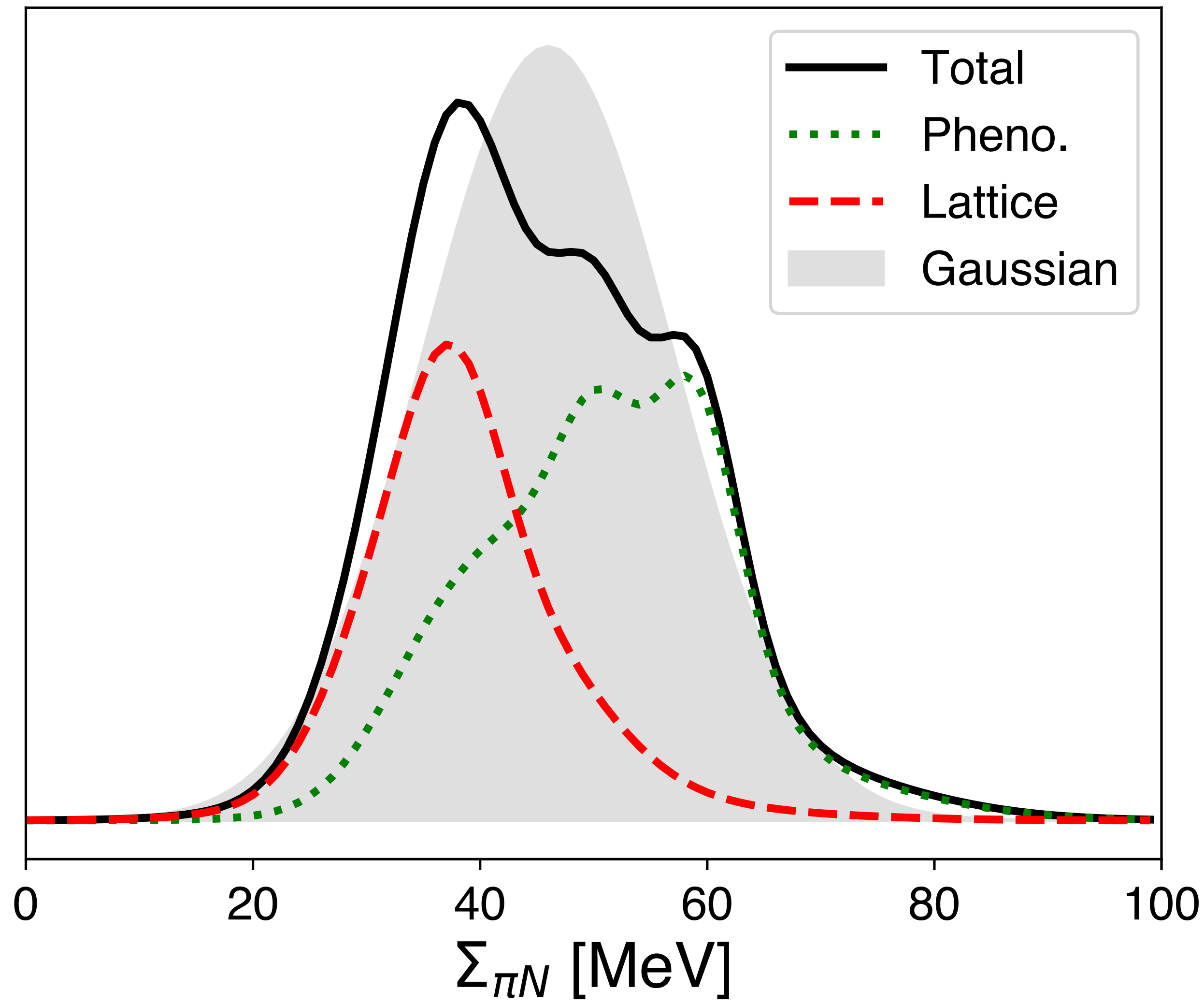
Ideogram

$$I(x) = \sum_i \frac{1}{\sqrt{2\pi\delta x_i^2}} \exp\left[-\frac{(x - x_i)^2}{2\delta x_i^2} \right]$$

Sum of Gaussians with a central value x_i, error δx_i, and area proportional to $1/\delta x_i$.

Ideogram: $\Sigma_{\pi N}$





<u>PDG method</u>

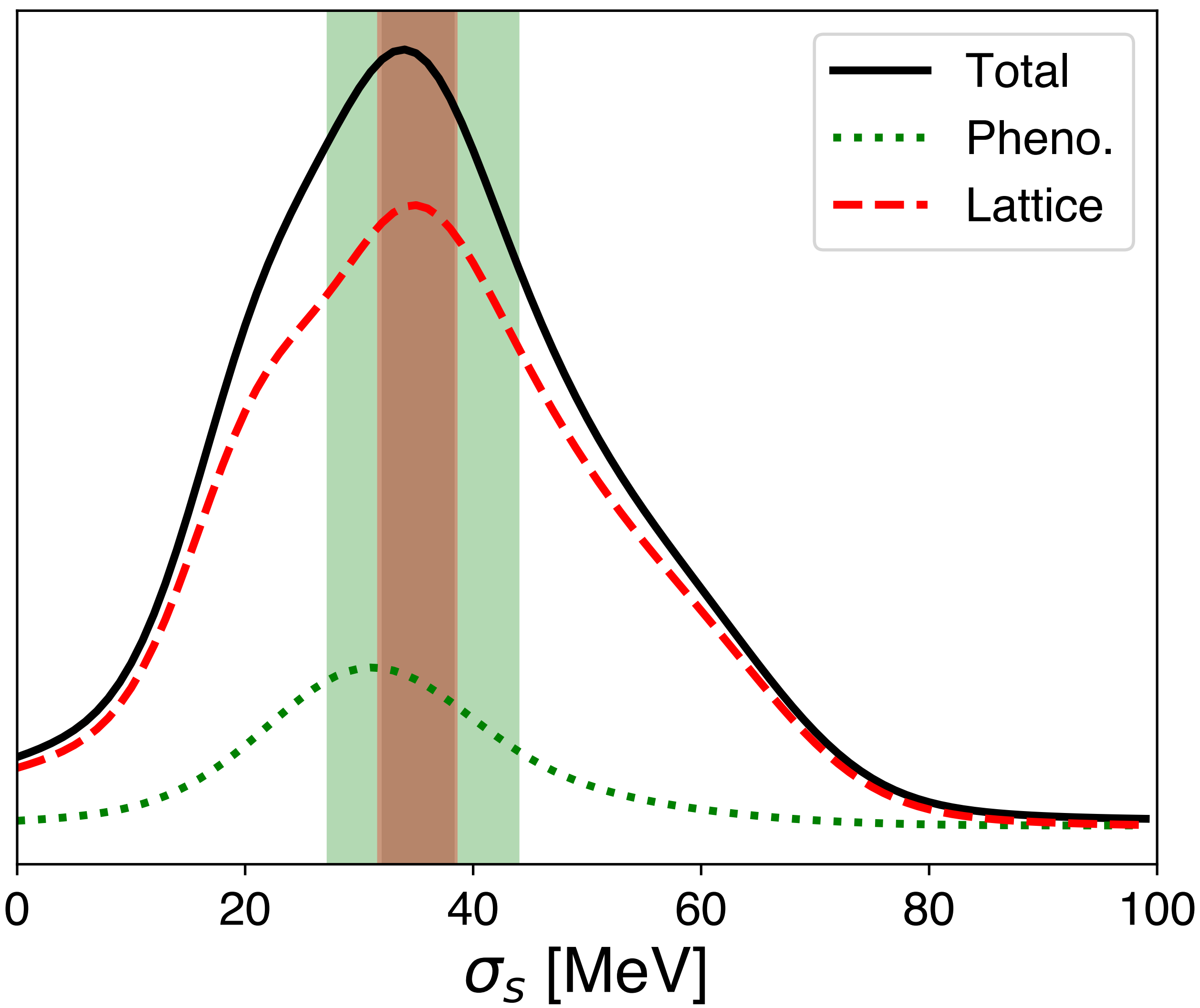
$$\Sigma_{\pi N} = 46.1 \pm 2.2 \text{ MeV}$$

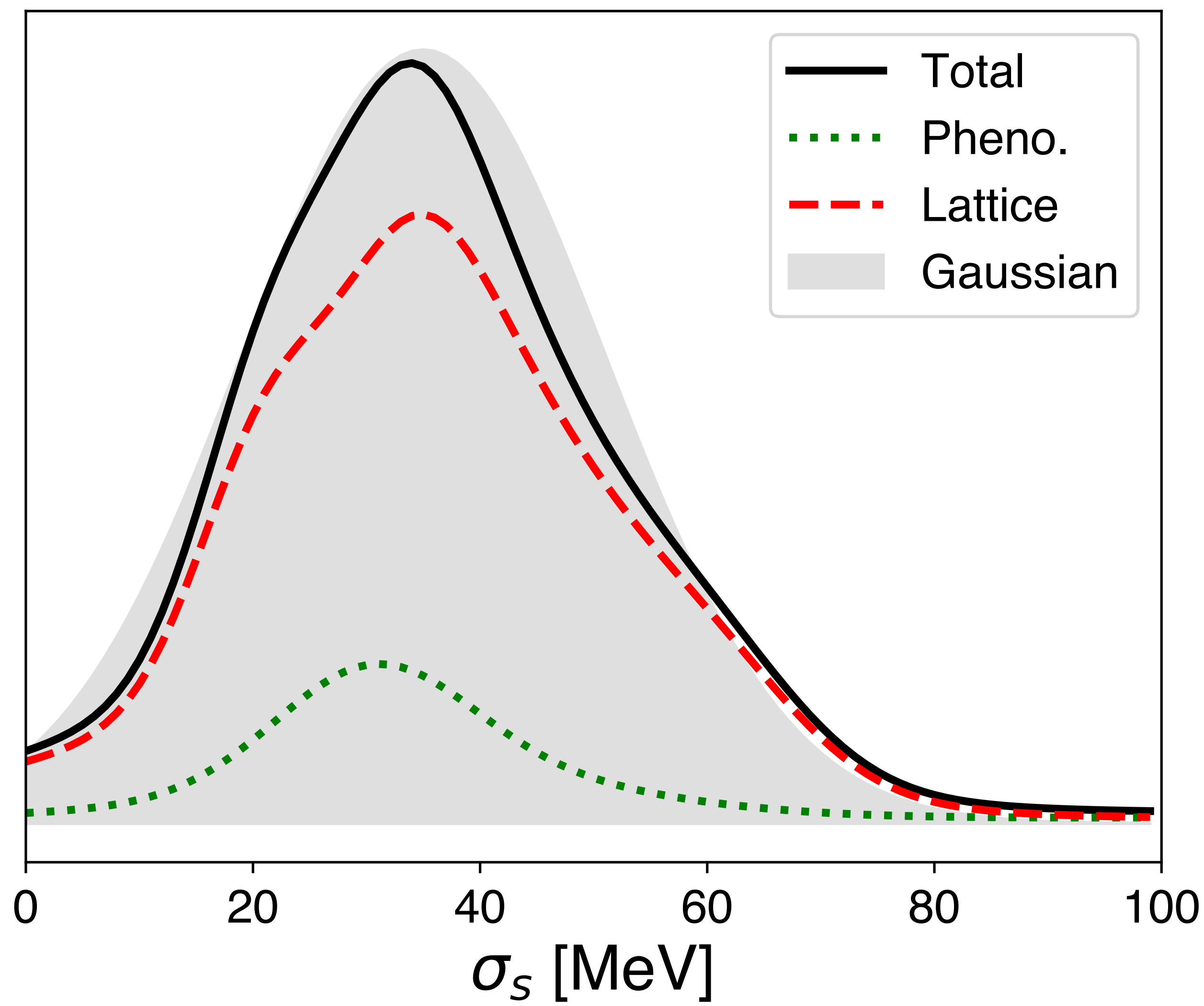
<u>Ours</u>

$$\Sigma_{\pi N} = 46 \pm 11 \text{ MeV}$$

J. Ellis, N. Nagata, K. A. Olive, arXiv: 1805.09795.

Ideogram: σ_s





PDG method

$$\sigma_s = 35.2 \pm 3.1 \text{ MeV}$$

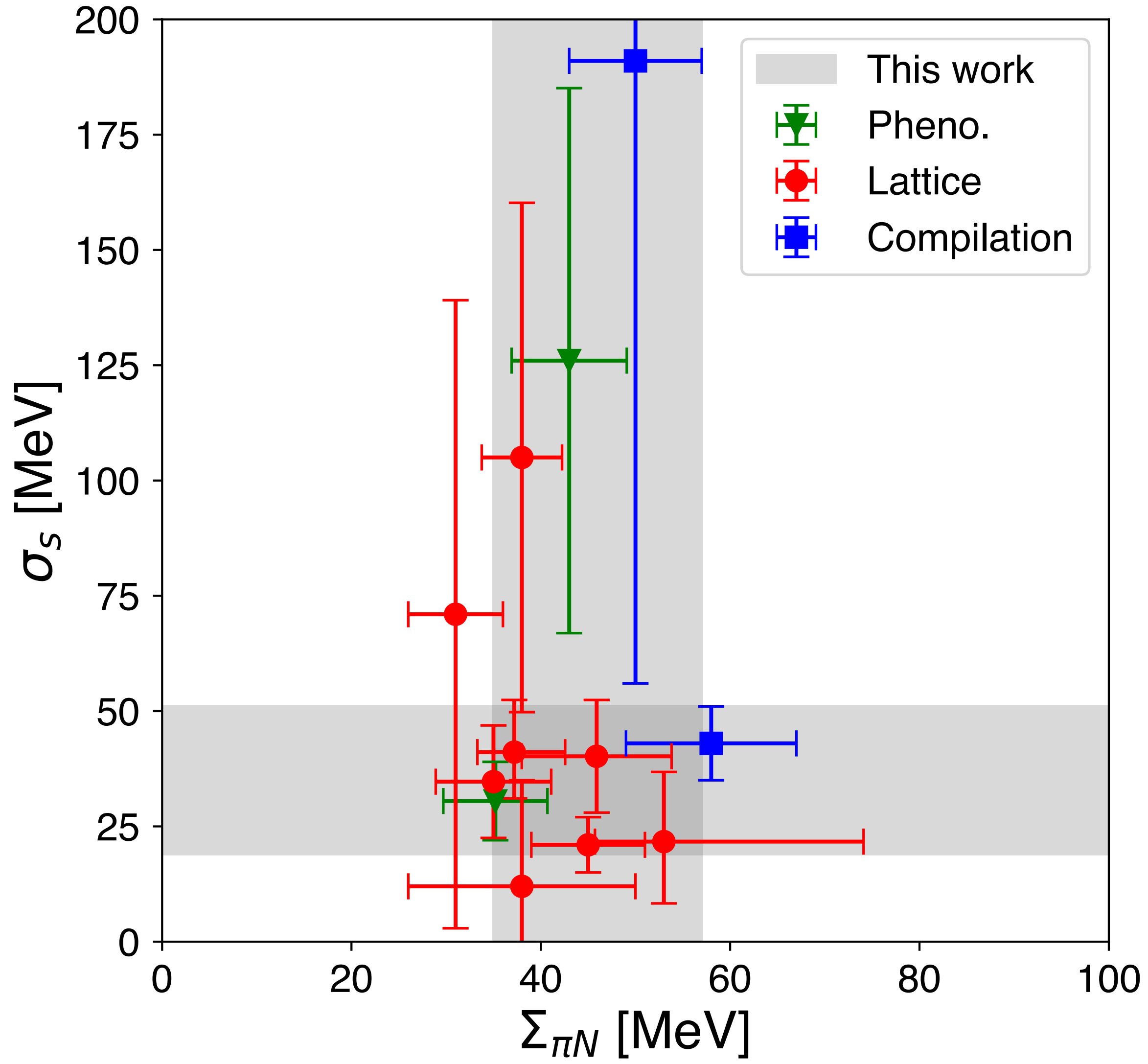
Ours

$$\sigma_s = 35 \pm 16 \text{ MeV}$$

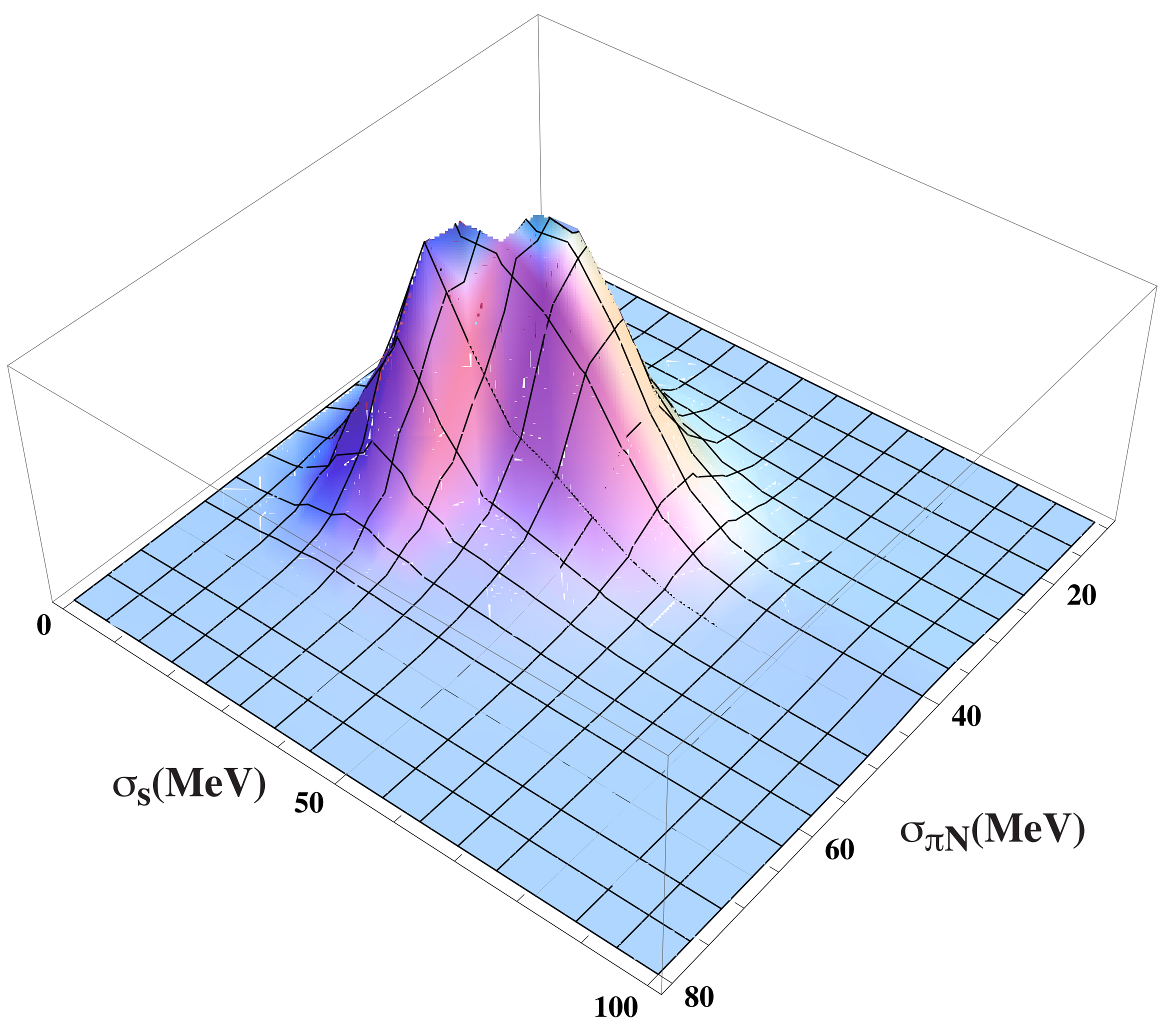
J. Ellis, N. Nagata, K. A. Olive, arXiv: 1805.09795.

Correlation between $\Sigma_{\pi N}$ and σ_s

Scatter plot



2-D ideogram



No significant correlation.

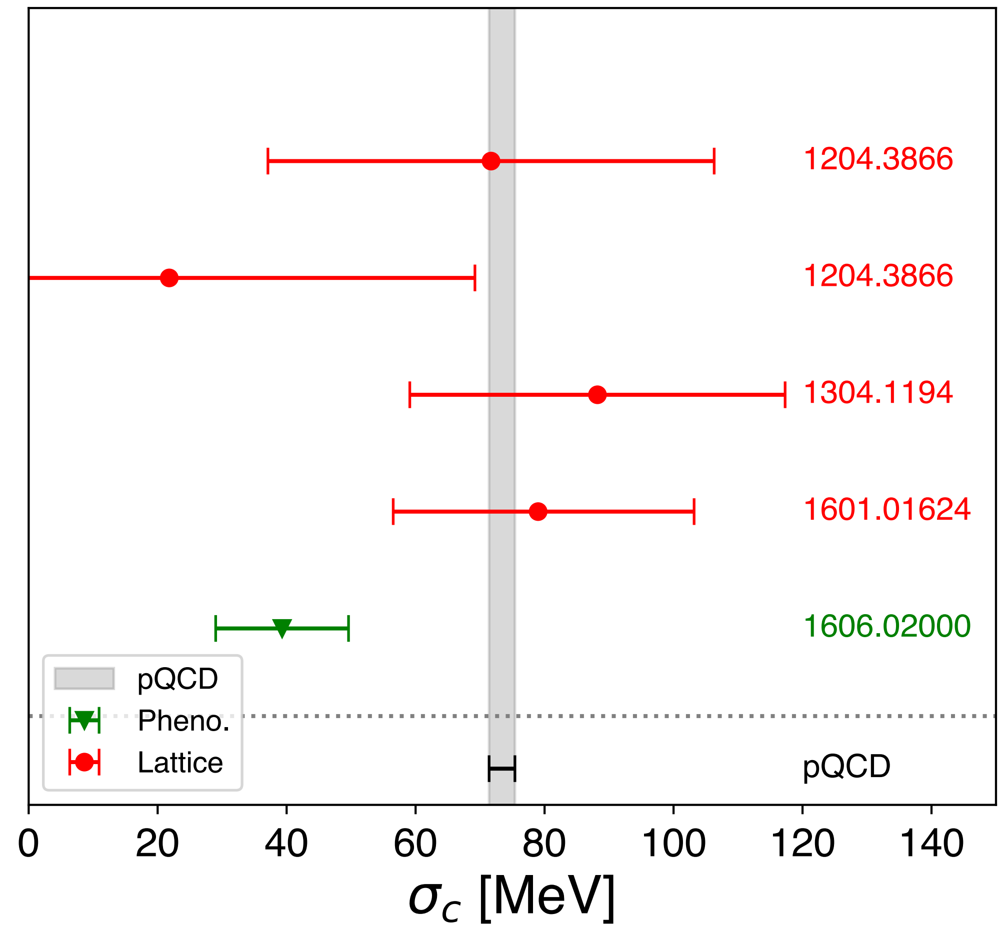
J. Ellis, N. Nagata, K. A. Olive, arXiv: 1805.09795.

Direct evaluation of σ_c

Results

Reference	σ_c	Uncertainties	Method
[44]	71.7	34.6	Lattice
	21.8	47.4	Lattice
[55]	88.2	29.1	Lattice
[60]	79	21^{+12}_{-8}	Lattice
[62]	39.3	10.3	Phenomenology
[68]	4.3	4.4	Phenomenology
	12.5	13	Phenomenology
	32.3	33.6	Phenomenology

Scatter plot



Errors are much larger than that obtained from pQCD.

J. Ellis, N. Nagata, K. A. Olive, arXiv: 1805.09795.

Singlet real scalar DM

Lagrangian

$$\mathcal{L}_{\rm int} = -\frac{1}{2}m^2 S^2 - \frac{1}{2}\lambda_{SH} S^2 |H|^2 - \frac{1}{4!}\lambda_S S^4$$

$$m_{\rm DM} = m^2 + \frac{\lambda_{SH} v^2}{2}$$

The DM phenomenology is governed by two parameters:

m_{DM} λ_{SH}

If you require its thermal relic abundance to agree with the observed DM density, only one free parameter remains.

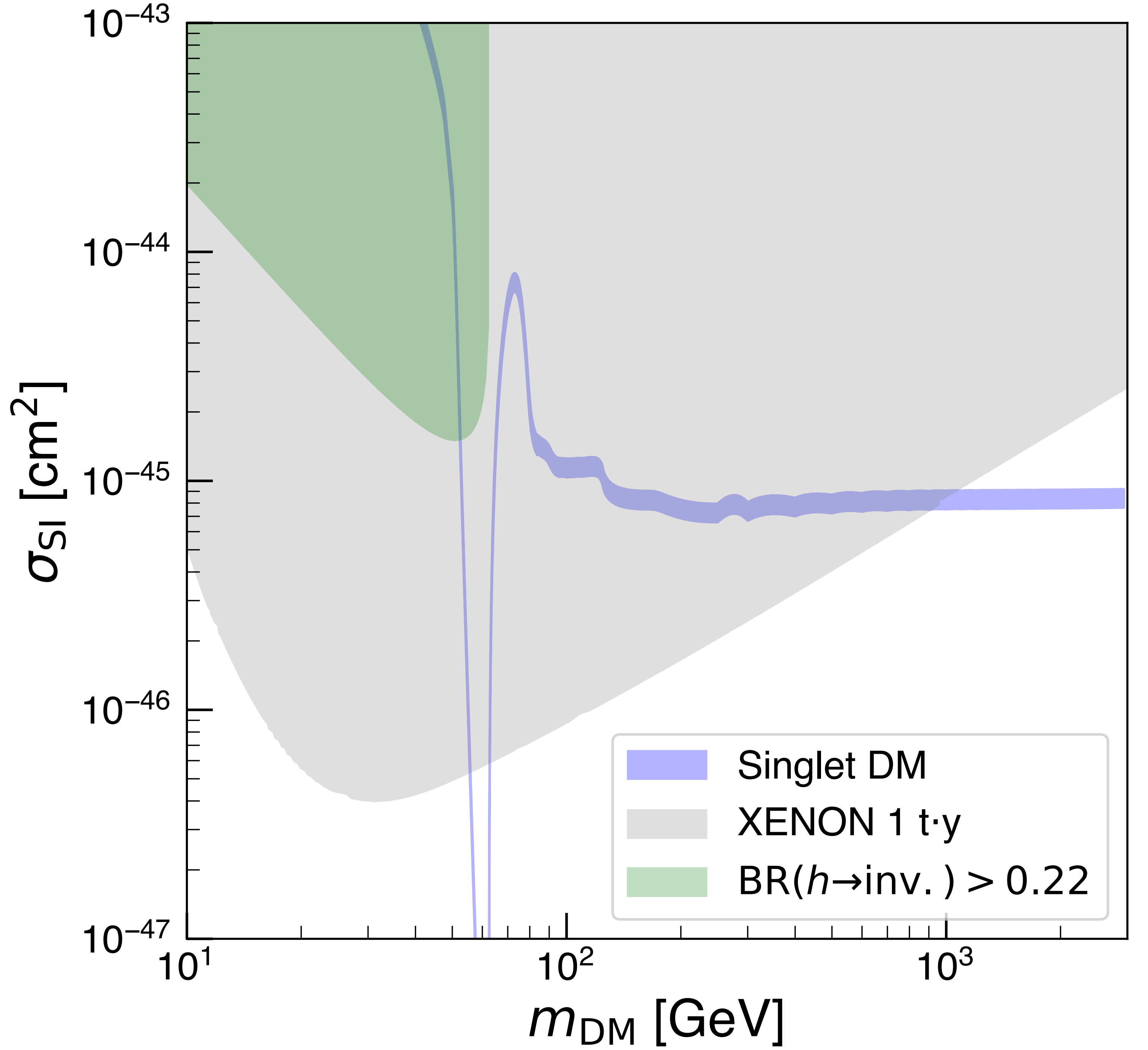
$$\sigma_{\rm ann} v_{\rm rel} \simeq \frac{\lambda_{sH}^2}{16\pi m_{\rm DM}^2}$$

$$\Omega_{\rm DM} h^2 \simeq \frac{3 \times 10^{-27}\ {\rm cm}^3\,{\rm s}^{-1}}{\langle \sigma_{\rm ann} v_{\rm rel}\rangle}$$

Observation

$$\Omega_{\rm DM} h^2 \simeq 0.12$$

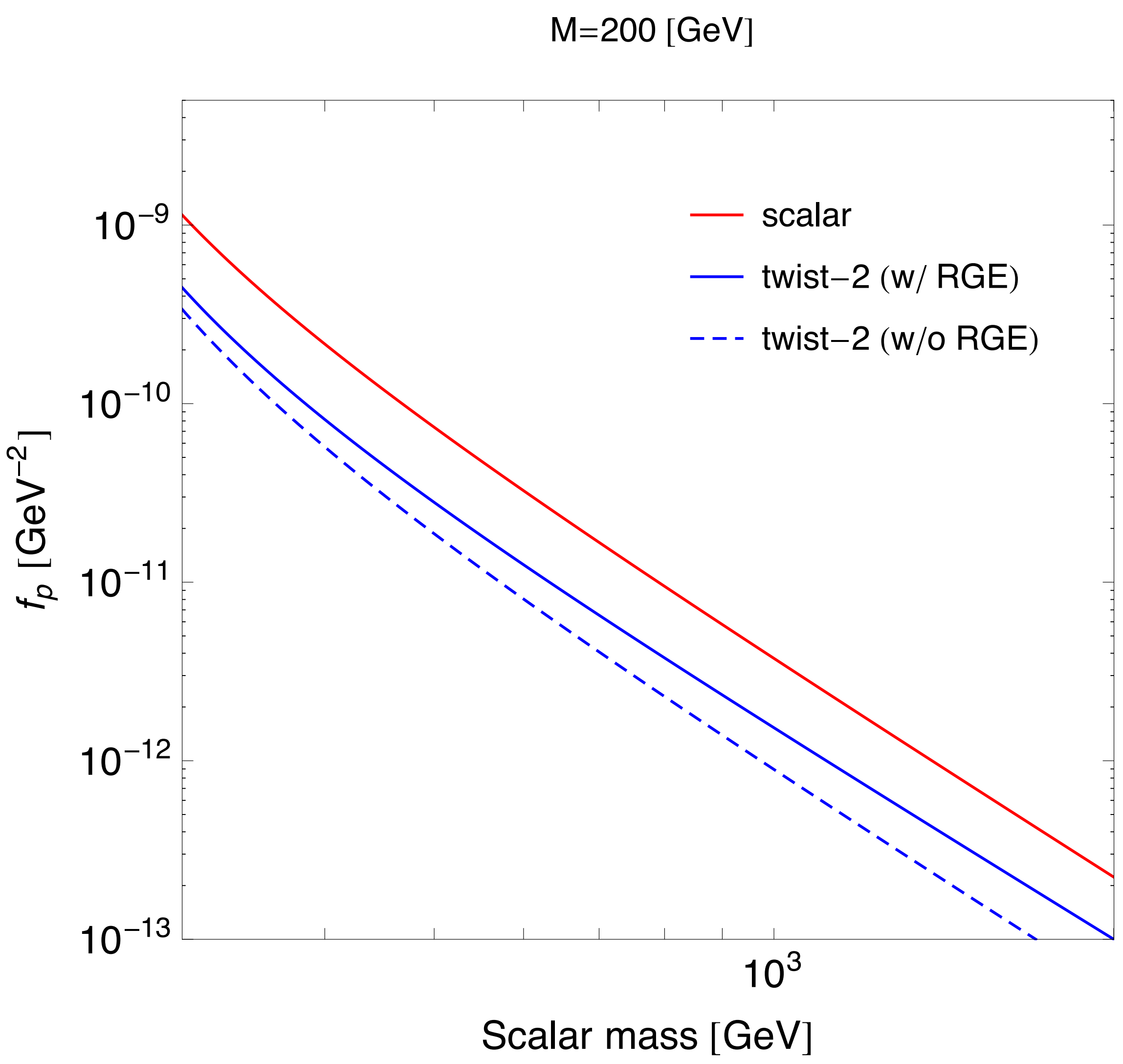
Singlet real scalar DM



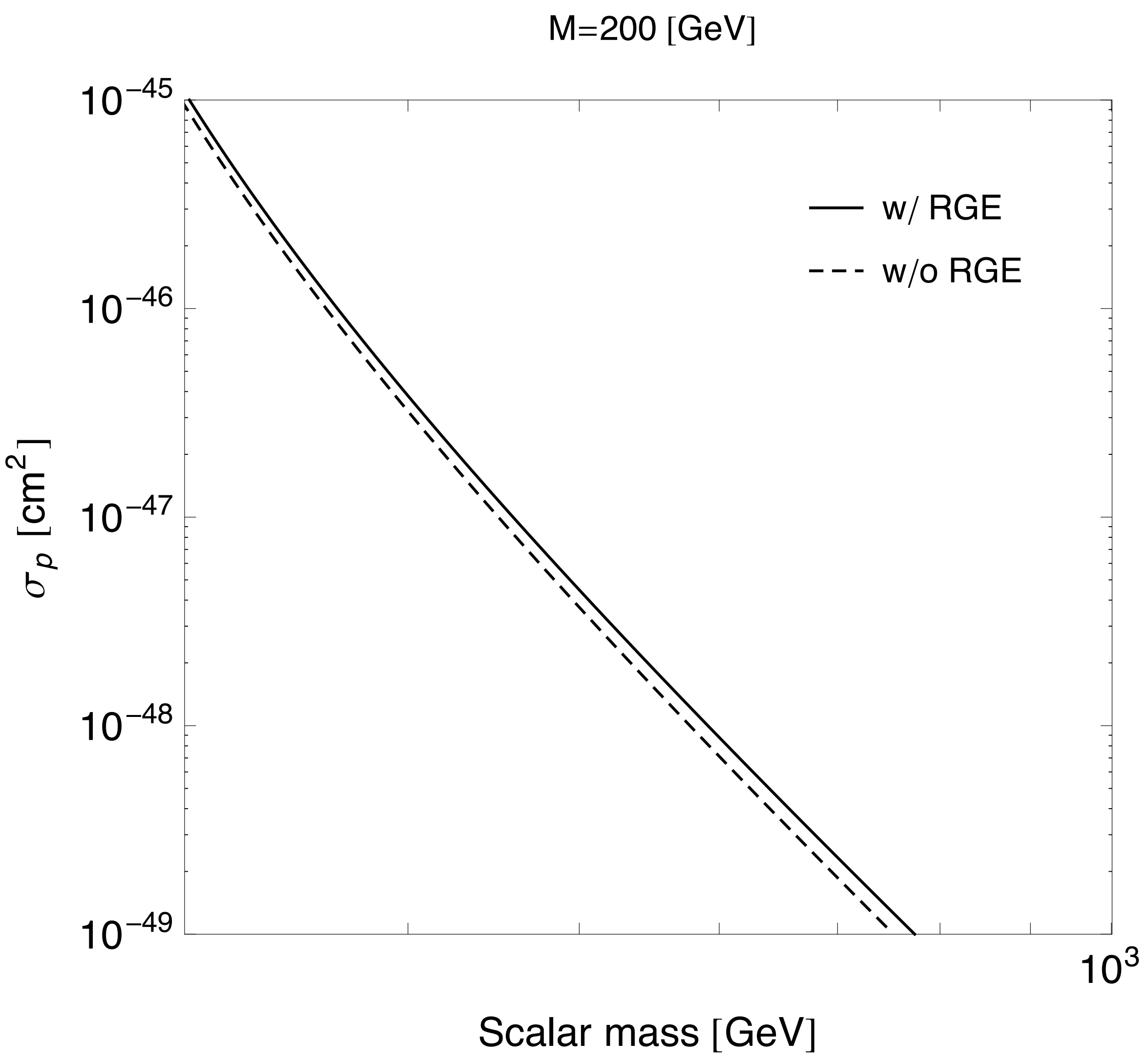
The simple DM model has been constrained stringently.

RGE effects

Effective coupling



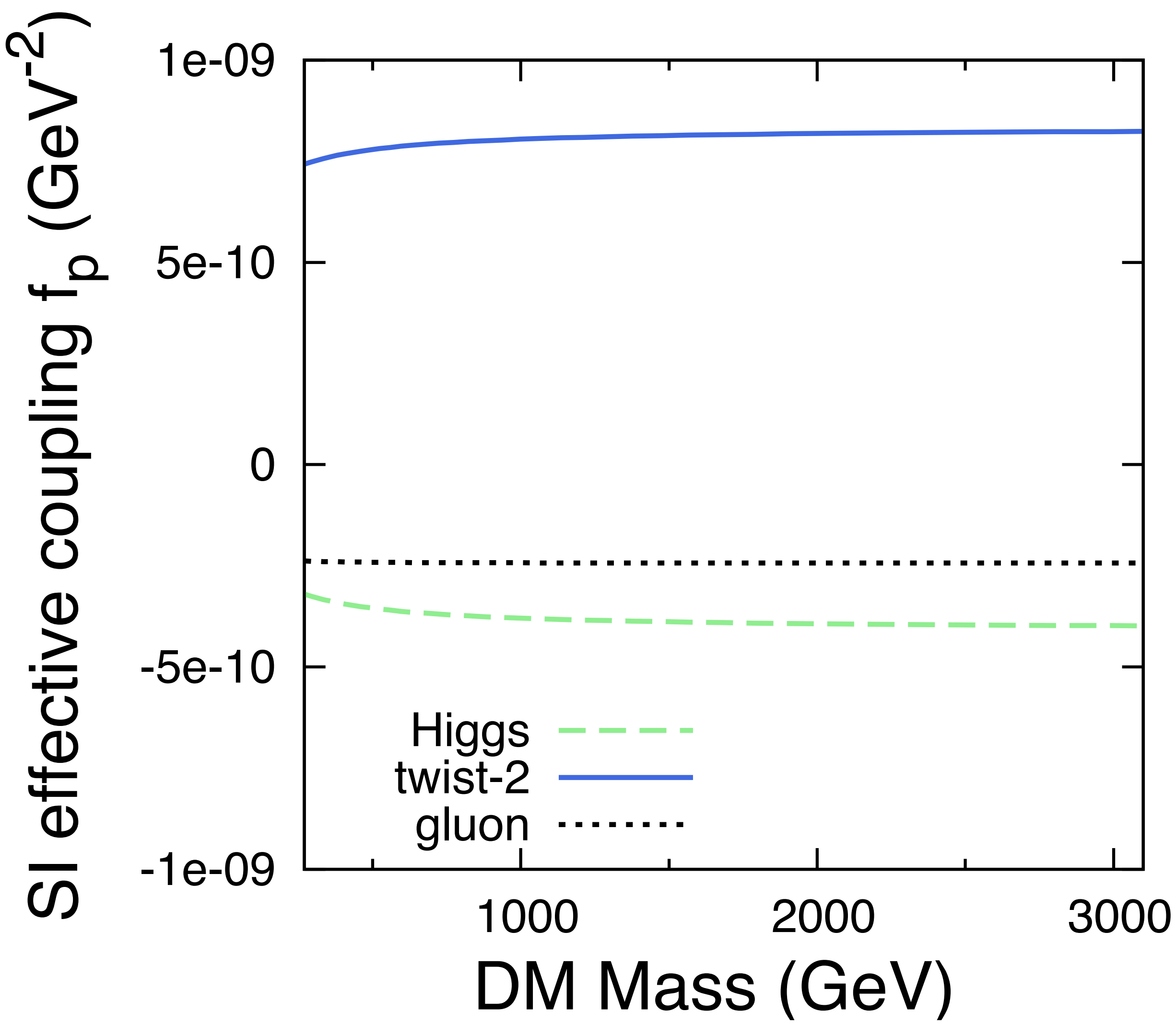
SI cross section

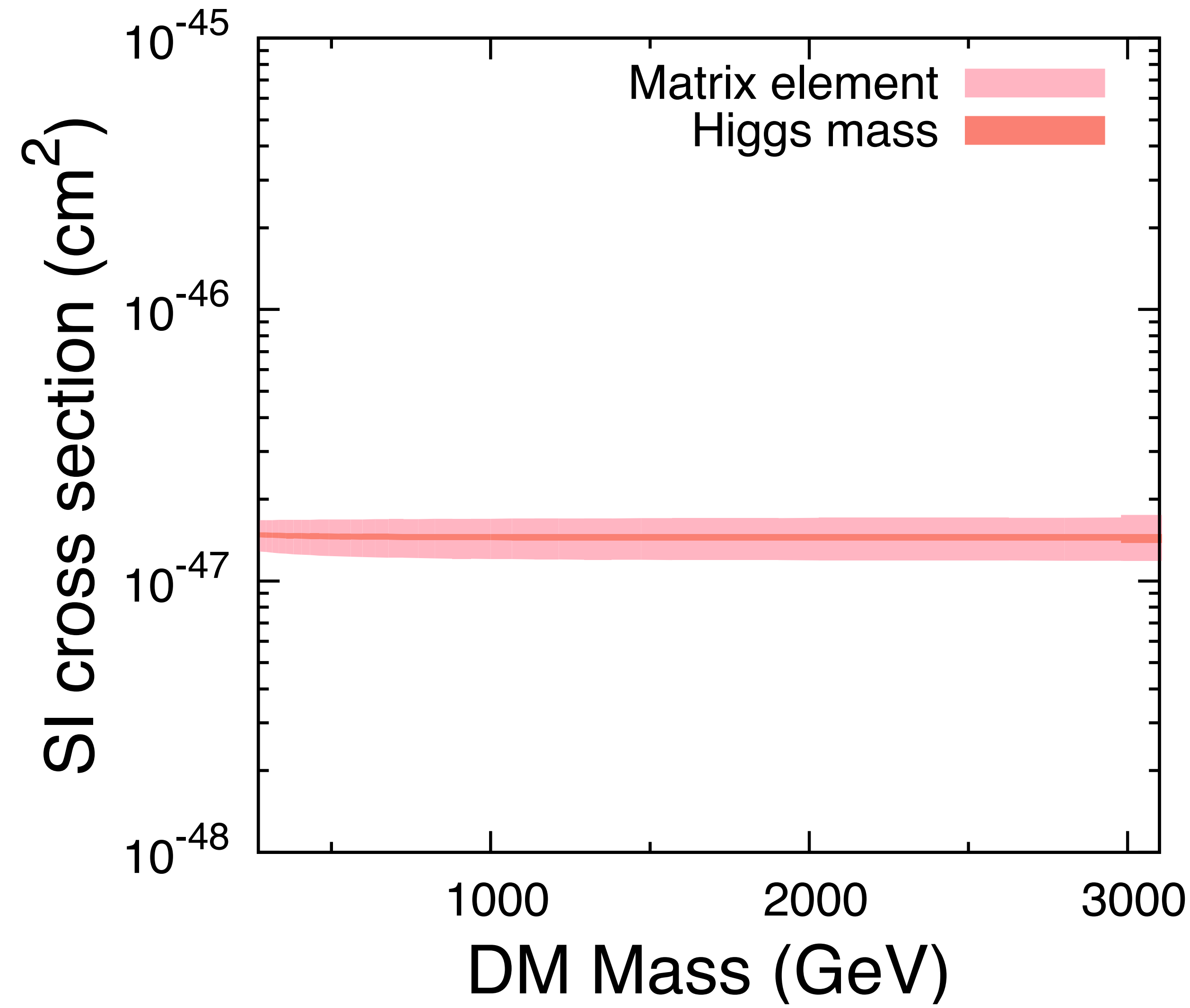


O(10)% effects.

J. Hisano, R. Nagai, N. Nagata, JHEP **1505**, 037 (2015).

LO results (**n** = 3, Y = 0)





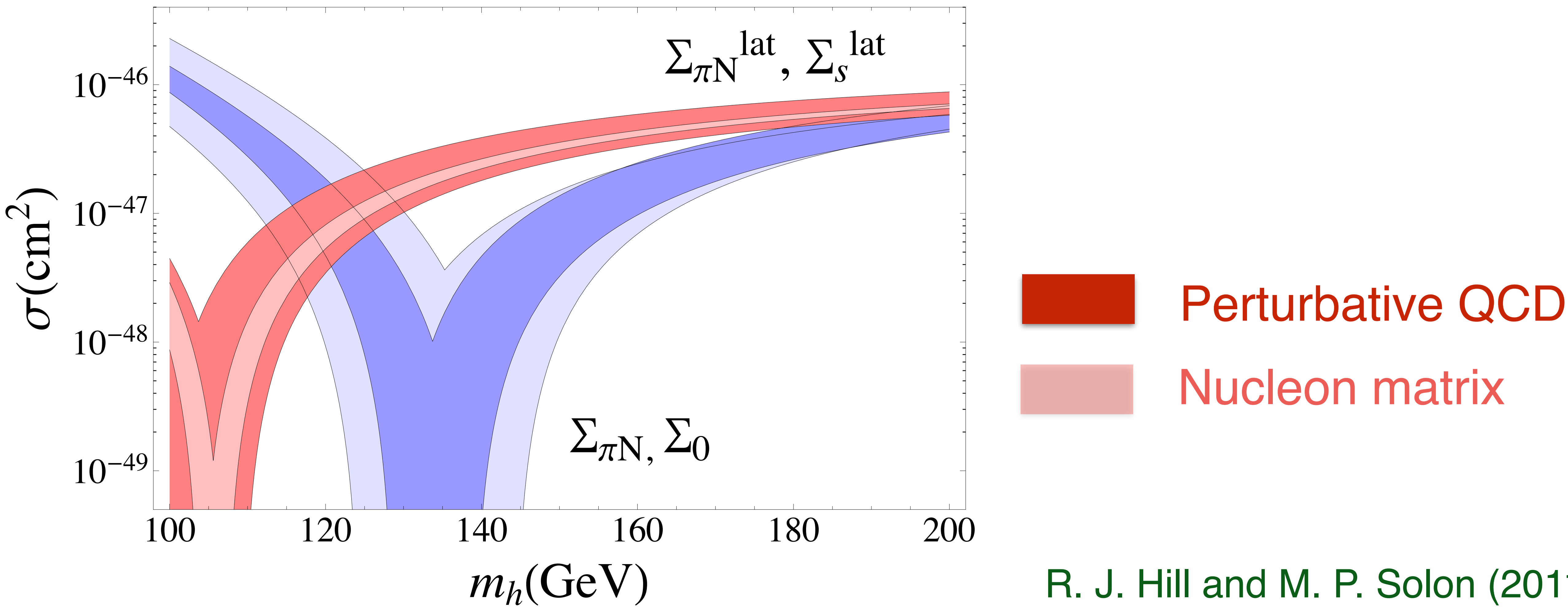
- Cancellation among the contributions.
- Resultant scattering cross sections are found to be quite suppressed.

$$\mathcal{O}(10^{-47})\ \mathrm{cm}^2$$

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

Uncertainty

Cancellation results in a large uncertainty.

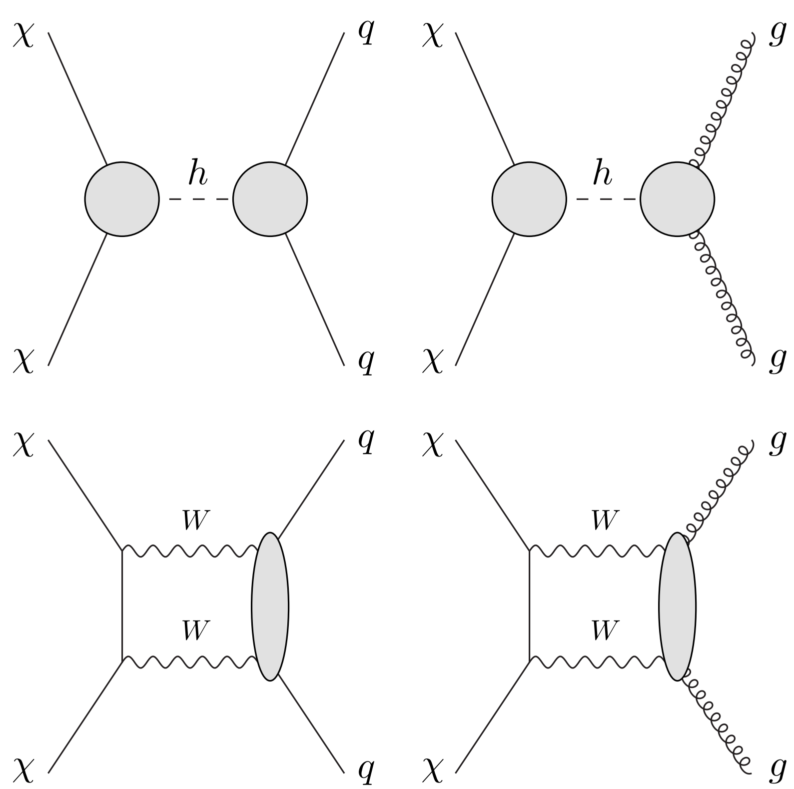


R. J. Hill and M. P. Solon (2011)

- Uncertainty mainly comes from perturbative QCD
- Need for NLO computation !

NLO calculation

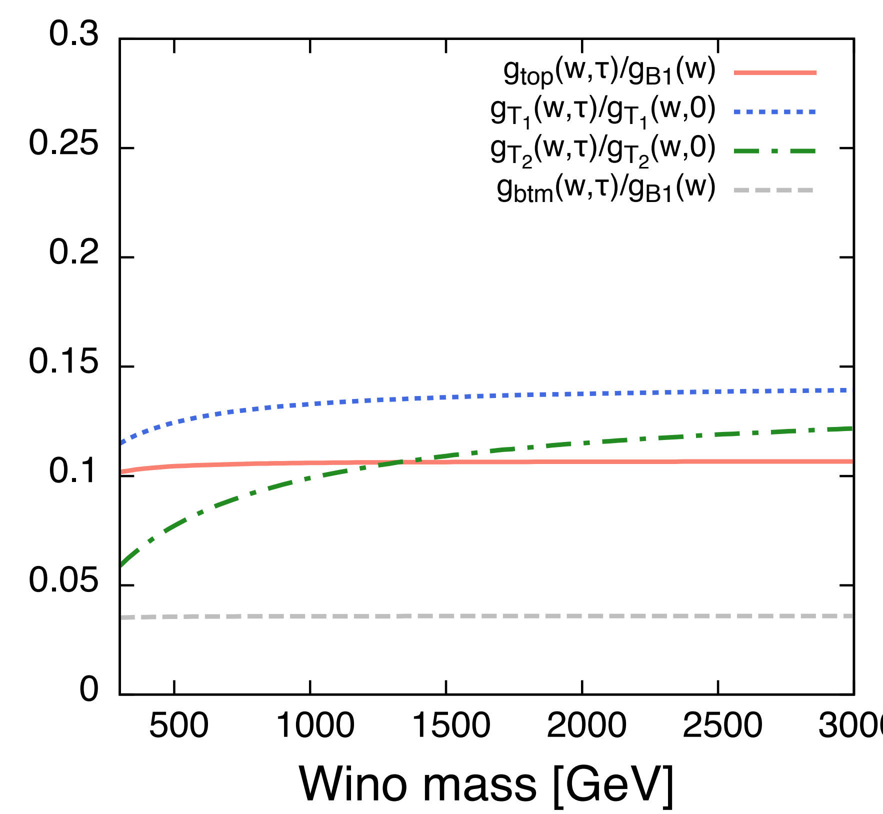
Diagrams



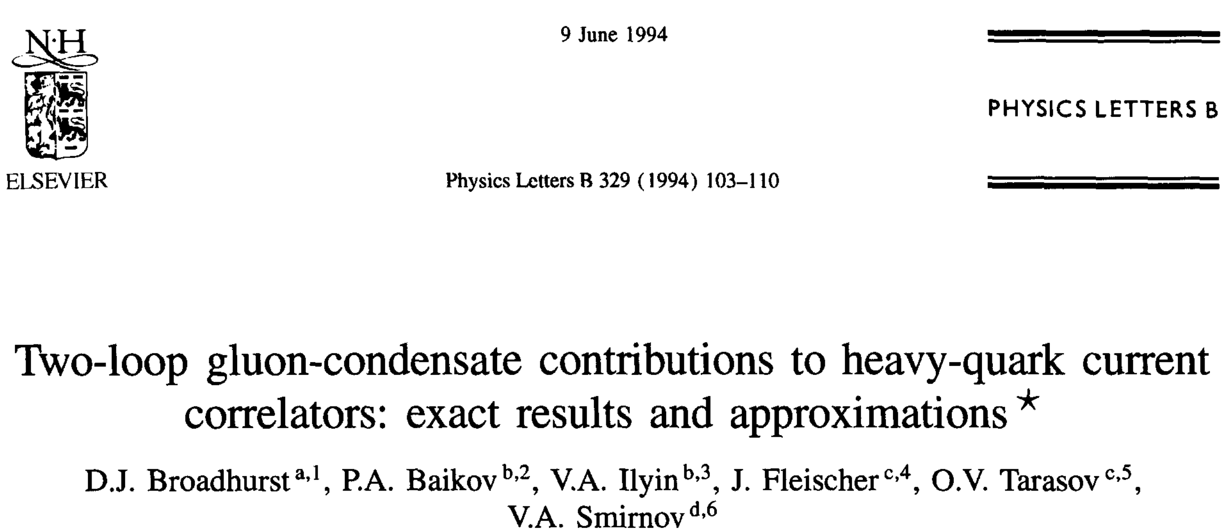
of loops

Operators		Higgs		Box	
Parton	Type	LO	NLO	LO	NLO
Quark	Scalar C_S^q	1-loop	2-loop	-	2-loop
(1st&2nd)	Twist-2 $C_{T_{1,2}}^q$	-	-	1-loop	2-loop
Quark	Scalar C_S^b	1-loop	2-loop	1-loop	2-loop (neglected)
(b-quark)	Twist-2 $C_{T_{1,2}}^b$	-	-	1-loop	2-loop (neglected)
Gluon	Scalar C_S^G	2-loop	3-loop	2-loop	3-loop
(1st & 2nd)	Twist-2 $C_{T_{1,2}}^G$	-	-	-	2-loop
Gluon	Scalar C_S^G	2-loop	3-loop	2-loop	3-loop (3rd gen. neglected)
(3rd)	Twist-2 $C_{T_{1,2}}^G$	-	-	-	2-loop (3rd gen. neglected)

3rd gen. contribution



OPEs of current-current correlators



ELSEVIER

9 June 1994

PHYSICS LETTERS B

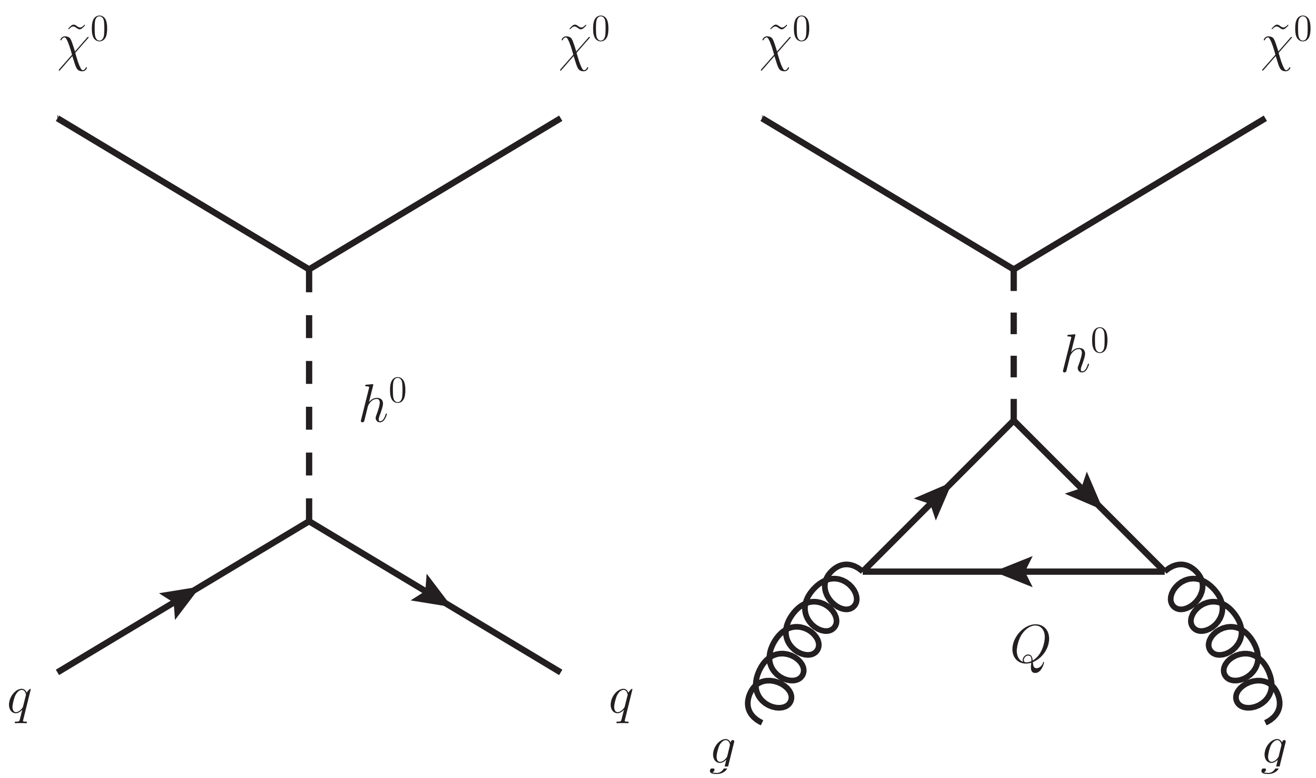
Physics Letters B 329 (1994) 103–110

Two-loop gluon-condensate contributions to heavy-quark current correlators: exact results and approximations ⋆

D.J. Broadhurst [a,1], P.A. Baikov [b,2], V.A. Ilyin [b,3], J. Fleischer [c,4], O.V. Tarasov [c,5], V.A. Smirnov [d,6]

Wino-like DM in high-scale SUSY

Tree-level contribution



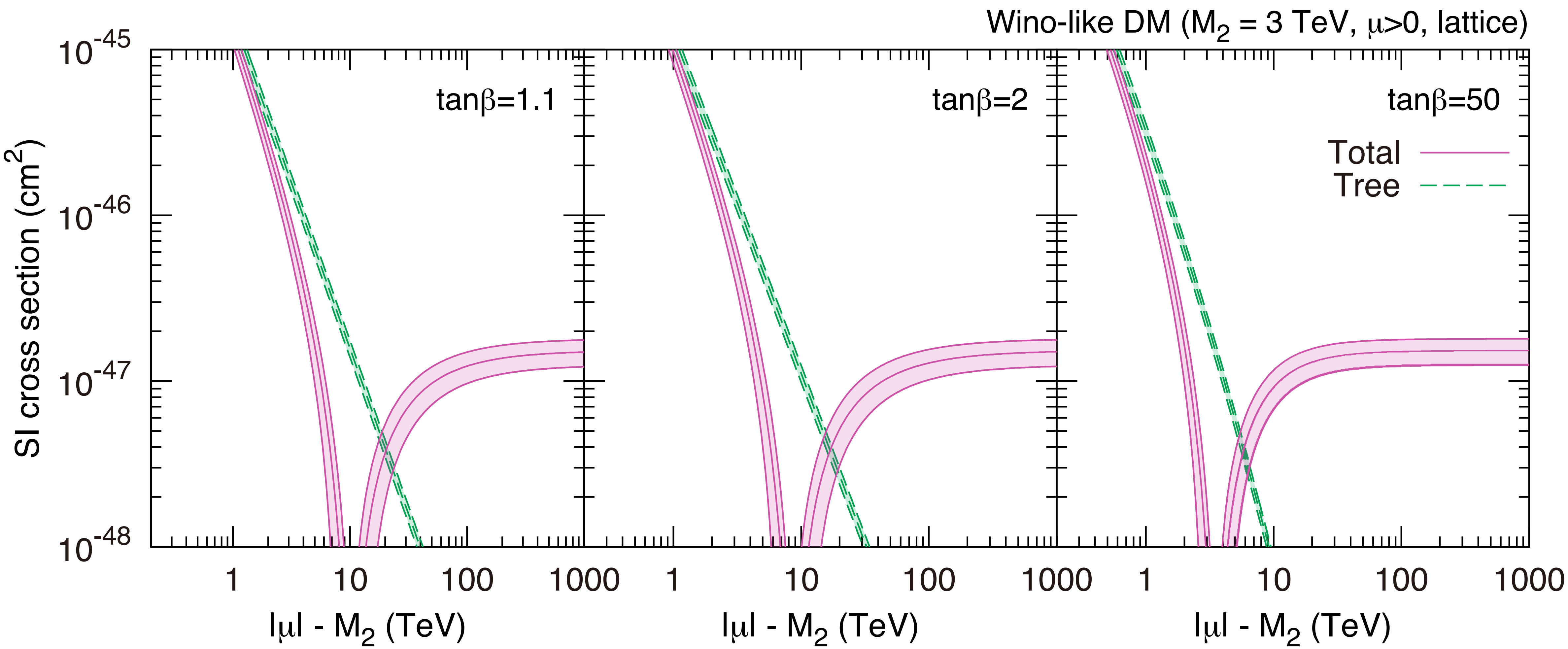
Effective coupling

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

(Z_{ij}: Neutralino mixing matrix)

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

Wino-like DM in high-scale SUSY



The loop contribution needs to be included when higgsino is much heavier than wino.

J. Hisano, K. Ishiwata, N. Nagata, Phys. Rev. D**87**, 035020 (2013)