

Predicting the neutralino relic density in the MSSM more precisely

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DM@NL collaboration — <http://dmnlo.hepforge.org>

- J. Harz, B. Herrmann, M. Klasen, K. Kovařík, P. Steppeler — Phys. Rev. D 93: 114023 (2016) — arXiv:1602.08103 [hep-ph]
- J. Harz, B. Herrmann, M. Klasen, K. Kovařík, M. Meinecke — Phys. Rev. D 91: 034012 (2015) — arXiv:1410.8063 [hep-ph]
- J. Harz, B. Herrmann, M. Klasen, K. Kovařík — Phys. Rev. D 91: 034028 (2015) — arXiv:1409.2898 [hep-ph]
- B. Herrmann, M. Klasen, K. Kovařík, M. Meinecke, P. Steppeler — Phys. Rev. D 89: 114012 (2014) — arXiv:1404.2931 [hep-ph]
- J. Harz, B. Herrmann, M. Klasen, K. Kovařík, Q. Le Boulc'h — Phys. Rev. D 87: 054031 (2013) — arXiv:1212.5241 [hep-ph]
- B. Herrmann, M. Klasen, K. Kovařík — Phys. Rev. D 79: 061701 (2009) — arXiv:0901.0481 [hep-ph]
- B. Herrmann, M. Klasen, K. Kovařík — Phys. Rev. D 80: 085025 (2009) — arXiv:0907.0030 [hep-ph]
- B. Herrmann, M. Klasen — Phys. Rev. D 76: 117704 (2007) — arXiv:0709.0043 [hep-ph]



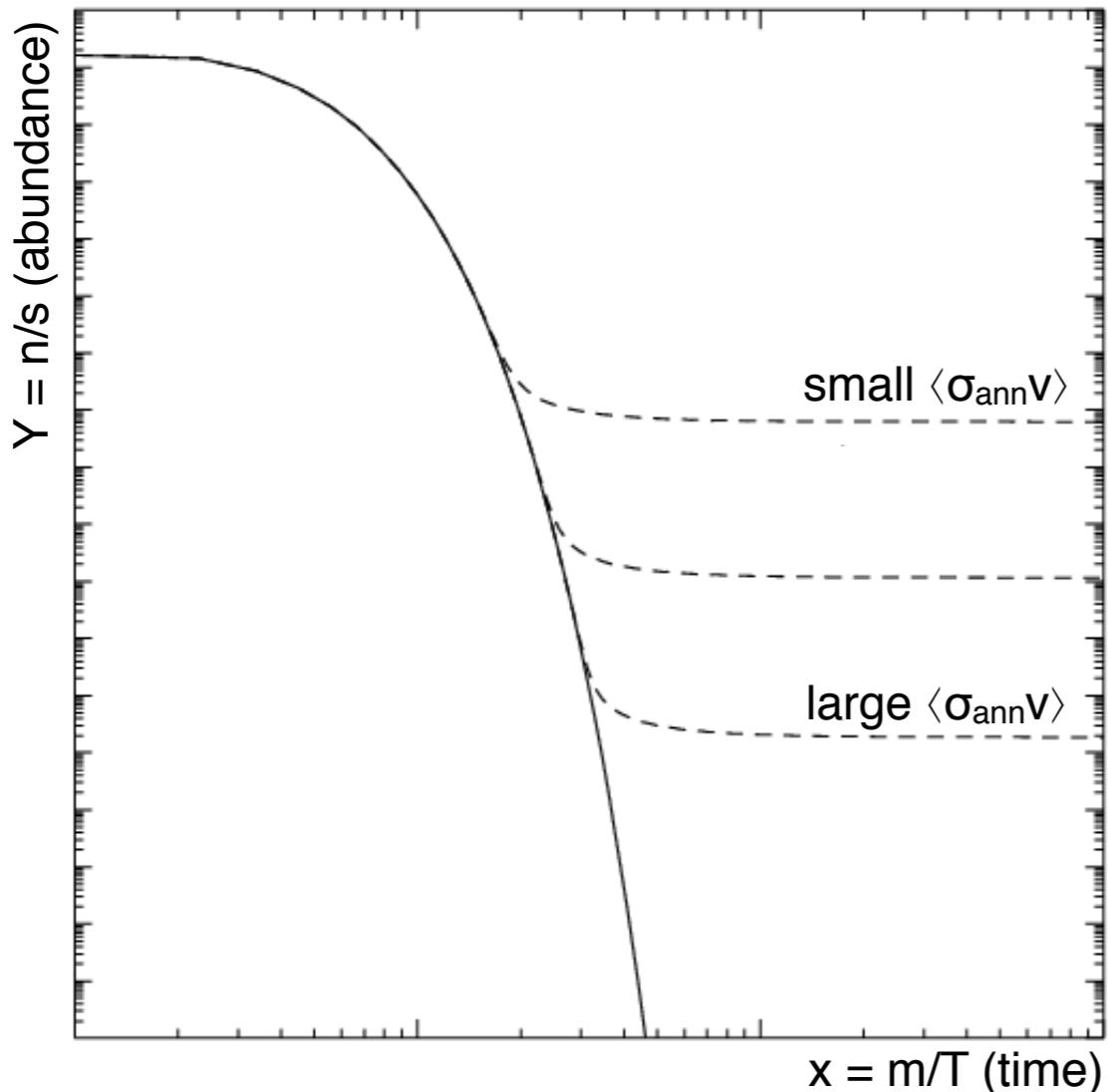
The Minimal Supersymmetric Standard Model (MSSM)

SM Particles		Spin		Spin		Superpartners
Quarks	$(u_L \ d_L)$	1/2	Q	0	$(\tilde{u}_L \ \tilde{d}_L)$	Squarks
	u_R^\dagger	1/2	\bar{u}	0	\tilde{u}_R^*	
	d_R^\dagger	1/2	\bar{d}	0	\tilde{d}_R^*	
Leptons	$(\nu \ e_L)$	1/2	L	0	$(\tilde{\nu} \ \tilde{e}_L)$	Sleptons
	e_R^\dagger	1/2	\bar{e}	0	\tilde{e}_R^*	
Higgs	$(H_u^+ \ H_u^0)$	0	H_u	1/2	$(\tilde{H}_u^+ \ \tilde{H}_u^0)$	Higgsinos
	$(H_d^0 \ H_d^-)$	0	H_d	1/2	$(\tilde{H}_d^0 \ \tilde{H}_d^-)$	
W bosons	W^0, W^\pm	1		1/2	$\tilde{W}^0, \tilde{W}^\pm$	Winos
B boson	B^0	1		1/2	\tilde{B}^0	Bino
Gluon	g	1		1/2	\tilde{g}	Gluino
Graviton	G	2		3/2	\tilde{G}	Gravitino

Lightest neutralino is dark matter (WIMP) candidate “par excellence”

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

Dark matter relic abundance — freeze-out picture



Dark matter relic abundance very precisely known
Planck collaboration 2015

Time evolution of number density of the relic particle described by Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle\sigma_{\text{ann}}v\rangle (n^2 - n_{\text{eq}}^2)$$

Prediction of dark matter relic density
(if masses and interactions are known)

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_{\text{crit}}} \sim \frac{1}{\langle\sigma_{\text{ann}}v\rangle}$$

(dis)favoured parameter regions...?

$$\Omega_{\text{CDM}} h^2 = 0.1199 \pm 0.0022$$

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

DarkSUSY Bergström, Edsjö, Gondolo *et al.* 2004-2016, **micrOMEGAs** Bélanger, Boudjema, Pukhov *et al.* 2003-2016,
SuperIsoRelic Arbey, Mahmoudi 2008, ...

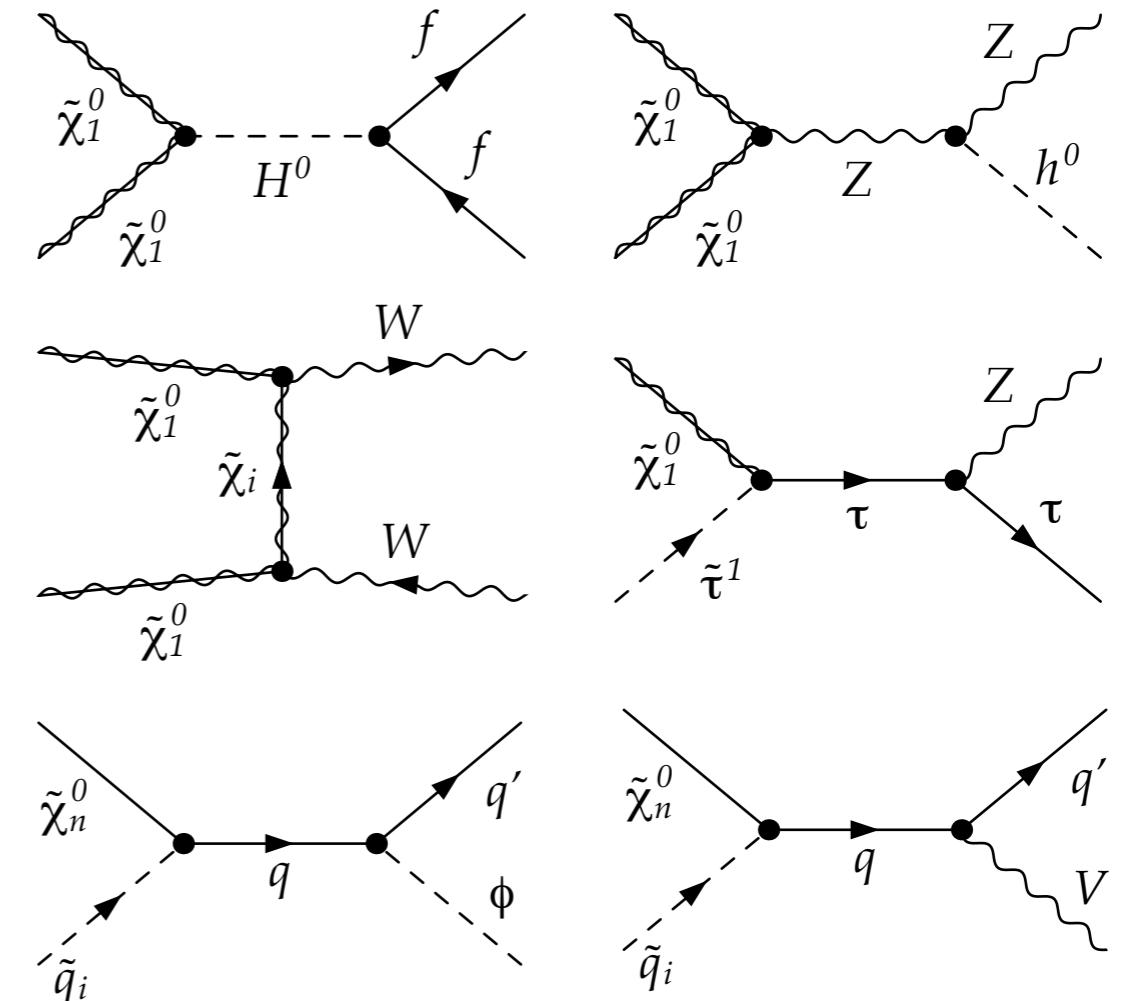
A closer look on the (co)annihilation cross-section

Time evolution of relic particle described by Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle\sigma_{\text{ann}}v\rangle (n^2 - n_{\text{eq}}^2)$$

$$\langle\sigma_{\text{ann}}v\rangle = \sum_{i,j} \sigma_{ij} v_{ij} \frac{n_i^{\text{eq}}}{n_\chi} \frac{n_j^{\text{eq}}}{n_\chi}$$

$$\frac{n_i^{\text{eq}}}{n_\chi^{\text{eq}}} \sim \exp \left\{ -\frac{m_i - m_\chi}{T} \right\}$$

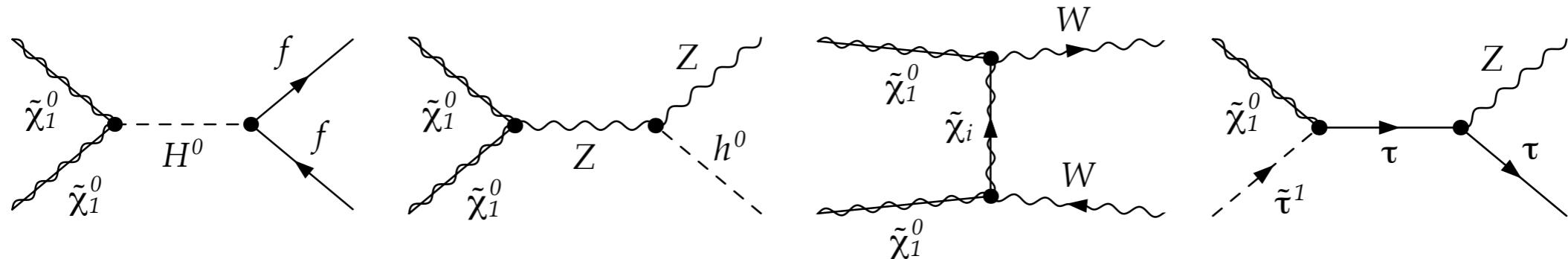


Only co-annihilations with almost mass-degenerate particles are numerical relevant

Typical examples in MSSM: other neutralinos, charginos, stau, stop

Motivation for higher order corrections

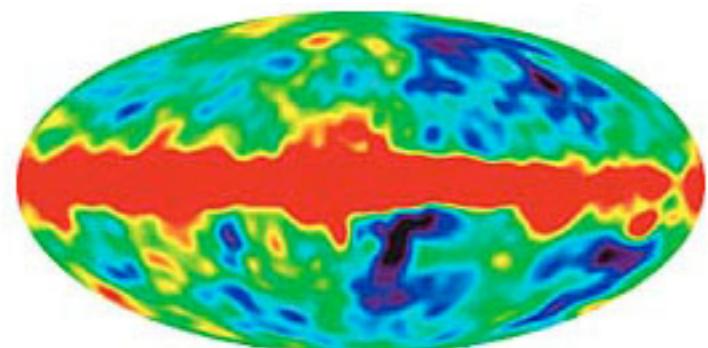
All processes implemented in public codes — **but only at the (effective) tree-level**



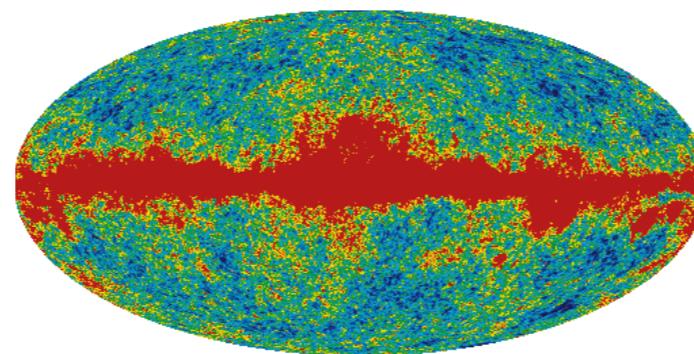
Higher-order loop corrections can give important contributions to cross-sections

In particular, sizeable impact from QCD corrections due to strong coupling constant

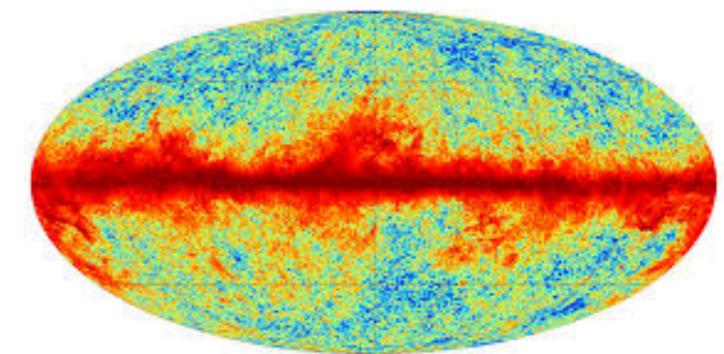
More precise theoretical predictions needed to keep up with experimental improvements



COBE 1989



WMAP 2002



Planck 2013

DM@NL project — **Provide calculation of σ_{ann} including QCD corrections**
— Extension to public codes (e.g. micrOMEGAs, DarkSUSY)...

The DM@NL project

Provide a **next-to-leading order calculation** (in QCD) for the neutralino (co-)annihilation cross section (and thus for the neutralino relic density)

$$\tilde{\chi}\tilde{\chi}' \rightarrow q\bar{q}'$$

$$\tilde{\chi}\tilde{q} \rightarrow q'H/q'V$$

$$\tilde{q}\tilde{q}^* \rightarrow HH/HV/VV$$

numerically implemented,
results published
Herrmann et al. 2009-2016

$$\tilde{\chi}\tilde{\chi}' \rightarrow gg/\gamma\gamma$$

$$\tilde{q}\tilde{q} \rightarrow qq$$

$$\tilde{q}\tilde{q}^* \rightarrow q\bar{q}'$$

$$\tilde{\tau}\tilde{\tau}^* \rightarrow qq'$$

work in progress...

Definition and implementation of a dedicated **renormalization scheme**

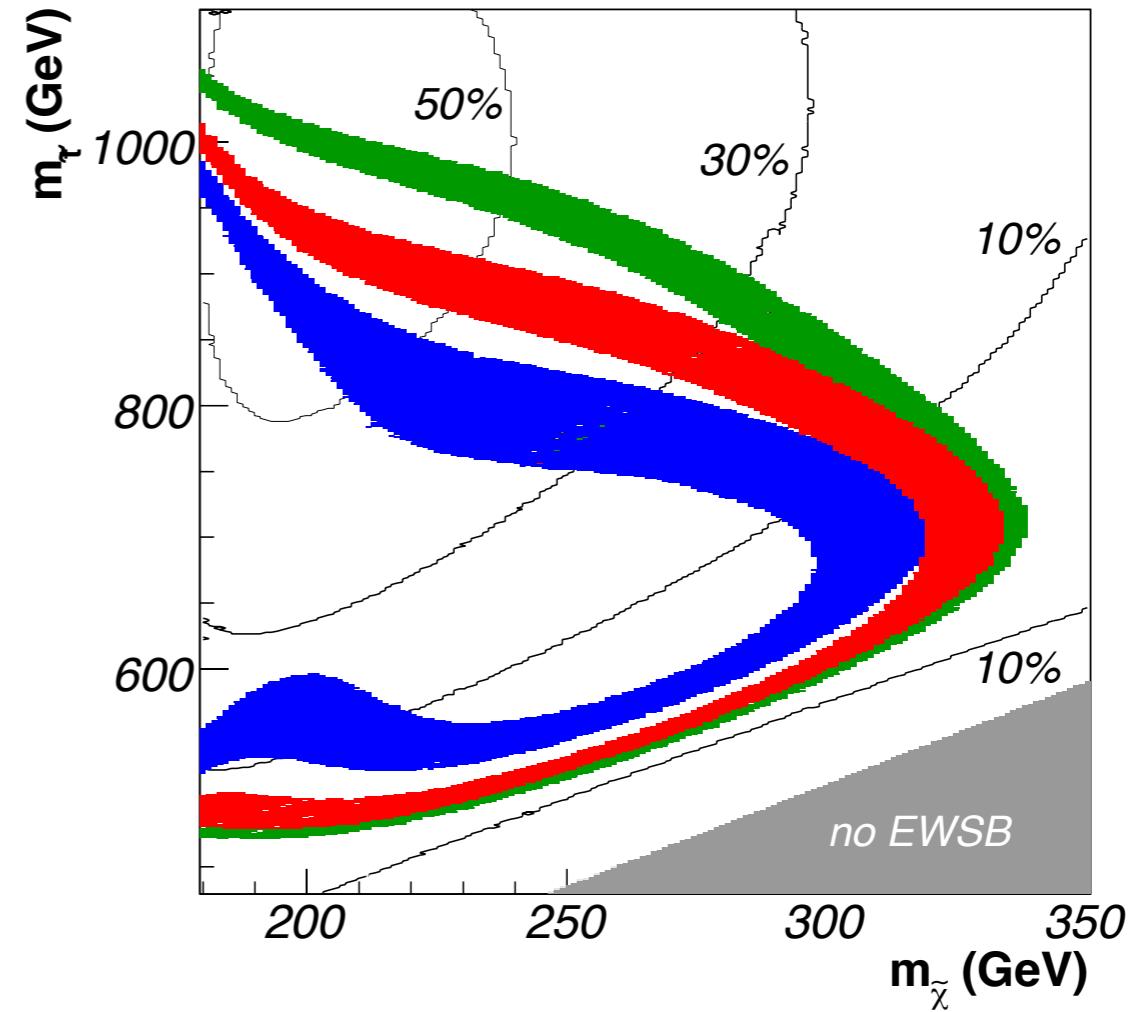
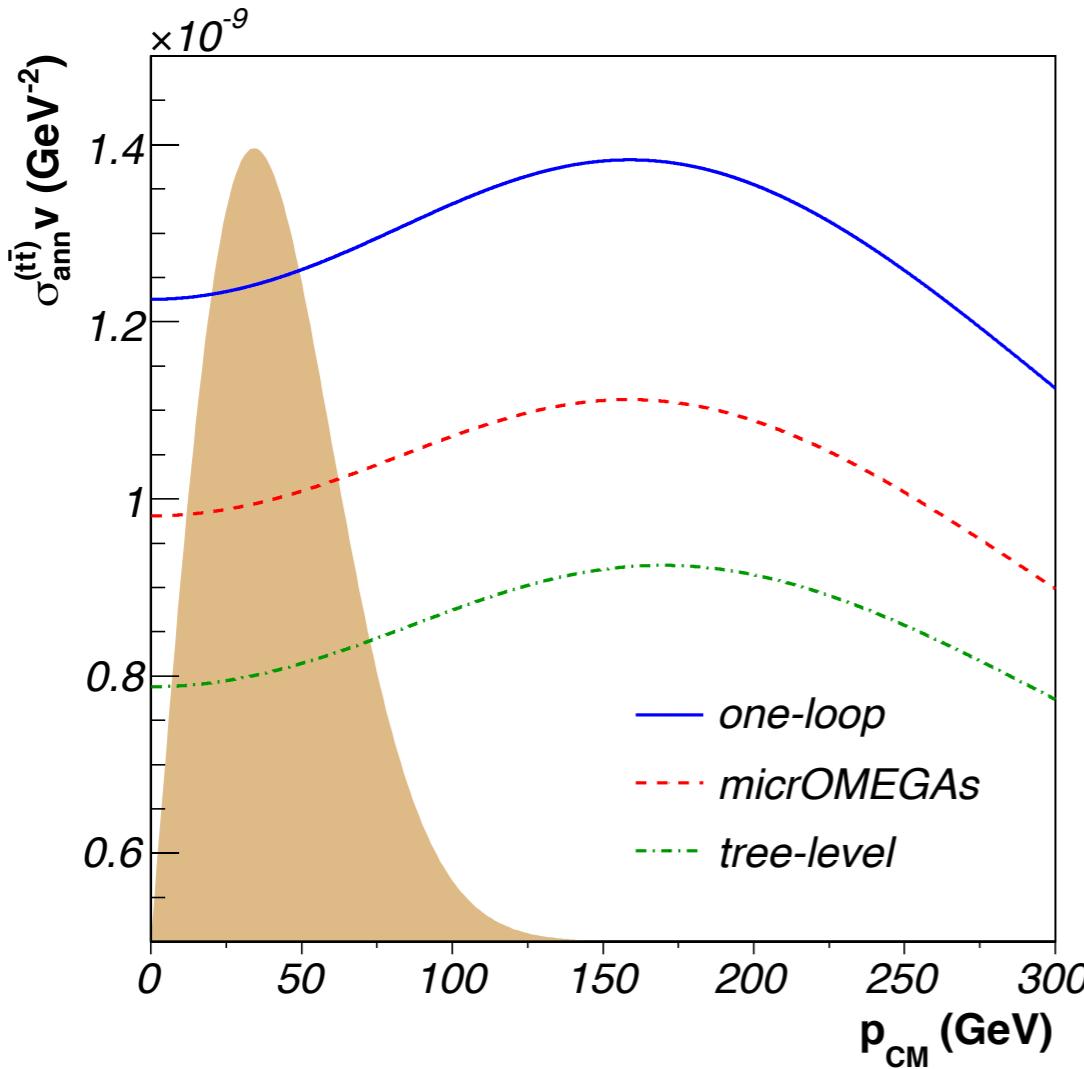
Infrared treatment — phase space slicing and dipole subtraction à la Catani-Seymour

Resummation of **Coulomb corrections** for stop-stop annihilation

Application of the results to **direct detection** (work in progress)

Interfaces to **micrOMEGAs** (since 2008) and **DarkSUSY** (work in progress)

Neutralino pair annihilation into top quarks

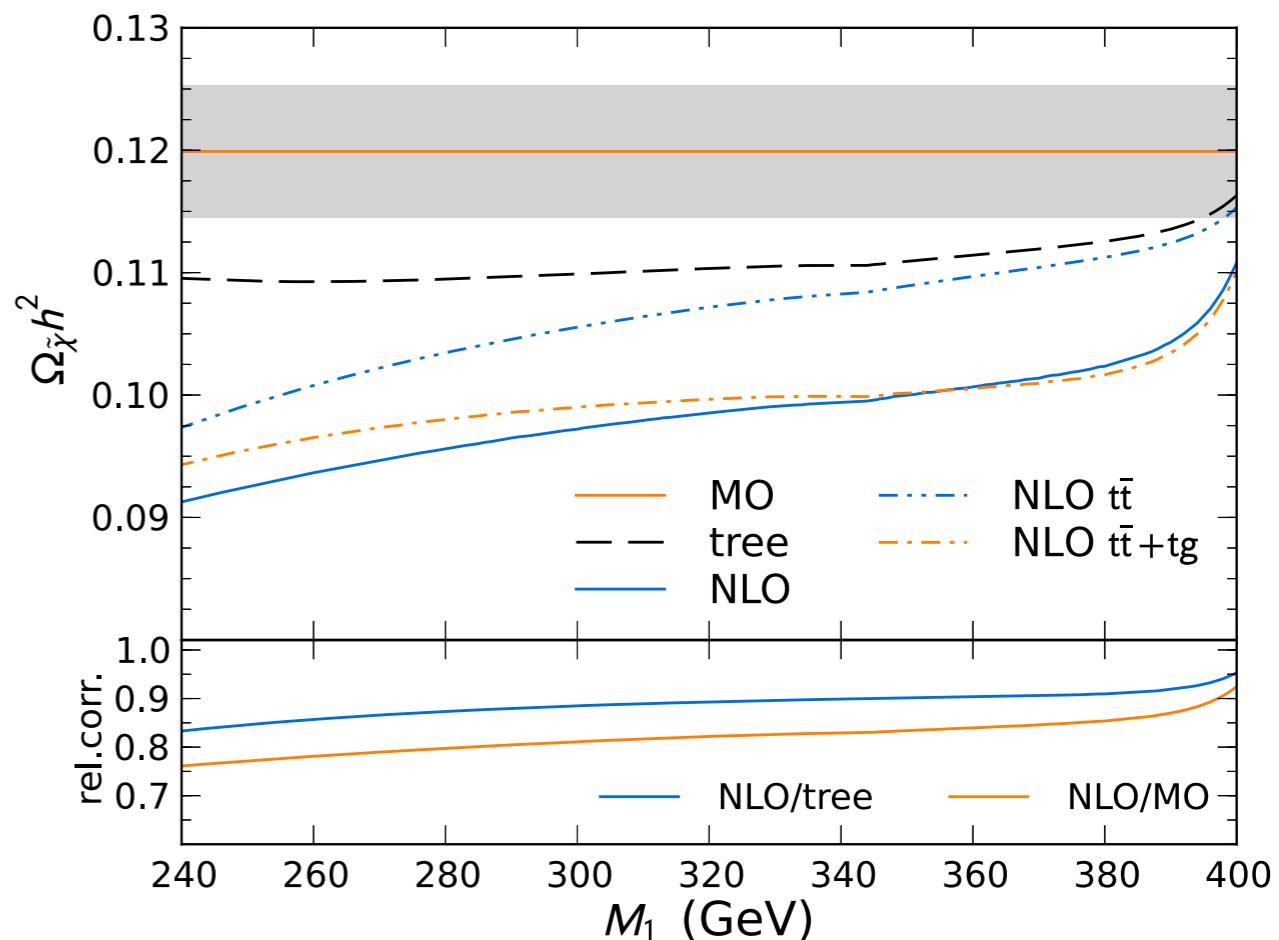
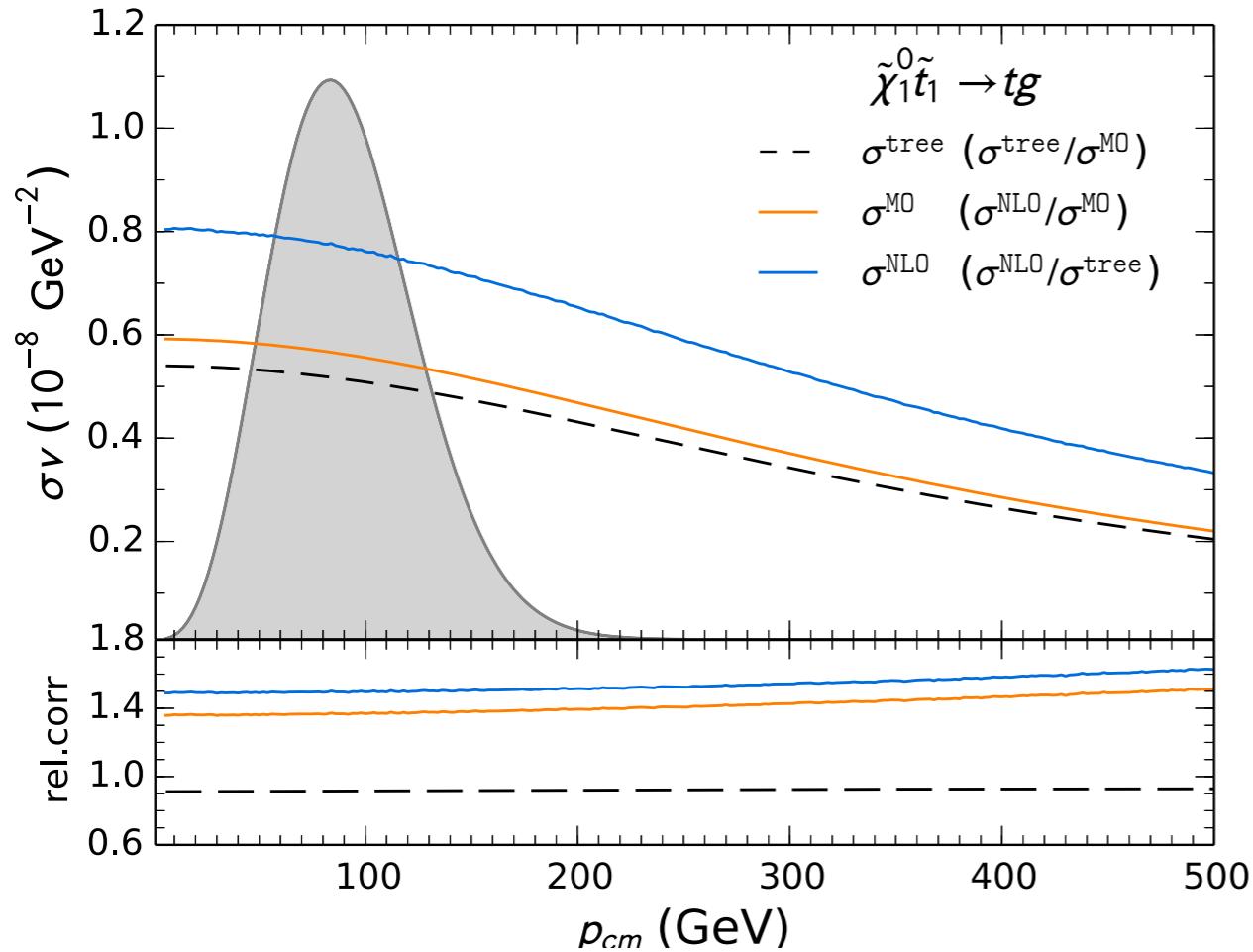


Annihilation cross-section enhanced by up to 50% by radiative corrections

Corrections can lead to **important shifts for preferred regions** (e.g. ~ 200 GeV for m_{stop})

Effective Yukawa couplings (as e.g. in micrOMEGAs) very good approximation around Higgs-resonances, **but other sub-channels can be dominant** (here: Z^0 /squark-exchange)

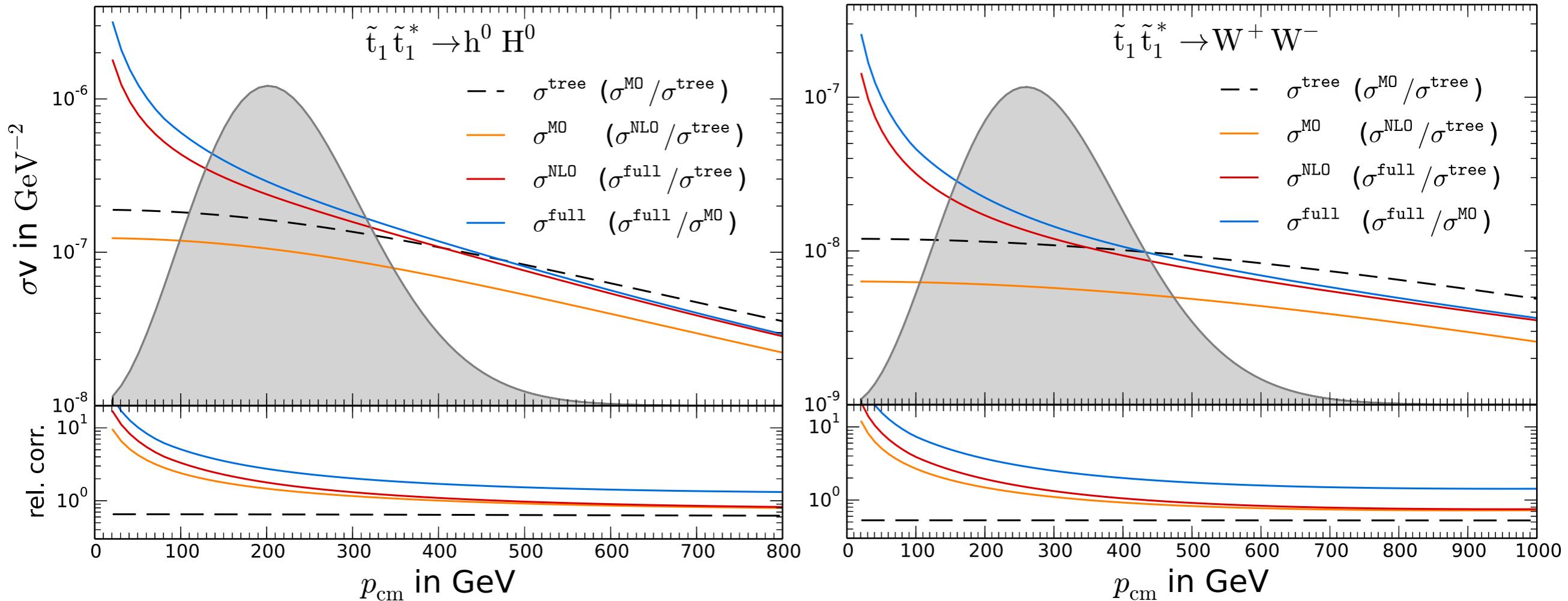
Neutralino-stop co-annihilation



Relative corrections of up to 40-50% observed for the co-annihilation cross-section, leading to a **numerically important shift** for the predicted **neutralino relic density** (up to almost 25% — more than Planck uncertainty!)

Co-annihilation into **SM-like Higgs** and gluon most important (other final states generally subdominant)

Stop pair annihilation — electroweak final states



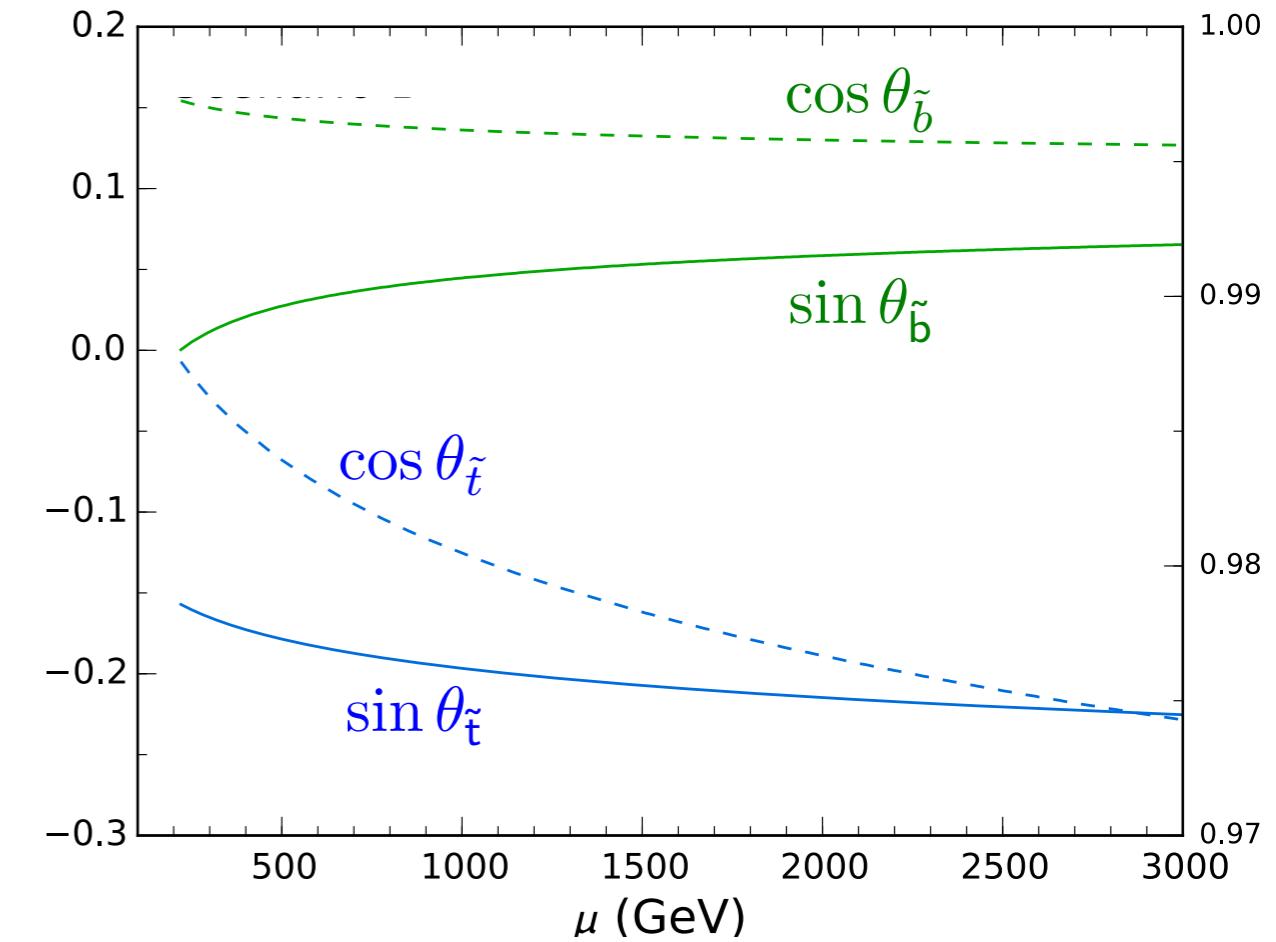
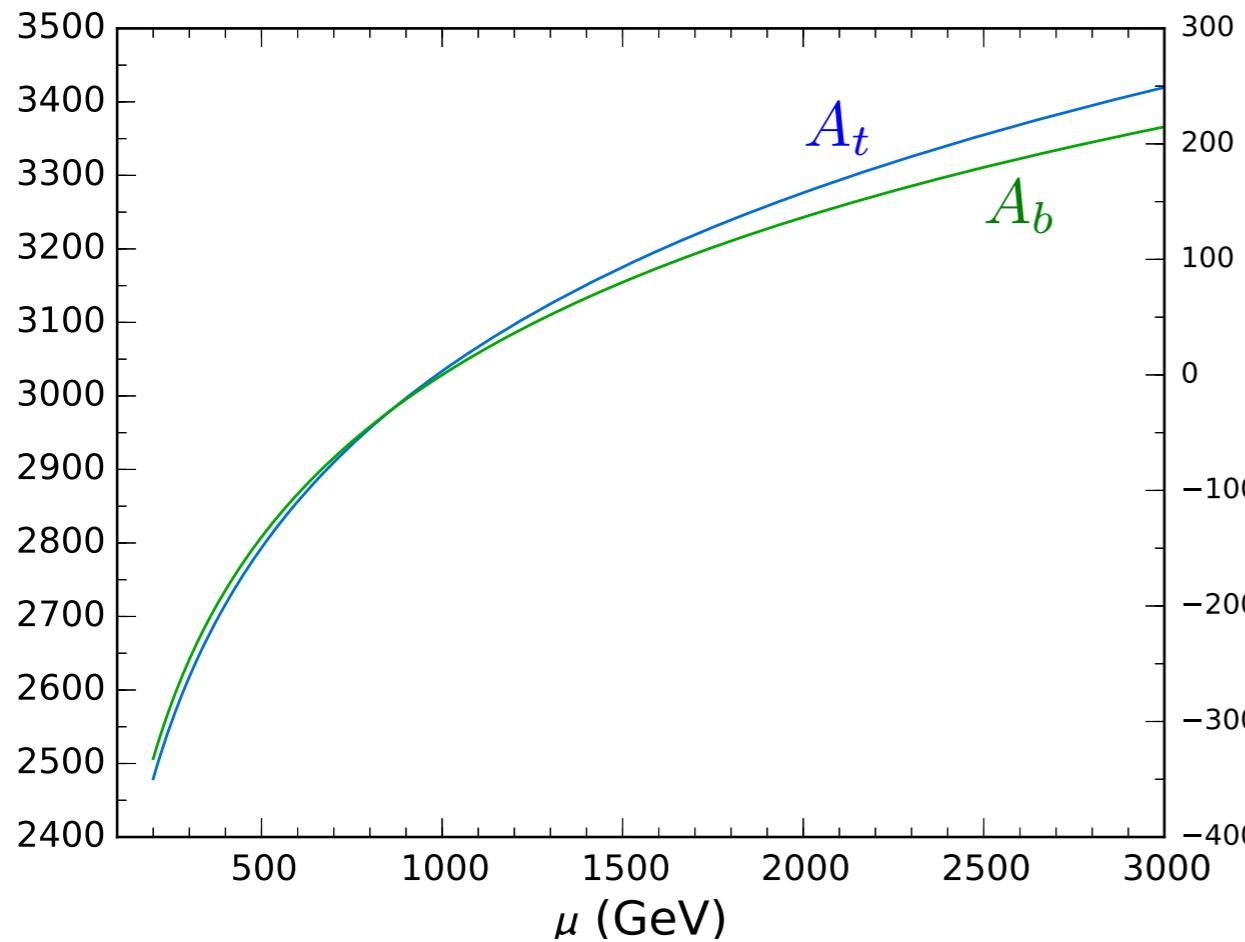
Coulomb corrections **dominant for small values of p_{cm}** (Coulomb singularity),
while fixed-order corrections dominant for high-momentum region

Resulting relic density receives corrections of up to 40% (more important than Planck uncertainty!)

Scale dependence of neutralino (co-)annihilation

Evaluation of theoretical uncertainty by **varying** (unphysical) **renormalization scale**

— hybrid on-shell / DRbar renormalization scheme designed for neutralino (co-)annihilation



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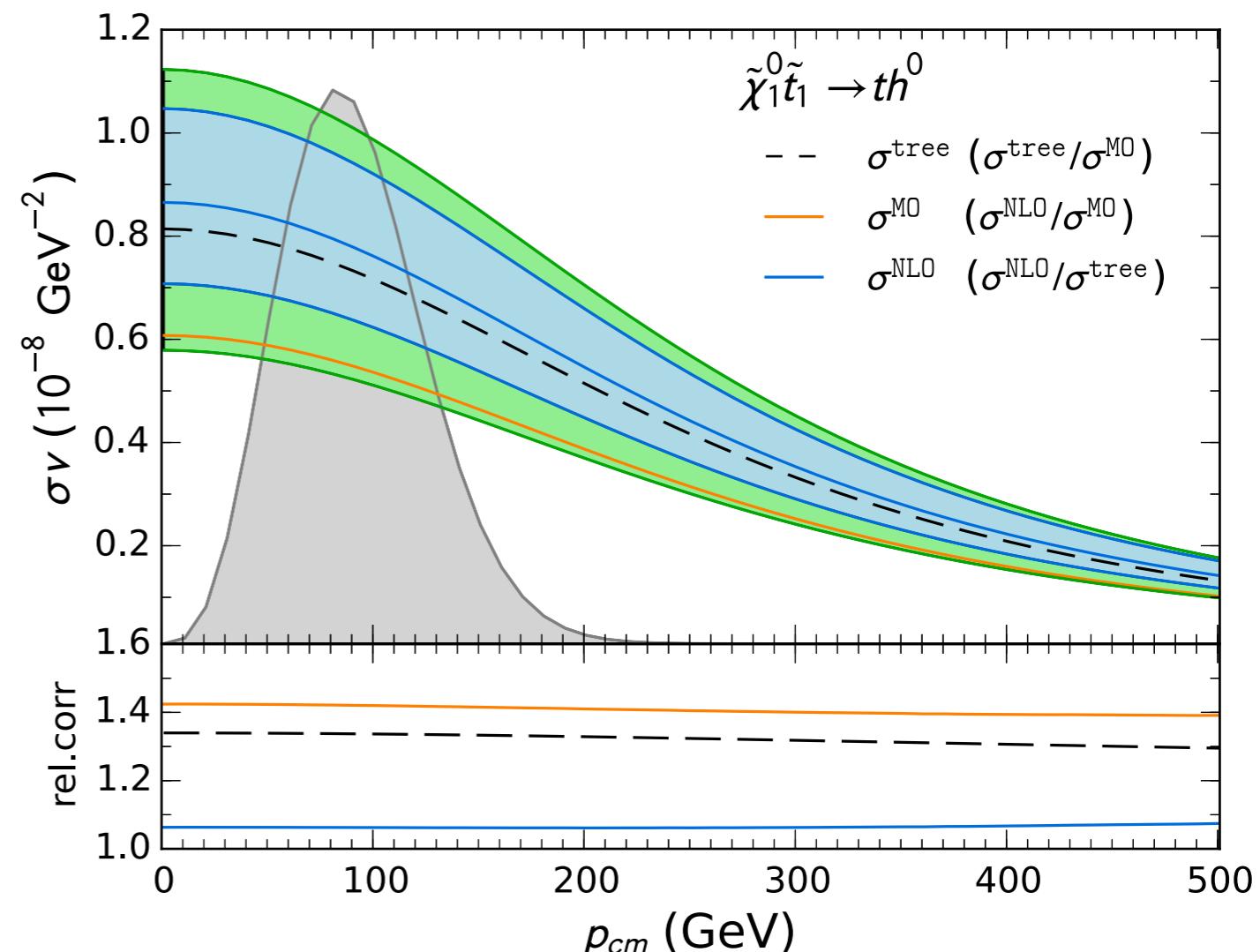
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Within the scale uncertainty,
the **tree-level result agrees**
with the NLO calculation and
the micrOMEGAs value

Scale uncertainty reduced at the
one-loop level w.r.t. to tree-level
result (as expected)

- main effect from **mixing angle**
and **trilinear coupling**
- dependence of α_s subdominant



Scale dependence of neutralino relic density

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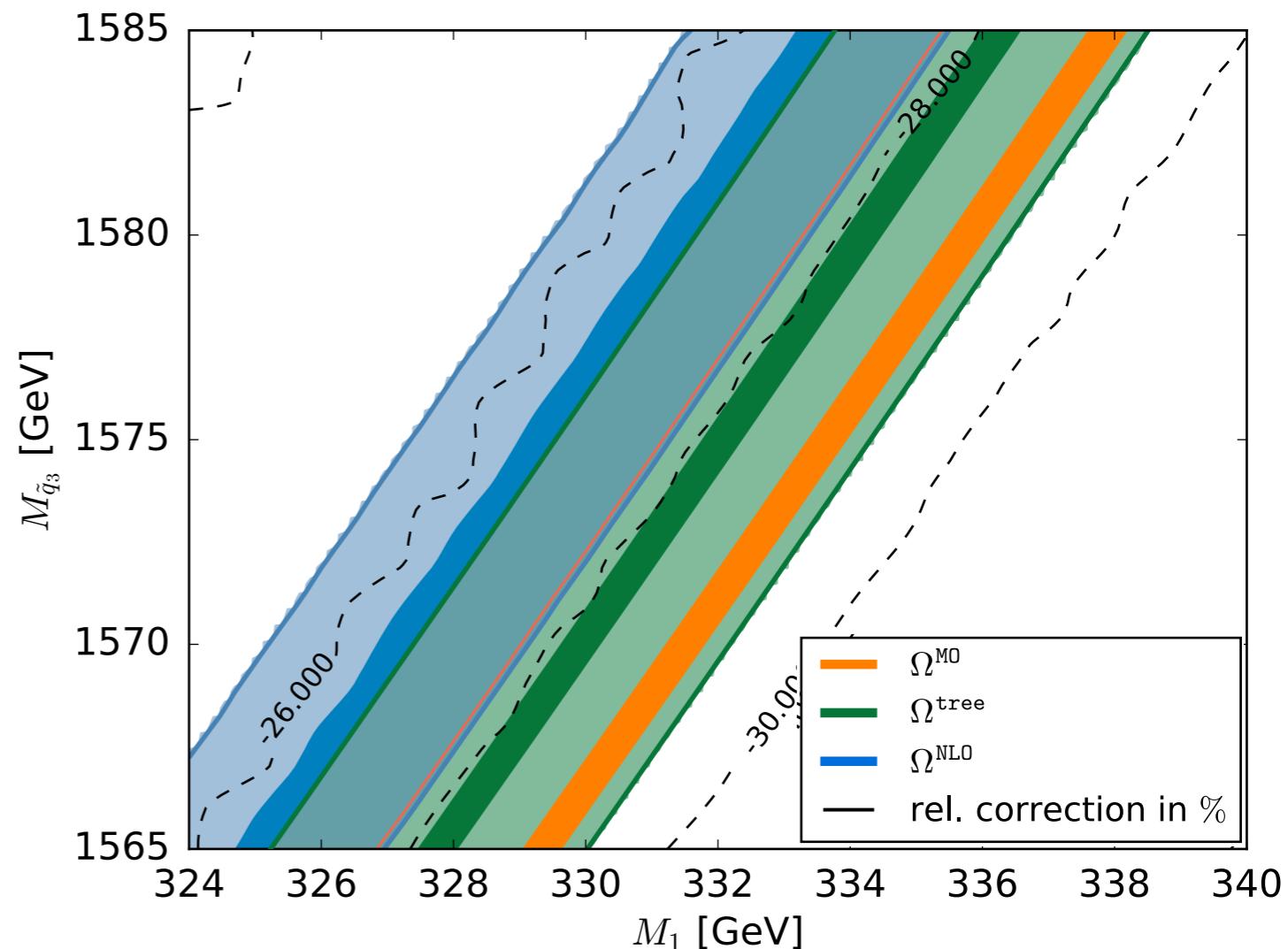
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Summary

Recent experimental improvements (WMAP, Planck...) require more precise predictions of the dark matter relic density on the theory side...

DM@NL — calculation of neutralino (co)annihilation including QCD corrections

$$\tilde{\chi}\tilde{\chi}' \rightarrow q\bar{q}'$$

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numerically implemented
results published

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work in progress...

Impact of corrections on the relic density more important than current exp. uncertainty

— Higher-order corrections important when extracting parameters from cosmological data

Variation of the renormalization scale shows that the **relic density cannot always be determined theoretically with a precision of 2%** similar to the experimental result