One-loop corrections to gaugino (co-)annihilation into quarks in the MSSM

Björn Herrmann
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DM@NLO collaboration — http://dmnlo.hepforge.org

B. Herrmann, M. Klasen, K. Kovarik, M. Meinecke, P. Steppeler
Phys. Rev. D 89: 114012 (2014) — arXiv:1404.2931 [hep-ph]

J. Harz, B. Herrmann, M. Klasen, K. Kovarik — to be published

J. Harz, B. Herrmann, M. Klasen, K. Kovarik, Q. Le Boulc'h
Phys. Rev. D 87: 054031 (2013) — arXiv:1212.5241 [hep-ph]

B. Herrmann, M. Klasen, K. Kovarik
Phys. Rev. D 79: 061701 (2009) — arXiv:0901.0481 [hep-ph]

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Phys. Rev. D 80: 085025 (2009) — arXiv:0907.0030 [hep-ph]

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SUSY2014
THE 22ND INTERNATIONAL CONFERENCE ON SUPERSYMMETRY AND UNIFICATION OF FUNDAMENTAL INTERACTIONS

We consider **neutralino dark matter** in the Minimal Supersymmetric Standard Model (MSSM)

$$\tilde{\chi}_1^0 \;=\; Z_{1\tilde{B}}\tilde{B} + Z_{1\tilde{W}}\tilde{W} + Z_{1\tilde{H}_1}\tilde{H}_1 + Z_{1\tilde{H}_2}\tilde{H}_2$$

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Time evolution of the neutralino number density described by **Boltzmann equation**
— solution leads to **prediction of neutralino relic density** (if masses and interactions known)
— comparison to recent cosmological data (WMAP, Planck,...)

$$\frac{\mathrm{d}n}{\mathrm{d}t} = -3Hn - \langle\sigma_{\mathrm{ann}}v\rangle\left(n^2 - n_{\mathrm{eq}}^2\right)$$

↓

$$\Omega_{\mathrm{CDM}}h^2 = \frac{m_\chi n_\chi}{\rho_c} \sim \frac{1}{\langle\sigma_{\mathrm{ann}}v\rangle}$$

$$\Omega_{\mathrm{CDM}}h^2 = 0.1199 \pm 0.0027$$

Planck collaboration 2013

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(dis)favoured parameter regions...?

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(dis)favoured parameter regions…?

Several computational tools allow an efficient calculation of the (neutralino) relic density:

— **micrOMEGAs** Bélanger, Boudjema, Pukhov *et al.* 2003-2014

— **DarkSUSY** Bergström, Edsjö, Gondolo *et al.* 2004-2014

Annihilation cross-section includes all relevant **annihilation and co-annihilation** processes

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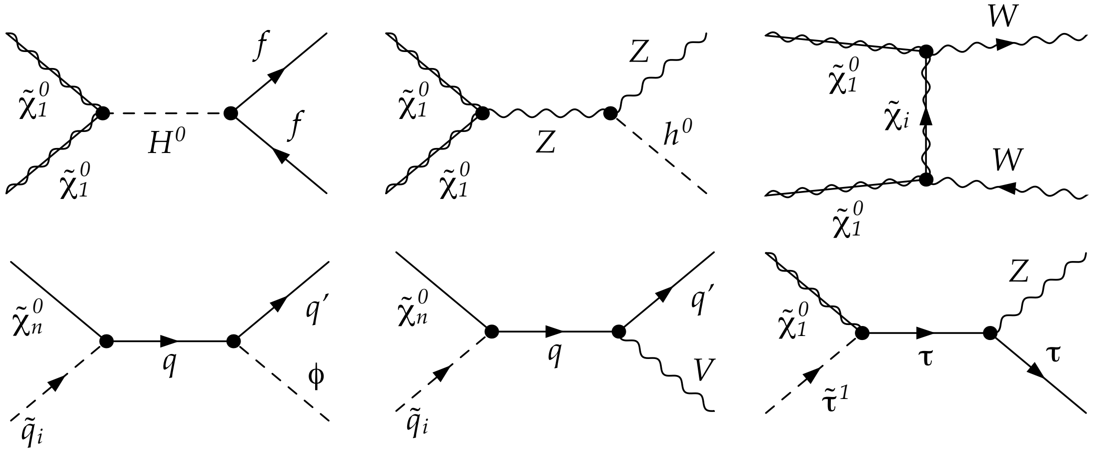

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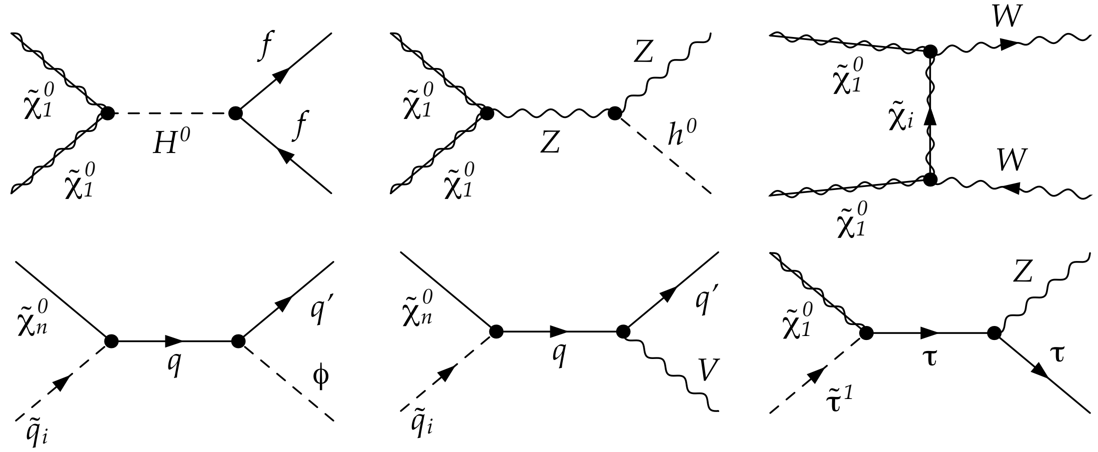

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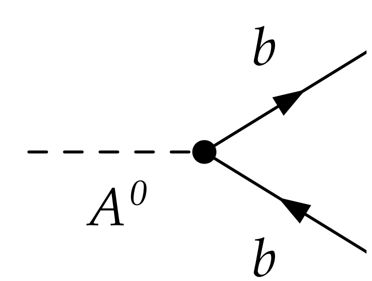
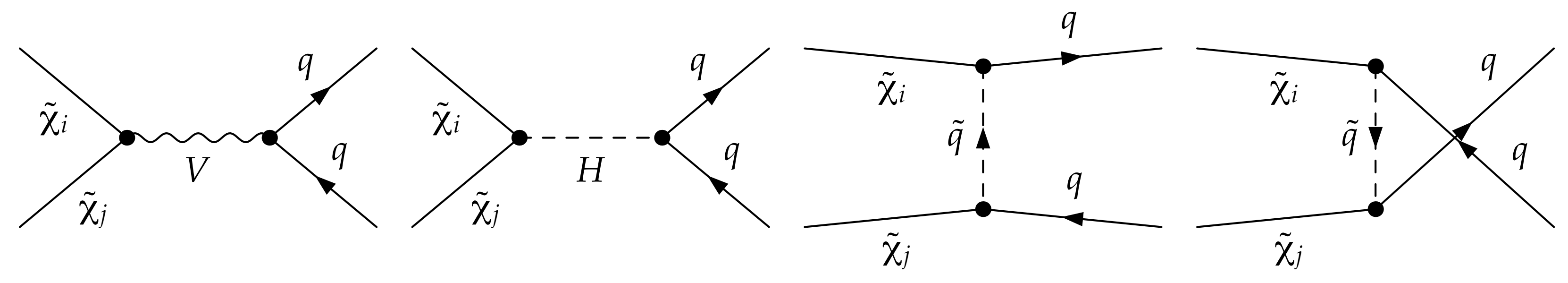
All processes implemented in public codes — **but only at the (effective) tree-level**
Higher-order effects included only for strong and Yukawa couplings

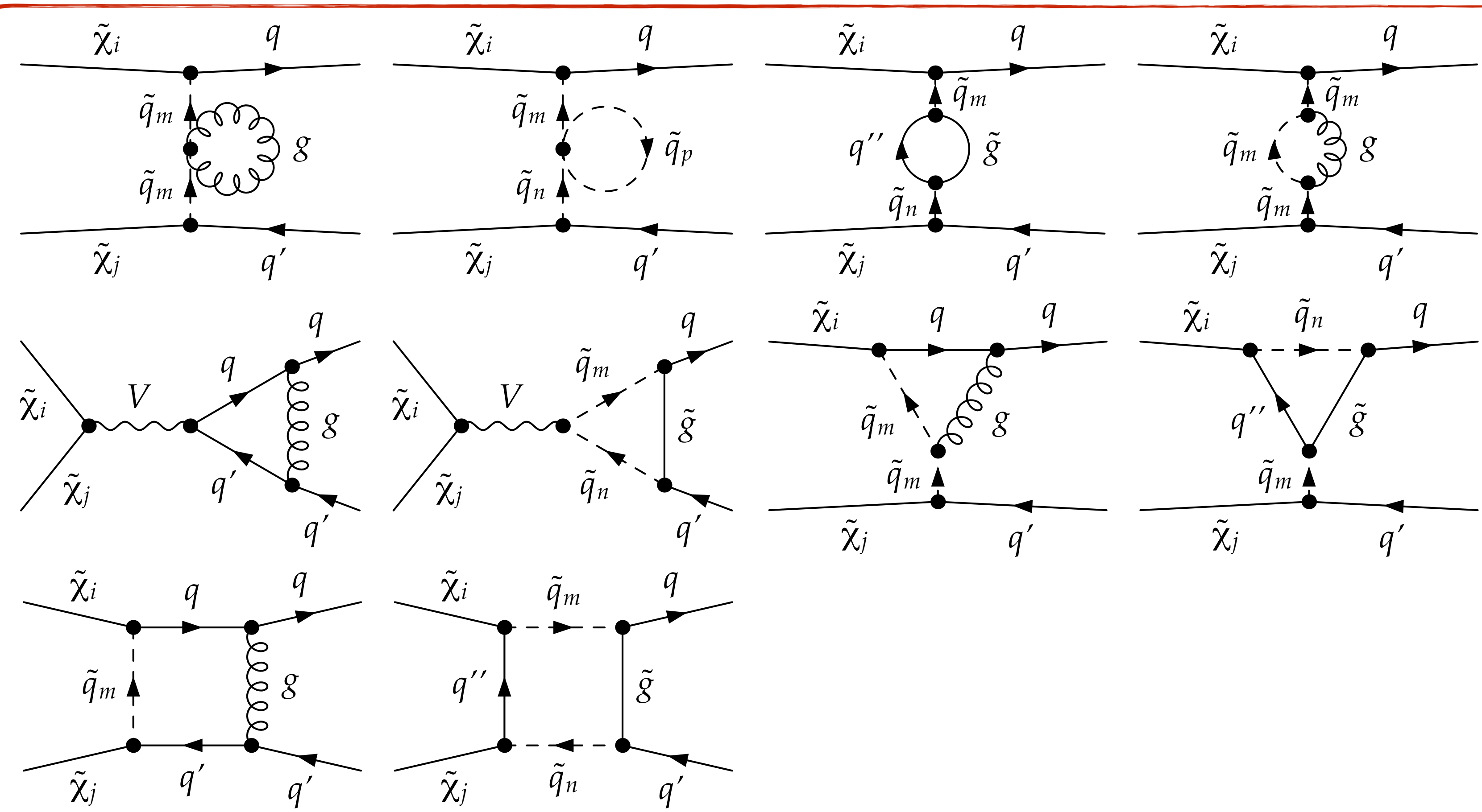
$$h_{Abb} \propto \frac{\overline{m}_b(Q)}{1+\Delta_b} \tan\beta$$



Higher-order corrections may give important contributions to cross-sections
More precise theory predictions needed to keep up with exp. improvements!

For **gaugino (co-)annihilation**, the following diagrams are relevant up to one-loop in α_s:





\+ counter-terms

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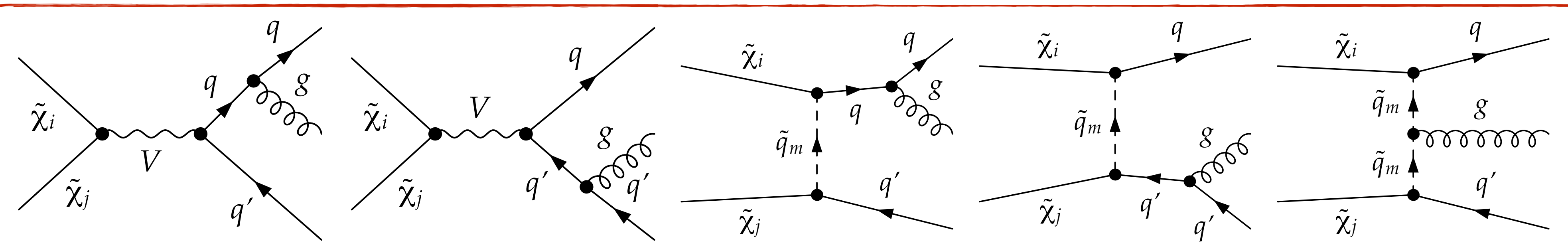
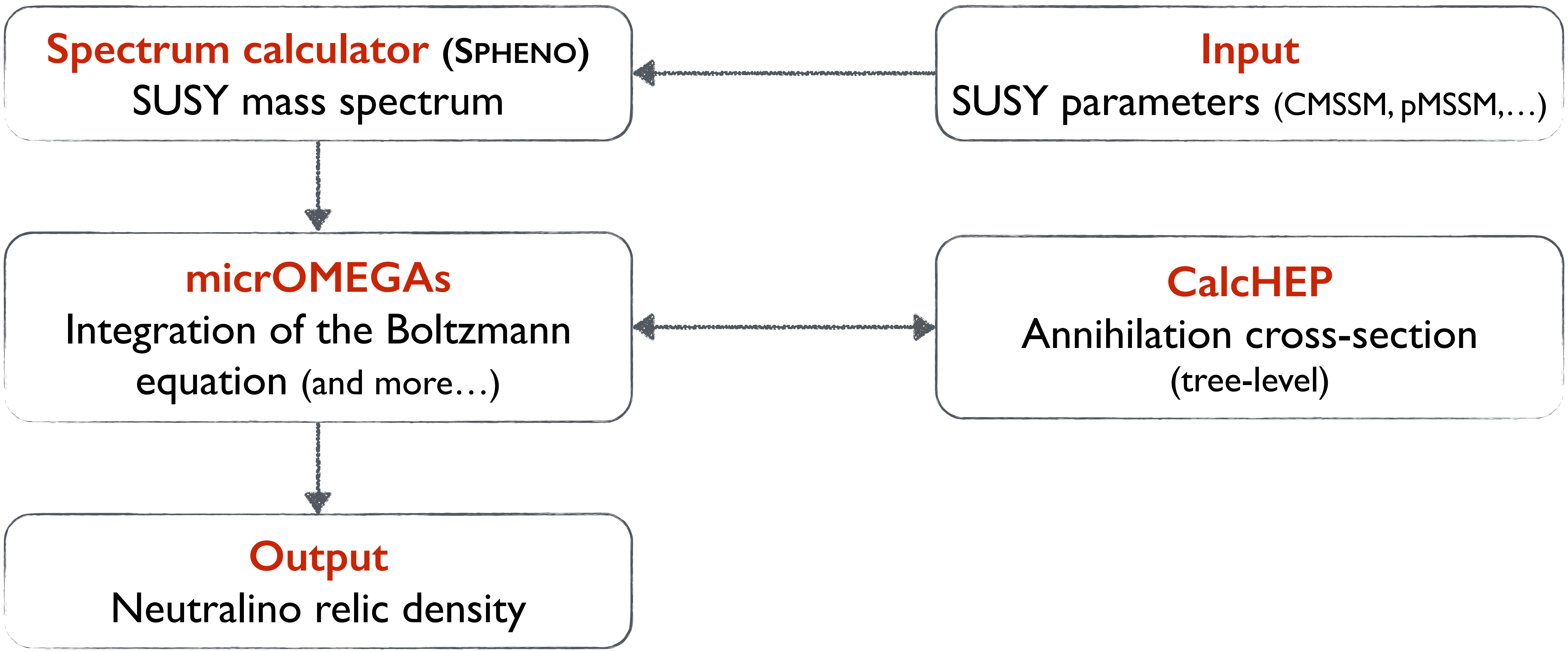


All contributions computed analytically and implemented in **numerical Fortran package**
DM@NLO — **extension to existing codes** to improve theoretical prediction



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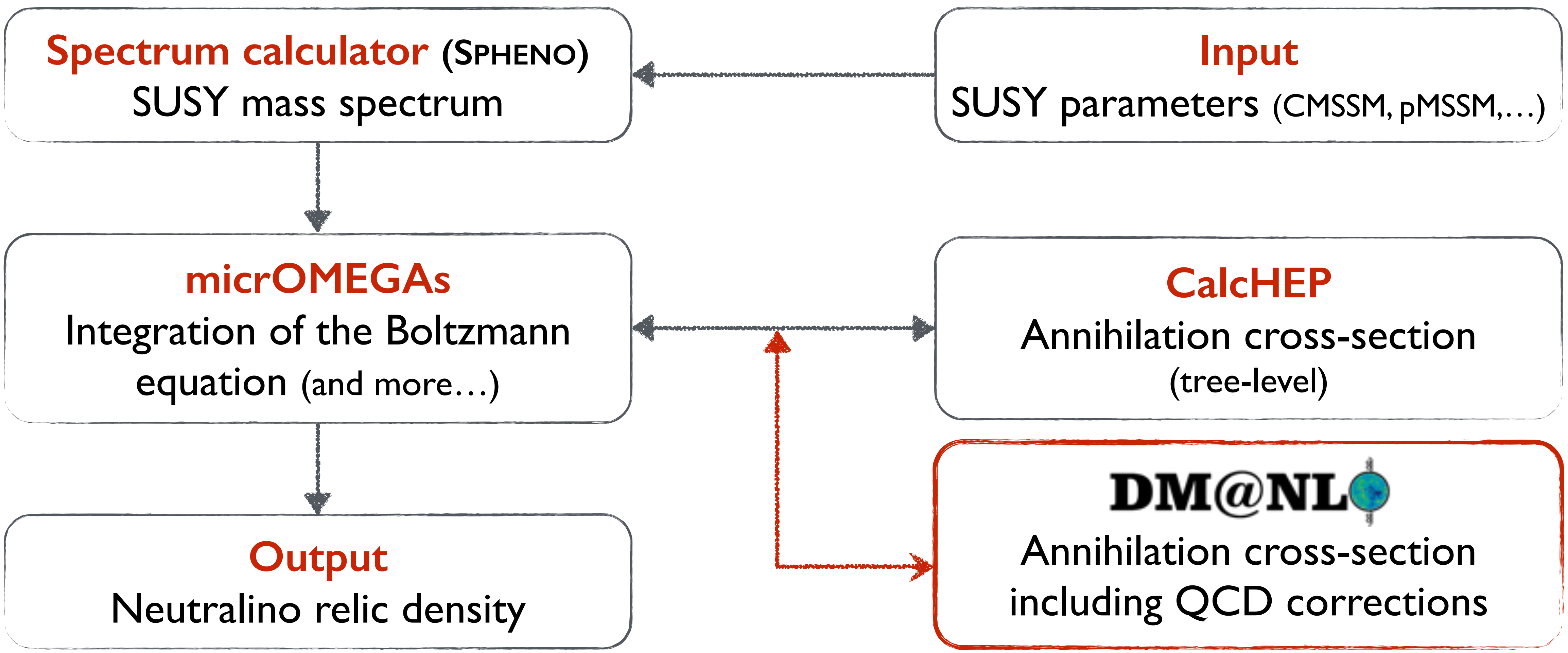

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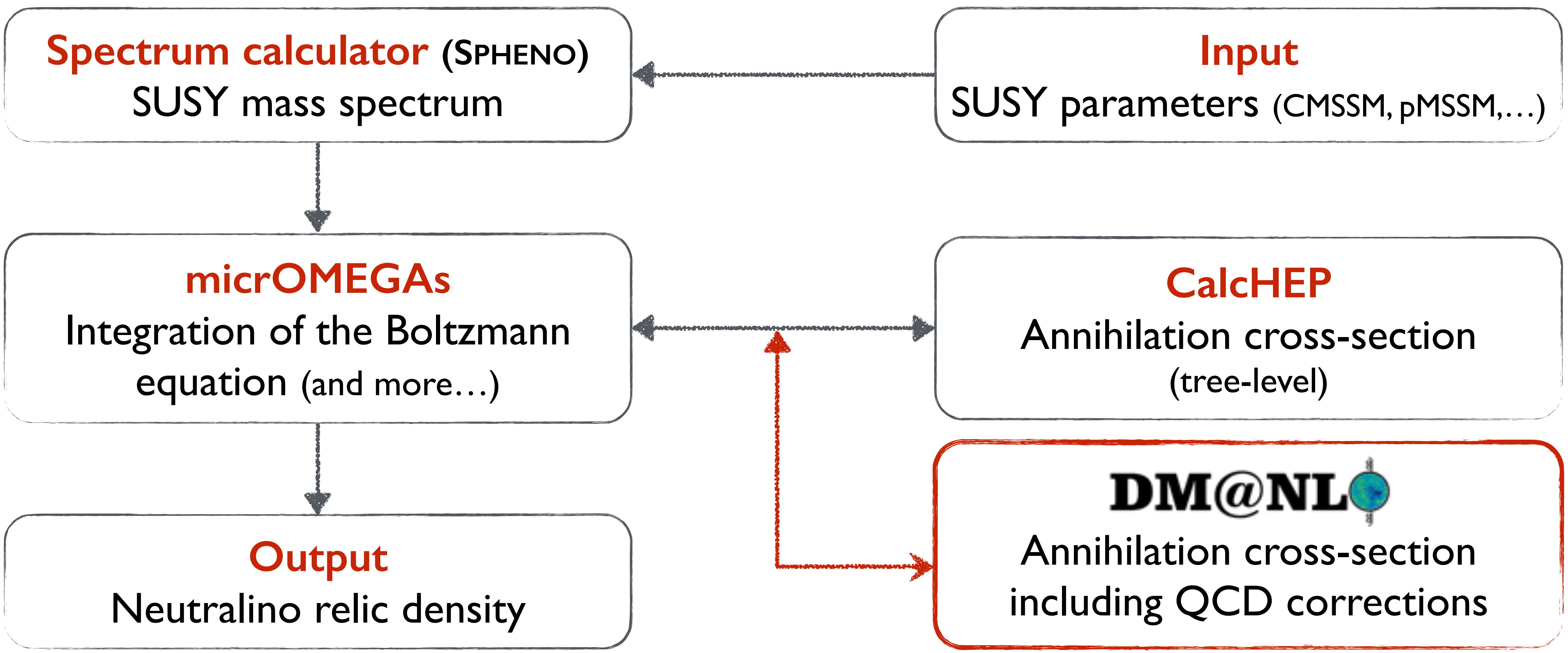
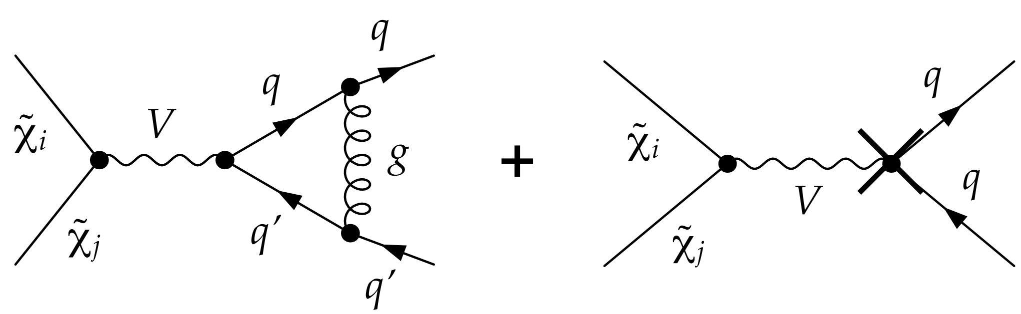


DM@NLO includes the following classes of processes:

$\tilde{\chi}_i^{0,\pm}\tilde{\chi}_j^{0,\pm} \to q\bar{q}'$	$\tilde{\chi}_i^0\tilde{q}_j \to qH, qV, qg$	$\tilde{q}_i\tilde{q}_j^{(*)} \to VV, HH, HV, q\bar{q}$
this talk	Julia's talk (monday 21/07, "Precision SUSY")	work in progress…

Virtual contributions include UV-divergent integrals — convergence achieved using dimensional reduction and dedicated **on-shell/$\overline{\text{DR}}$ renormalisation scheme**

Herrmann, Klasen, Kovarik, Meinecke, Steppeler (2014); Harz, Herrmann, Klasen, Kovarik (to be published)



= UV-finite

$$A_t, A_b$$
$$m_{\tilde{t}_1}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$$

Independent "input" parameters

→

$$M^2_{\tilde{Q}}, M^2_{\tilde{U}}, M^2_{\tilde{D}}$$
$$m_{\tilde{t}_2}, \theta_{\tilde{t}}, \theta_{\tilde{b}}$$

Dependent parameters

(redefinition of stop mixing angle)

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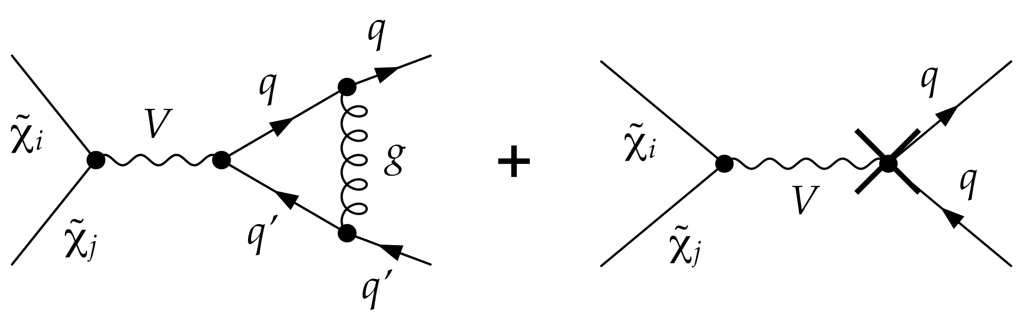

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Loop diagrams contain IR-divergencies, which vanish when taking into account the real emission of a gluon — **dipole subtraction method** Catani, Seymour (2001)

$$\sigma_{\rm NLO} = \int_3 \left[{\rm d}\sigma^{\rm R}\Big|_{\epsilon=0} - {\rm d}\sigma^{\rm A}\Big|_{\epsilon=0} \right] + \int_2 \left[{\rm d}\sigma^{\rm V} + \int_1 {\rm d}\sigma^{\rm A} \right]_{\epsilon=0}$$

Study **three example scenarios** in the pMSSM (11 parameters at the TeV scale) featuring different phenomenological aspects Herrmann, Klasen, Kovarik, Meinecke, Steppeler (2014)
— Numerical values obtained using **SPheno** and **micrOMEGAs**

	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$Z_{1\tilde{B}}$	$Z_{1\tilde{W}}$	$Z_{1\tilde{H}_1}$	$Z_{1\tilde{H}_2}$	m_{h^0}	$\Omega_{\tilde{\chi}_1^0}h^2$
I	738.2	802.4	1288.4	1294.5	802.3	1295.1	-0.996	0.049	-0.059	0.037	126.3	0.1243
II	698.9	850.5	854.0	1940.2	845.6	1940.4	-0.969	0.012	-0.187	0.162	125.2	0.1034
III	1106.7	1114.9	1855.0	1865.6	1109.6	1856.3	0.046	-0.082	0.706	-0.702	126.0	0.1190

	Scenario I	Scenario II	Scenario III
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to t\bar{t}$	1.4%	15.0%	–
$b\bar{b}$	9.1%	5.9%	–
$\tilde{\chi}_1^0\tilde{\chi}_2^0 \to t\bar{t}$	2.5%	12.0%	3.3%
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$\tilde{\chi}_1^0\tilde{\chi}_1^\pm \to t\bar{b}$	43.0%	40.0%	0.8%
$c\bar{s}$	–	–	8.5%
$u\bar{d}$	–	–	8.5%
$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to t\bar{b}$	0.4%	–	0.4%
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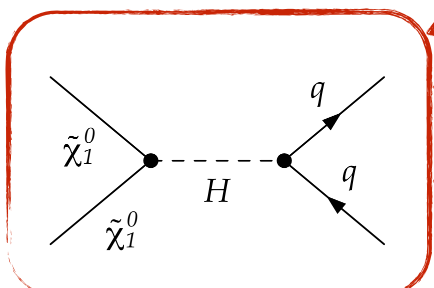

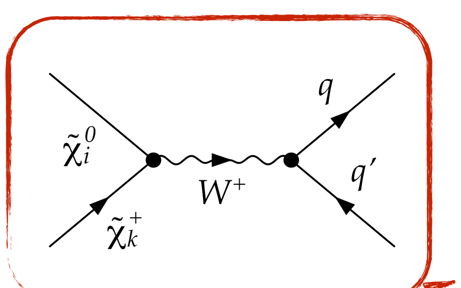

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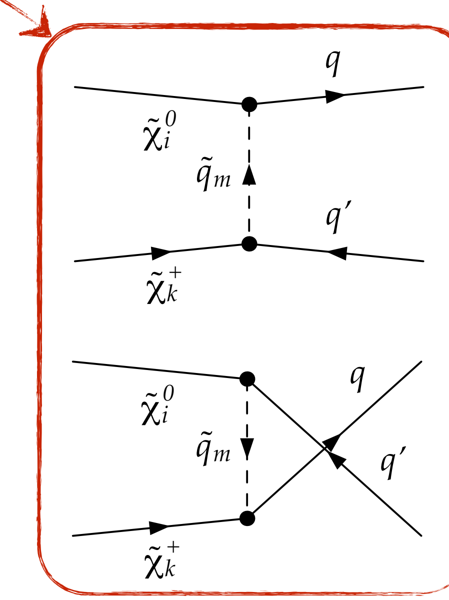
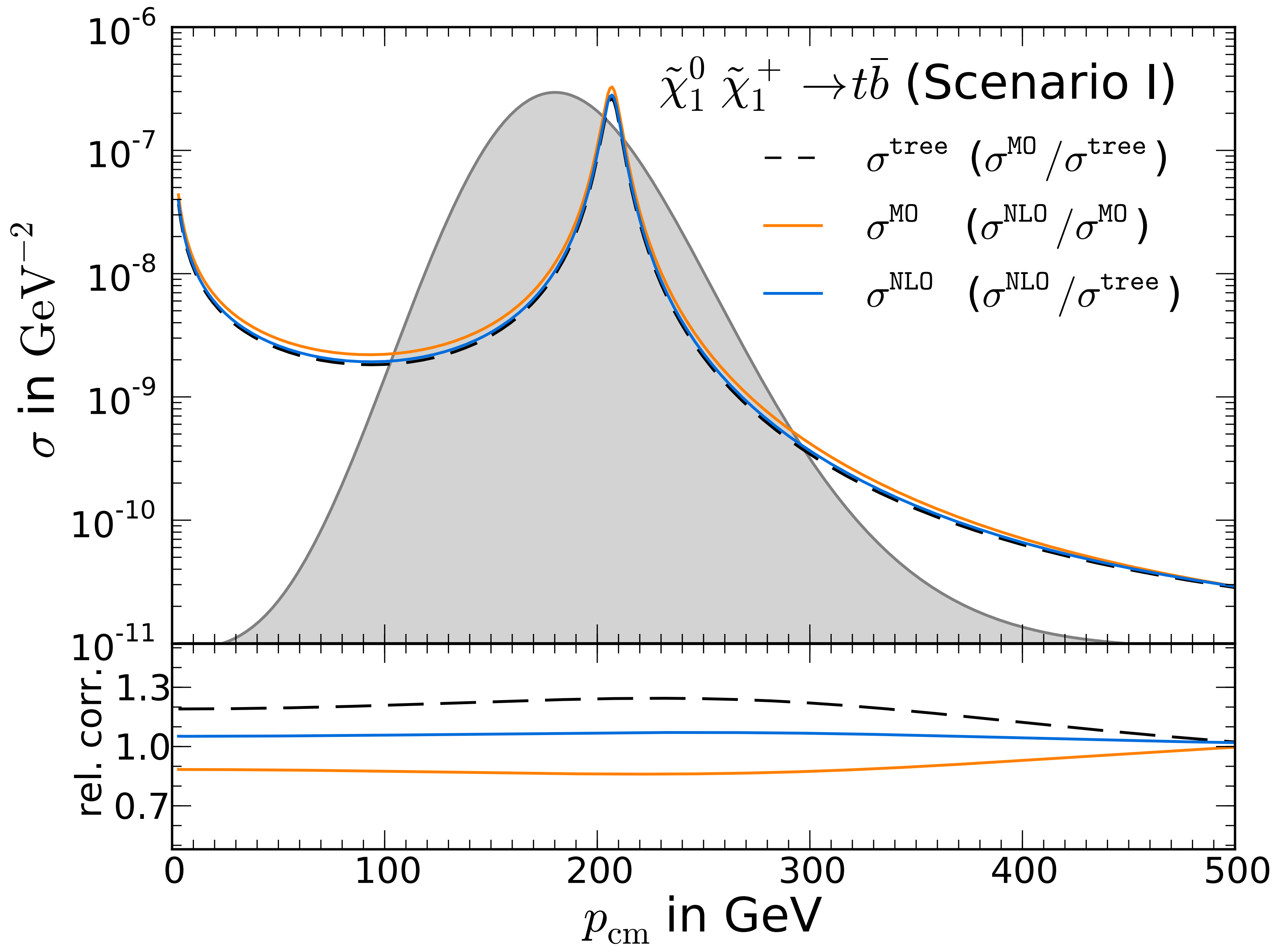


Radiative corrections change the (co-)annihilation cross-section by **up to 30%**

— tree-level values differ from **micrOMEGAs** result due to renormalisation scheme



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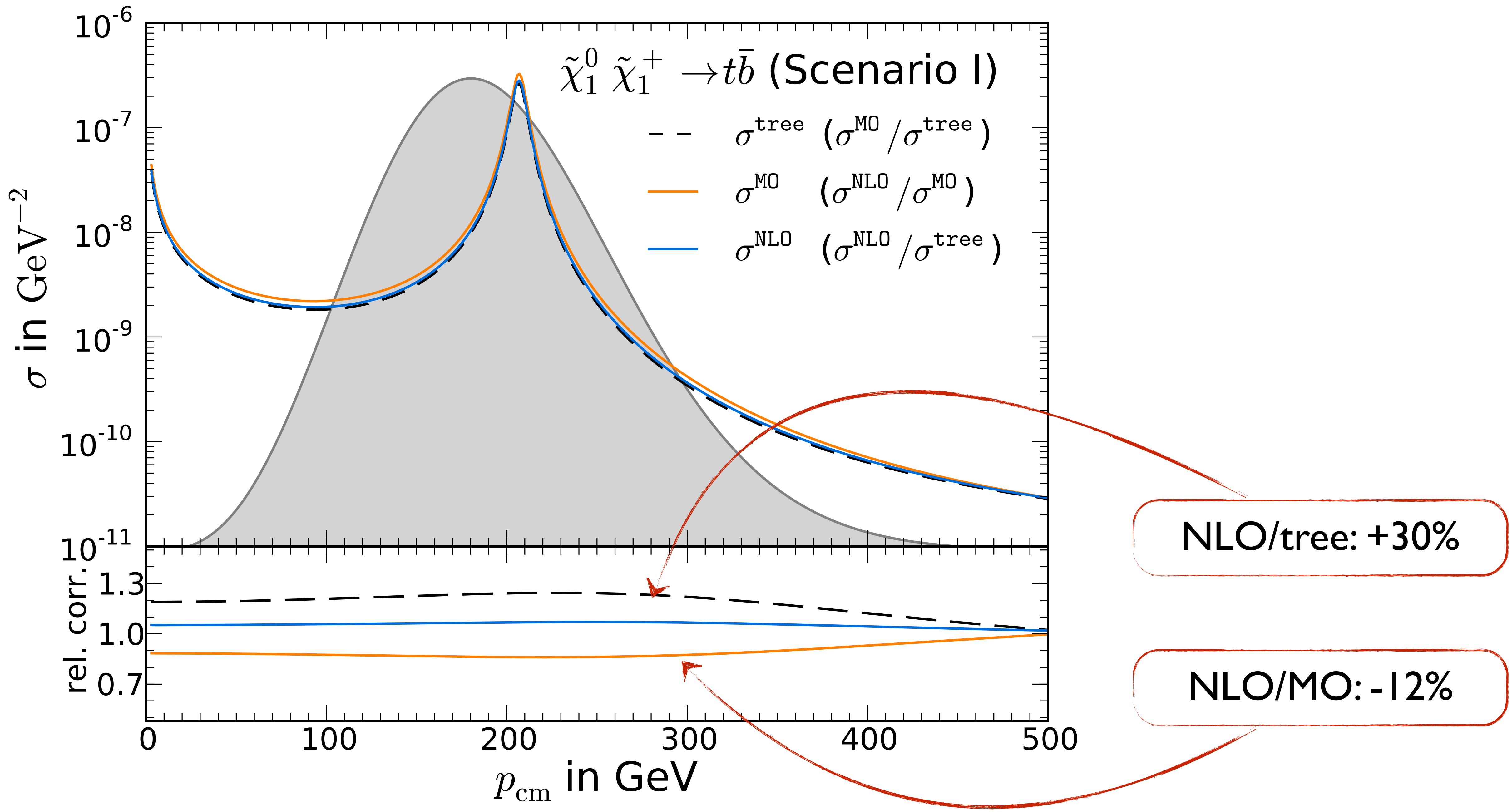

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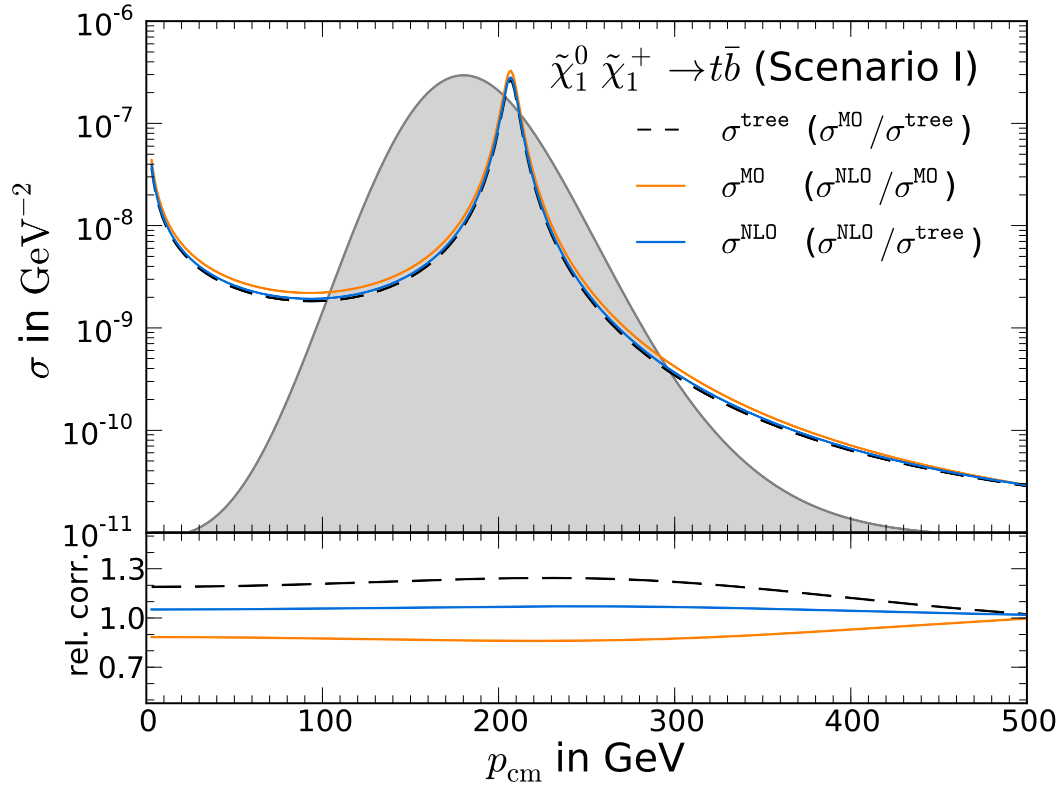

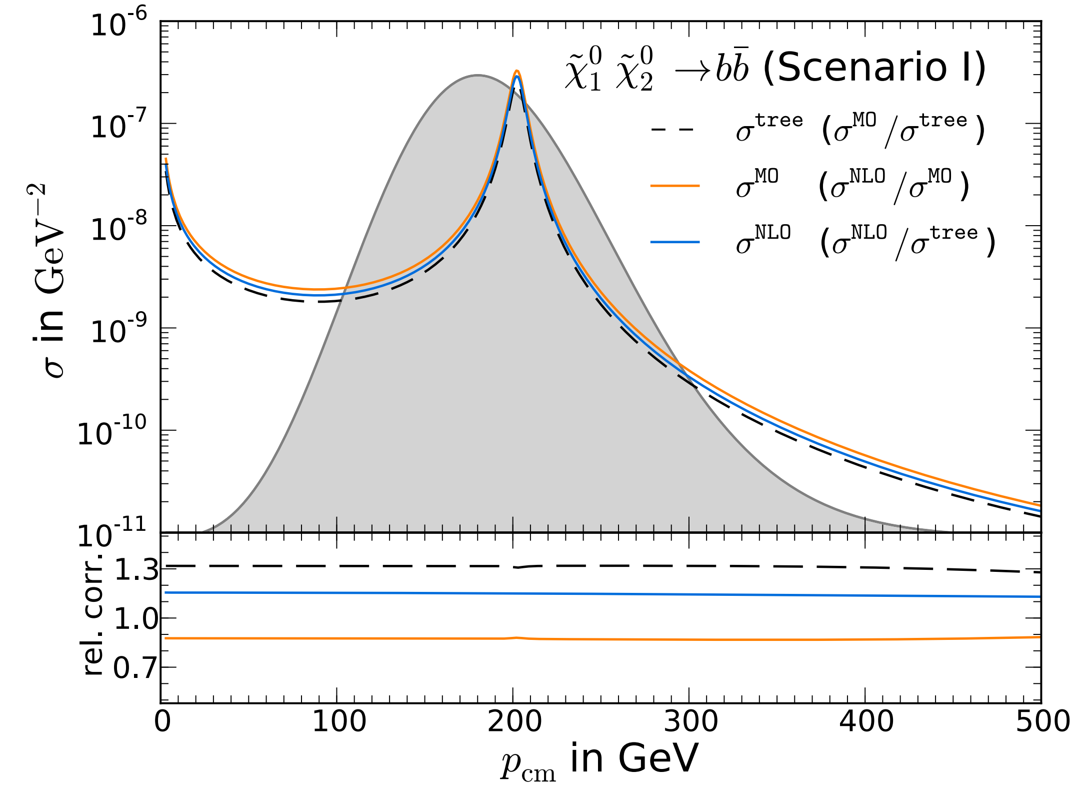

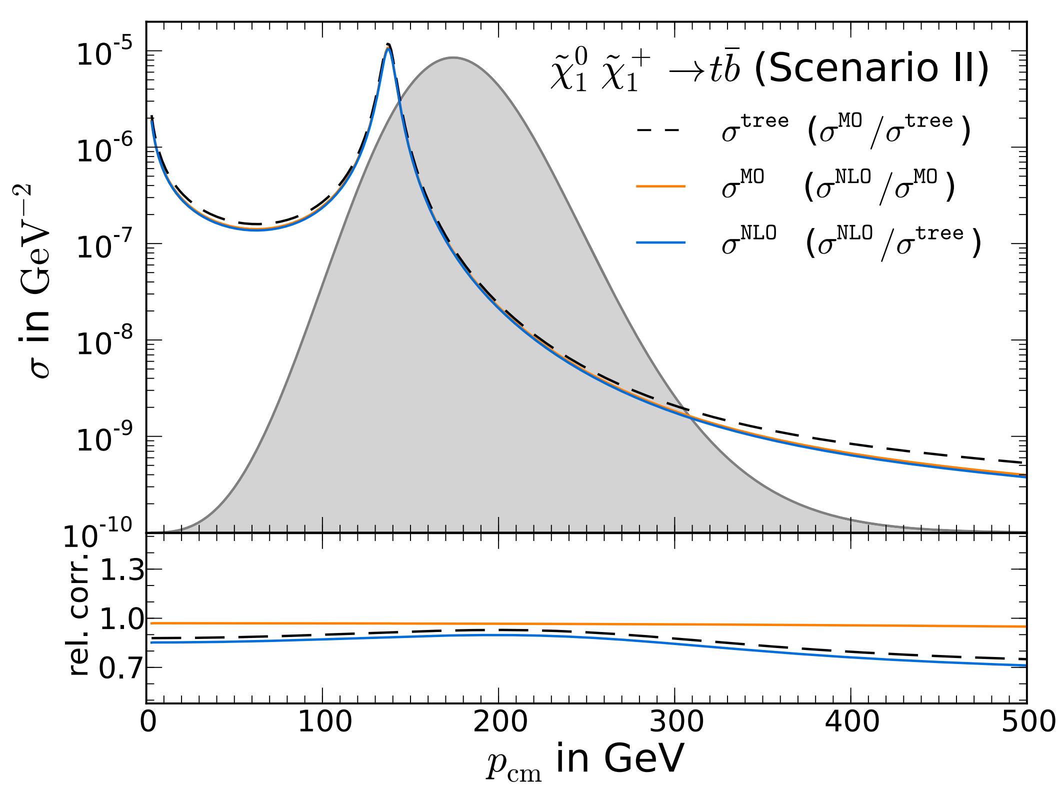

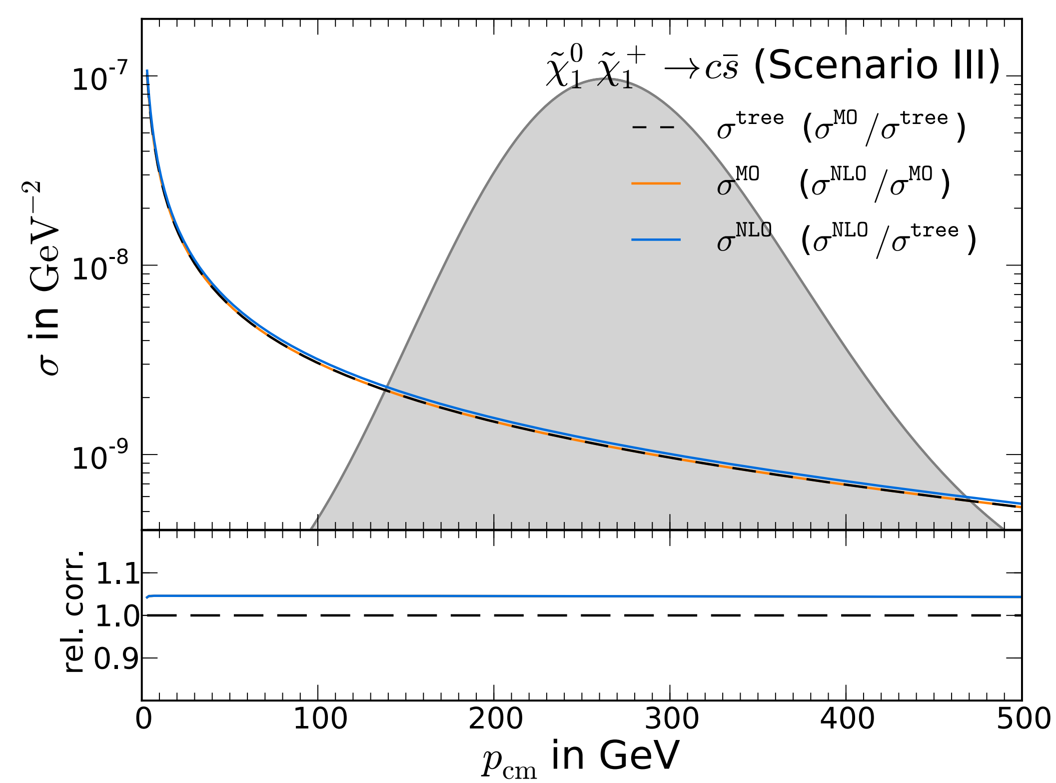

The change in the cross-section directly reflects in the prediction of the relic density — **Numerical impact larger than experimental uncertainty!**

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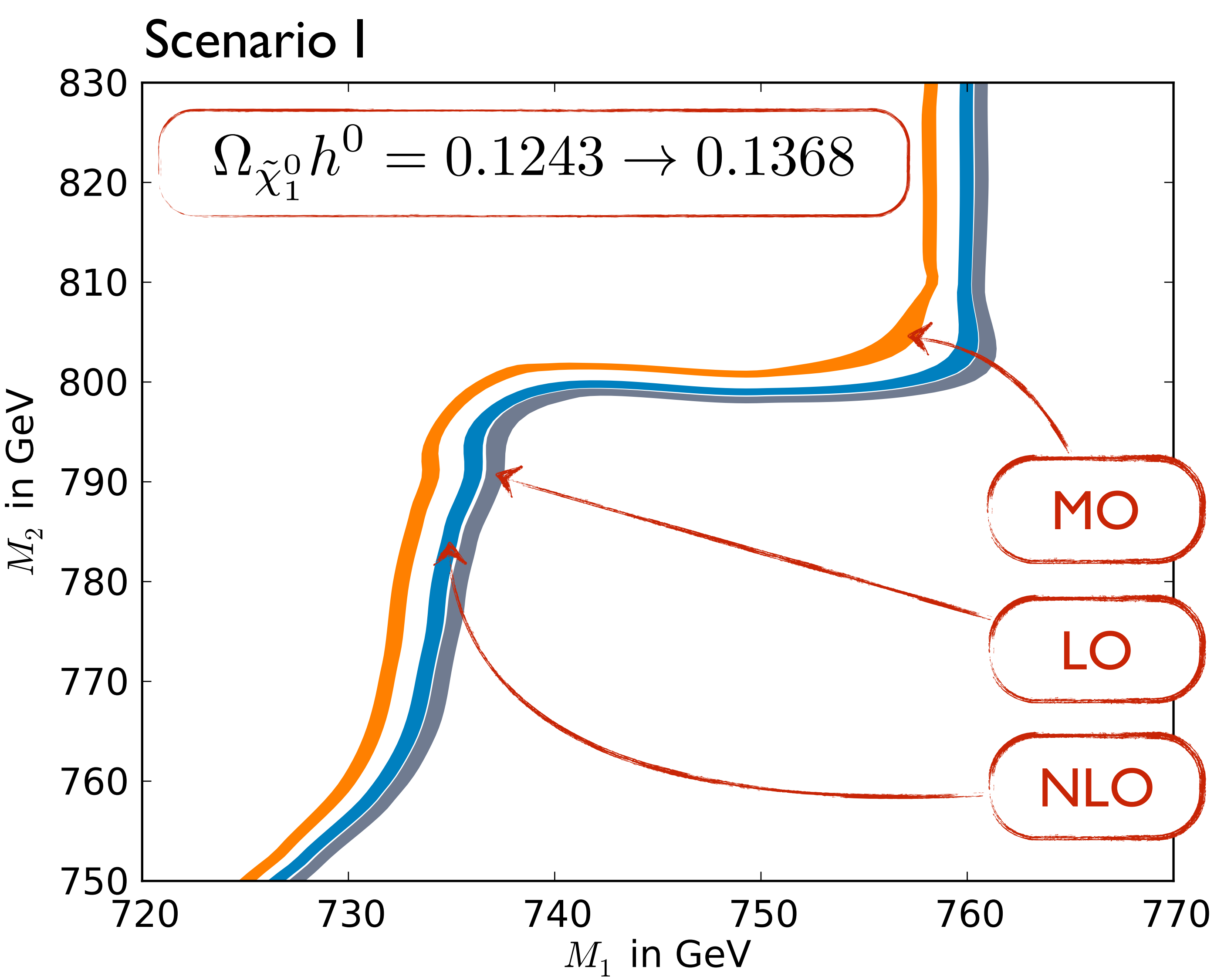

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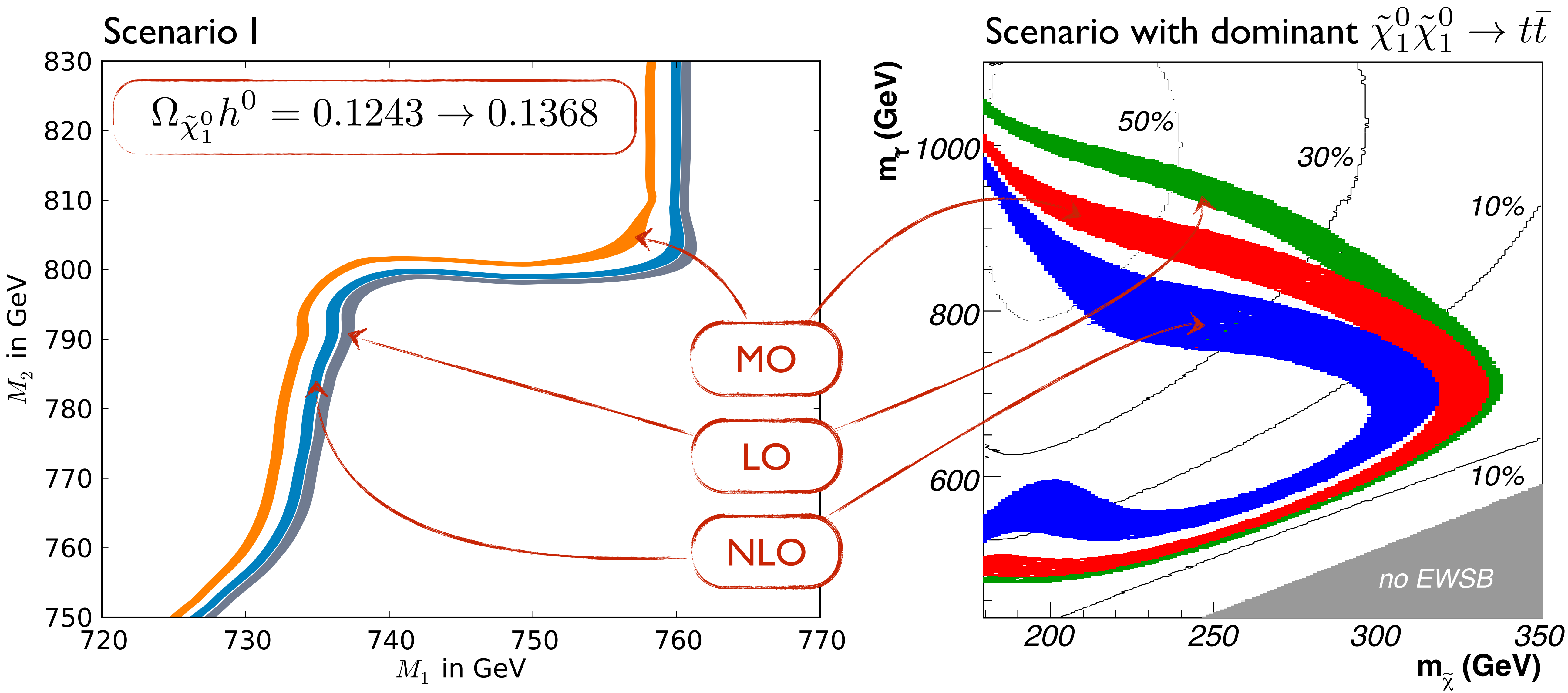

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Herrmann, Klasen, Kovarik (2009)

In summary, …

— Relic density calculation is a powerful tool to obtain complementary information on the new physics' parameter space w.r.t. collider and precision data

— **Improving the theoretical accuracy of relic density prediction is necessary in order to meet the current experimental precision**

— The numerical package **DM@NLO** allows computation of neutralino (co-)annihilation cross-section including one-loop corrections in QCD

$\tilde{\chi}_i^{0,\pm}\tilde{\chi}_j^{0,\pm} \to q\bar{q}'$ $\quad$ $\tilde{\chi}_i^{0}\tilde{q}_j \to qH, qV, qg$ $\quad$ $\tilde{q}_i\tilde{q}_j^{(*)} \to VV, HH, HV, q\bar{q}$

— Link to micrOMEGAs (link to DarkSUSY coming soon…)

— **Impact of radiative corrections can numerically be more important than current experimental uncertainty**

DM@NLO — http://dmnlo.hepforge.org