# Precision calculations related to dark matter: relic density, direct detection, uncertainty

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

M. Klasen, K. Kovařík, P. Steppeler — arXiv:1607.06396 [hep-ph]
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]
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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]

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# Outline

Introduction

**Corrections to the neutralino (co)annihilation cross-section and impact on relic density**

**Corrections to direct dark matter detection**

**Scale dependence and theoretical uncertainty**

Conclusion


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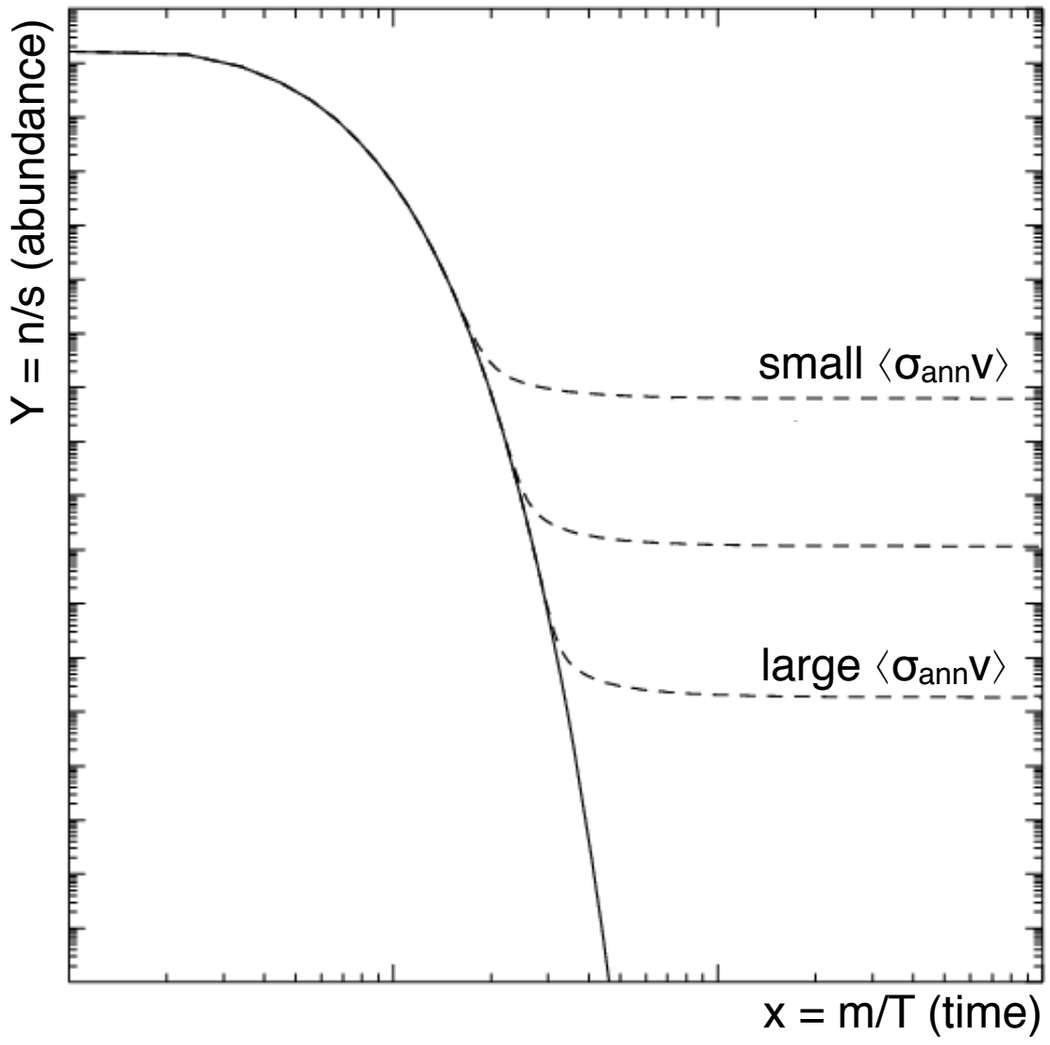
# Introduction

# Dark matter relic abundance — freeze-out picture




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

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

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

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

**(dis)favoured parameter regions…?**

Dark matter relic abundance very precisely known
Planck collaboration 2015

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

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, **…**

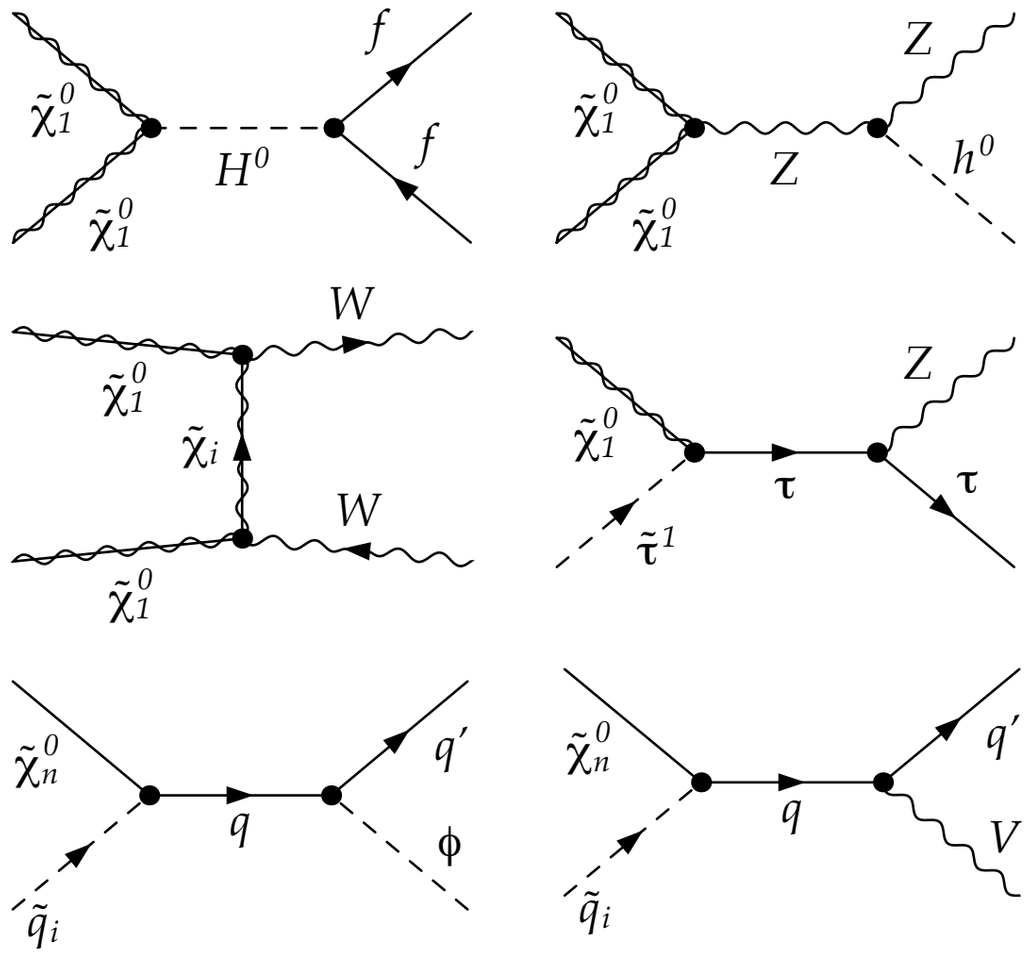
# A closer look on the (co)annihilation cross-section

Time evolution of relic particle described by Boltzmann equation

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

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

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

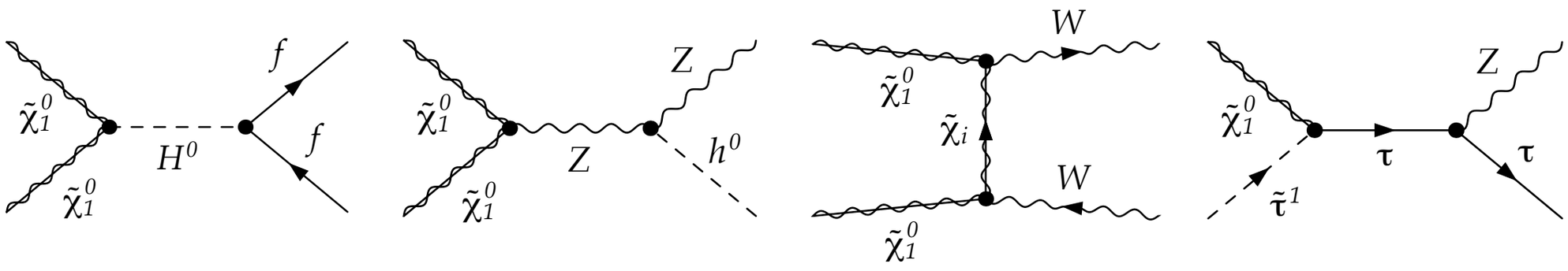



**Only co-annihilations with almost mass-degenerate particles are numerical relevant**

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

# Motivation for higher order corrections

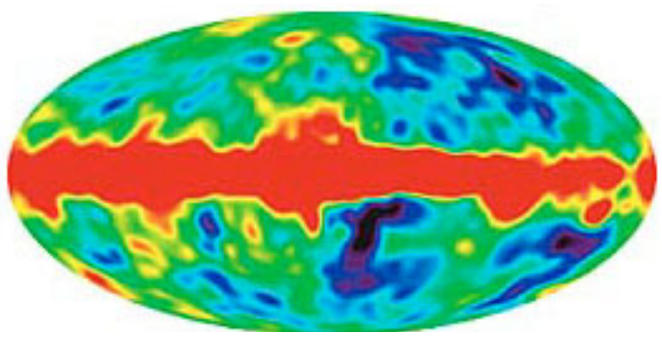
All processes implemented in public codes — **but only at the (effective) tree-level**



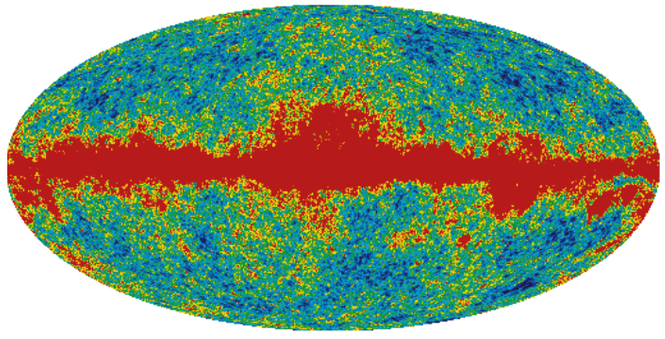

Higher-order loop corrections can give important contributions to cross-sections

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

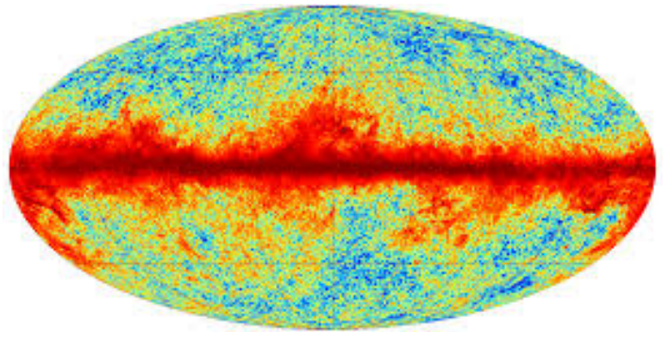
More precise theoretical predictions needed to keep up with experimental improvements



COBE 1989



WMAP 2002



Planck 2013

**DM@NL** project — **Provide calculation of $\sigma_{ann}$ including QCD corrections**

— Extension to public codes (e.g. micrOMEGAs, DarkSUSY)…

# Corrections to neutralino (co)annihilation and impact on the relic density

# The DM@NLO project

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

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

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

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

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

$$\tilde{\chi}\tilde{\chi}' \to gg/\gamma\gamma \qquad \tilde{q}\tilde{q} \to qq$$

$$\tilde{q}\tilde{q}^* \to q\bar{q}' \qquad \tilde{\tau}\tilde{\tau}^* \to qq'$$

→ **work in progress…**

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

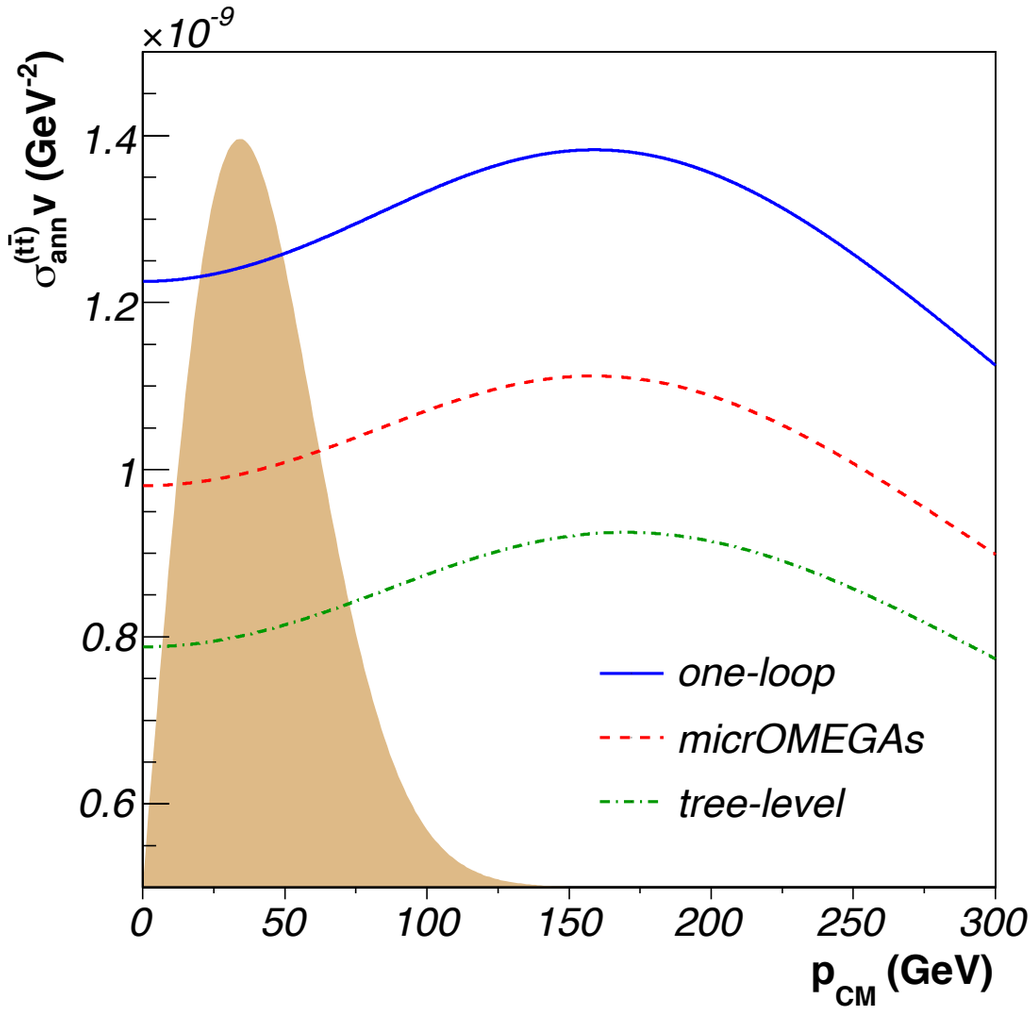
**Infrared treatment** — phase space slicing and dipole subtraction à la Catani-Seymour

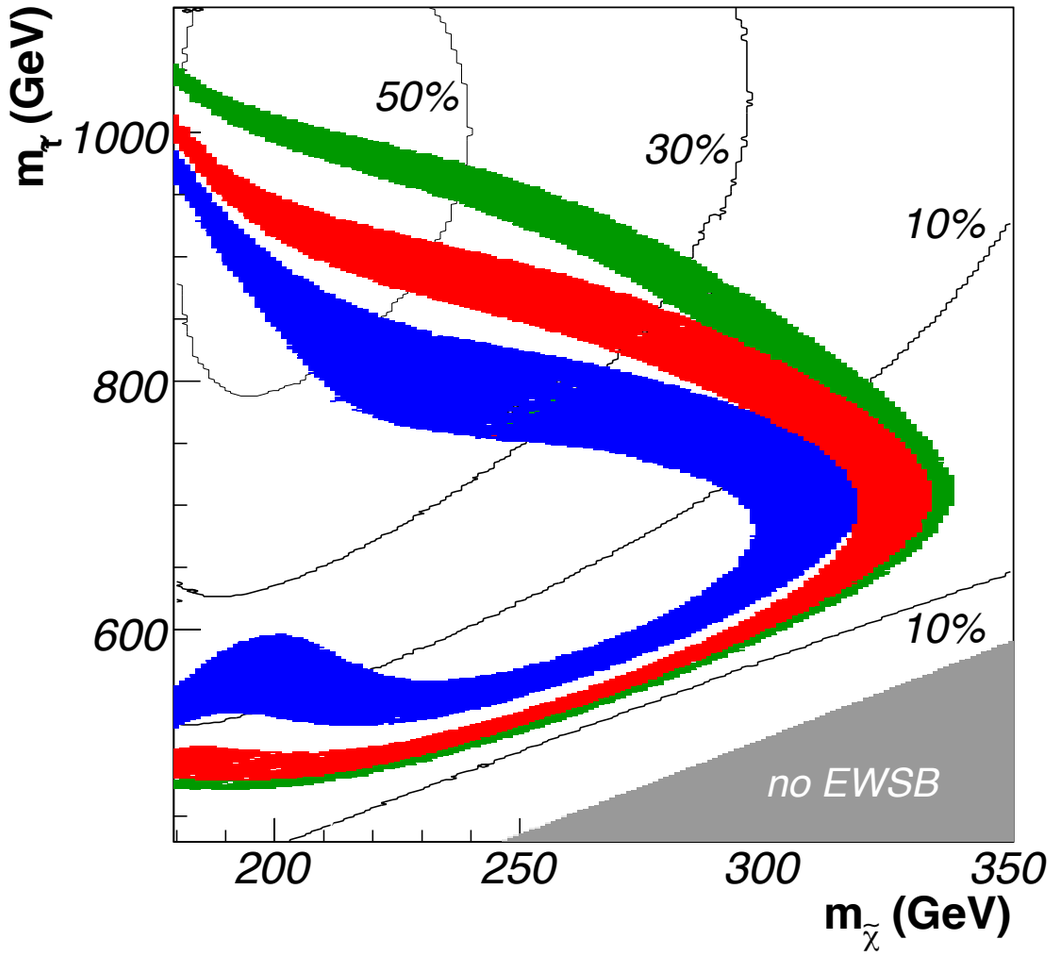
Resummation of **Coulomb corrections** for stop-stop annihilation

Application of the results to **direct detection**

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)


B. Herrmann, M. Klasen, K. Kovařík — Phys. Rev. D 80: 085025 (2009) — arXiv:0907.0030 [hep-ph]
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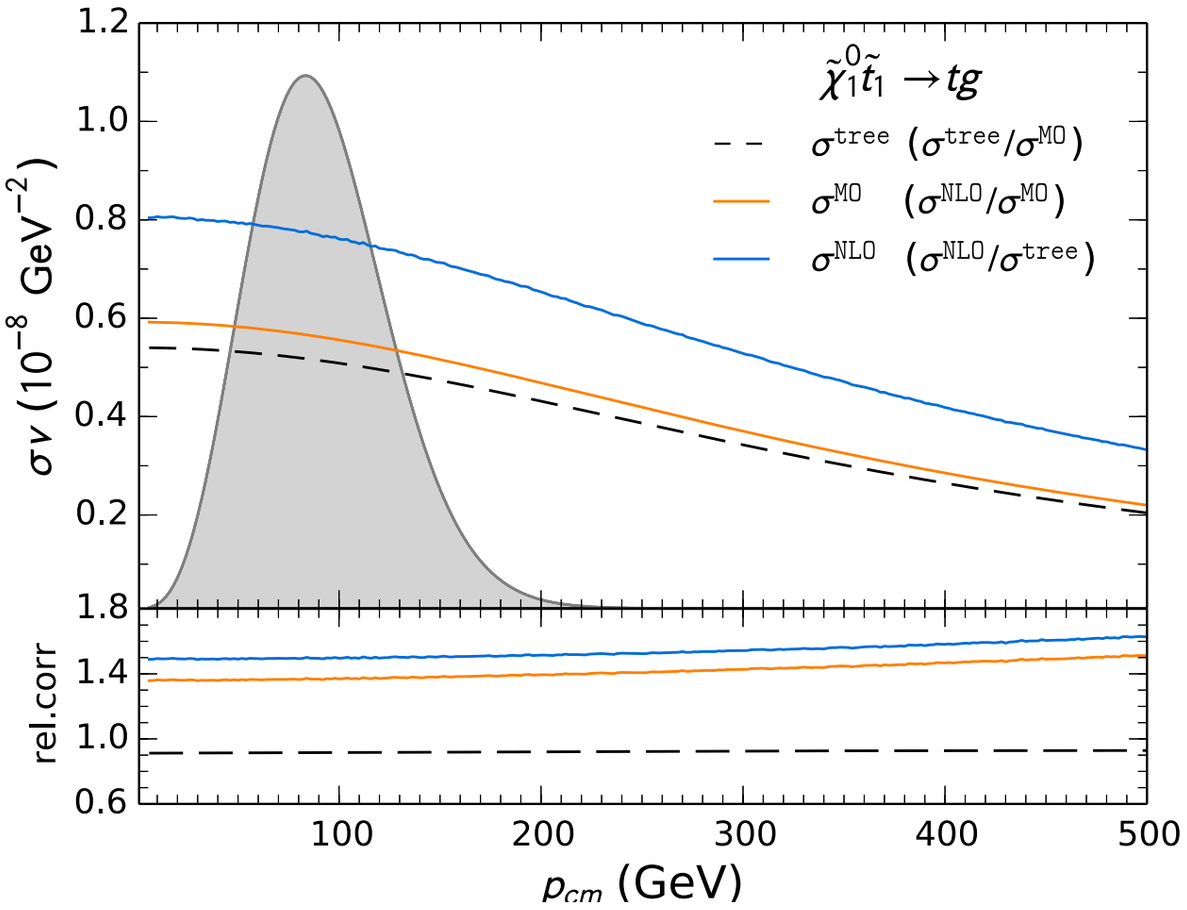
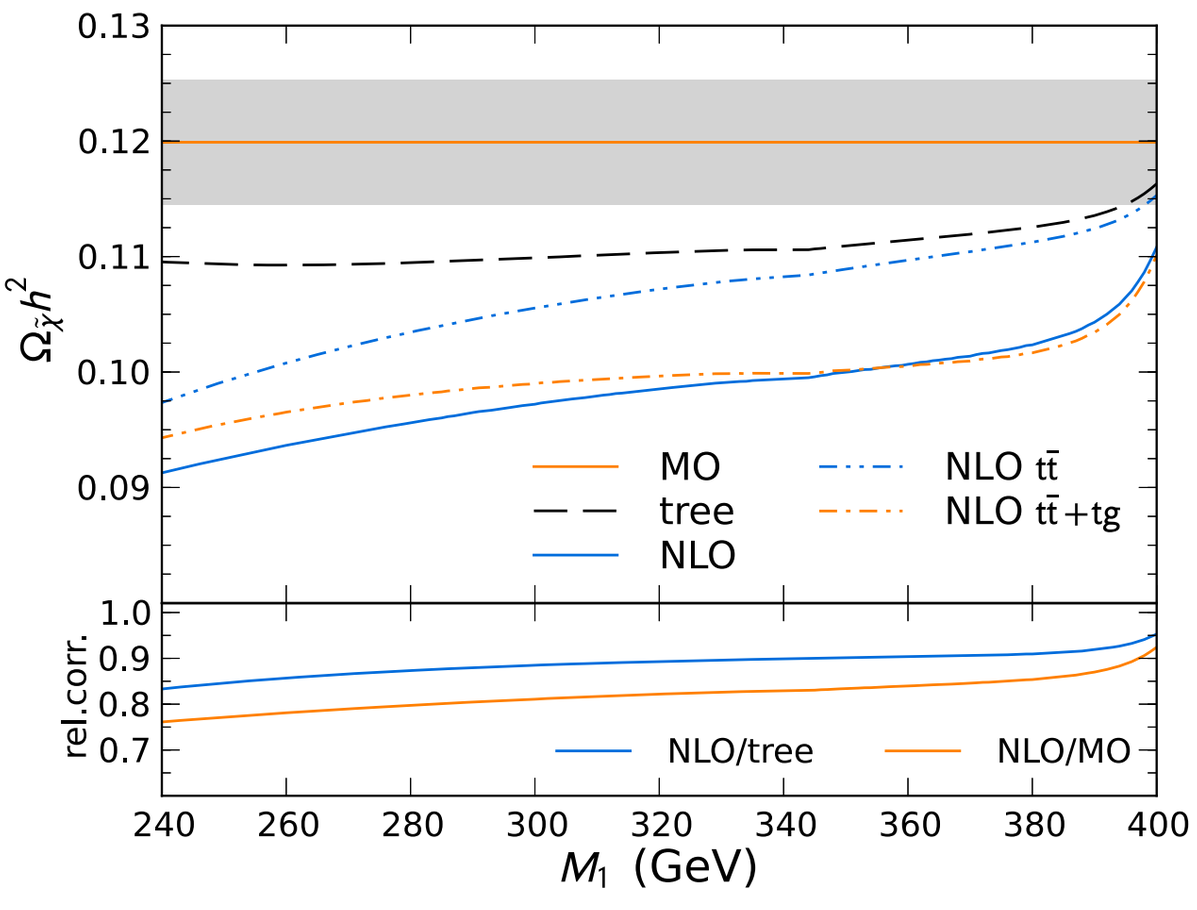
# Neutralino-stop co-annihilation




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 about 25% — more than Planck uncertainty!)

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

Harz, Herrmann, Klasen, Kovařík, Le Boulc'h — Phys. Rev. D 87: 054031 (2013) — arXiv:1212.5241 [hep-ph]
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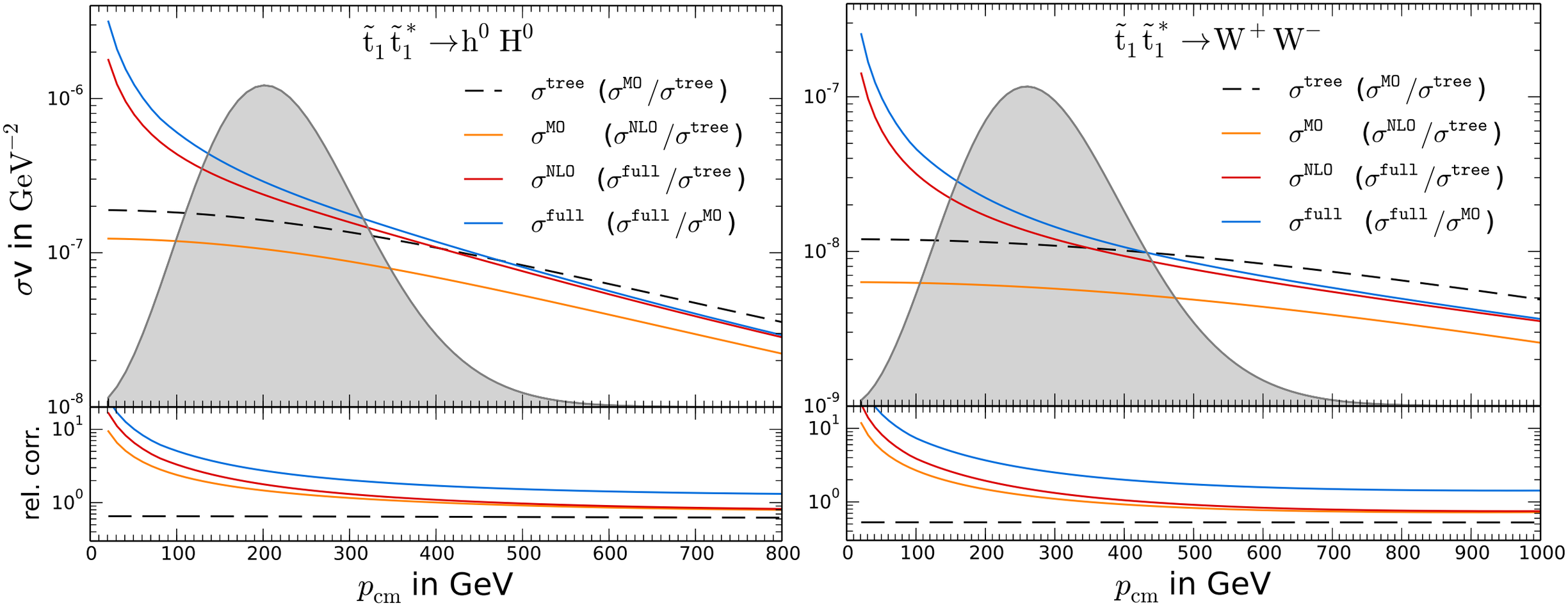
# Stop pair annihilation — electroweak final states



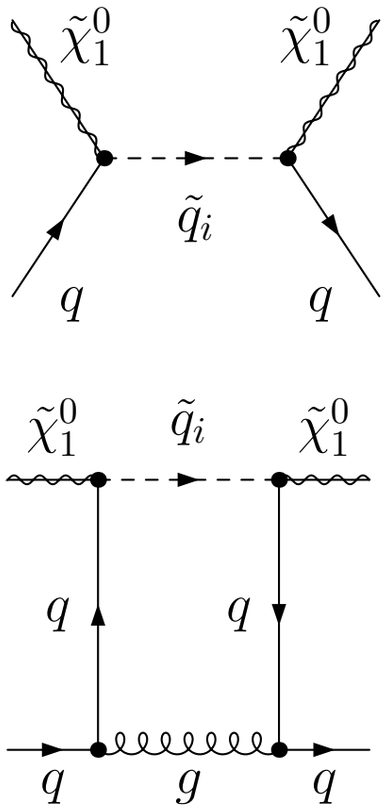

Coulomb corrections **dominant for small values of $p_{cm}$** (Coulomb singularity),
while fixed-order corrections dominant for high-momentum region

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


Harz, Herrmann, Klasen, Kovařík, Meinecke — Phys. Rev. D 91: 034012 (2015) — arXiv:1410.8063 [hep-ph]
Harz, Herrmann, Klasen, Kovařík, Schmiemann — work *in progress*…

# Application to direct detection

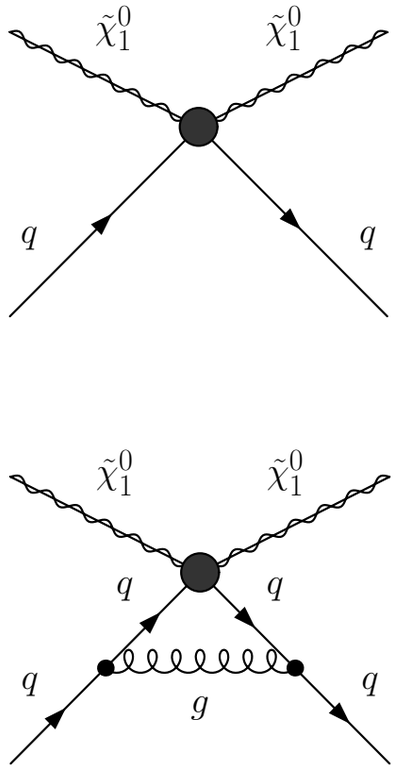
# Corrections to direct dark matter detection




**Full theory**
(LO + NLO)
valid at Q~1 TeV

**Matching**
at Q~1 TeV

**Effective theory**
(LO + NLO)
valid at Q~5 GeV




**Renormalization** (same scheme as before) in order to treat ultraviolet divergencies

Infrared divergencies cancel between the different contributions

Dedicated **integral reduction procedure applicable to zero-velocity limit**

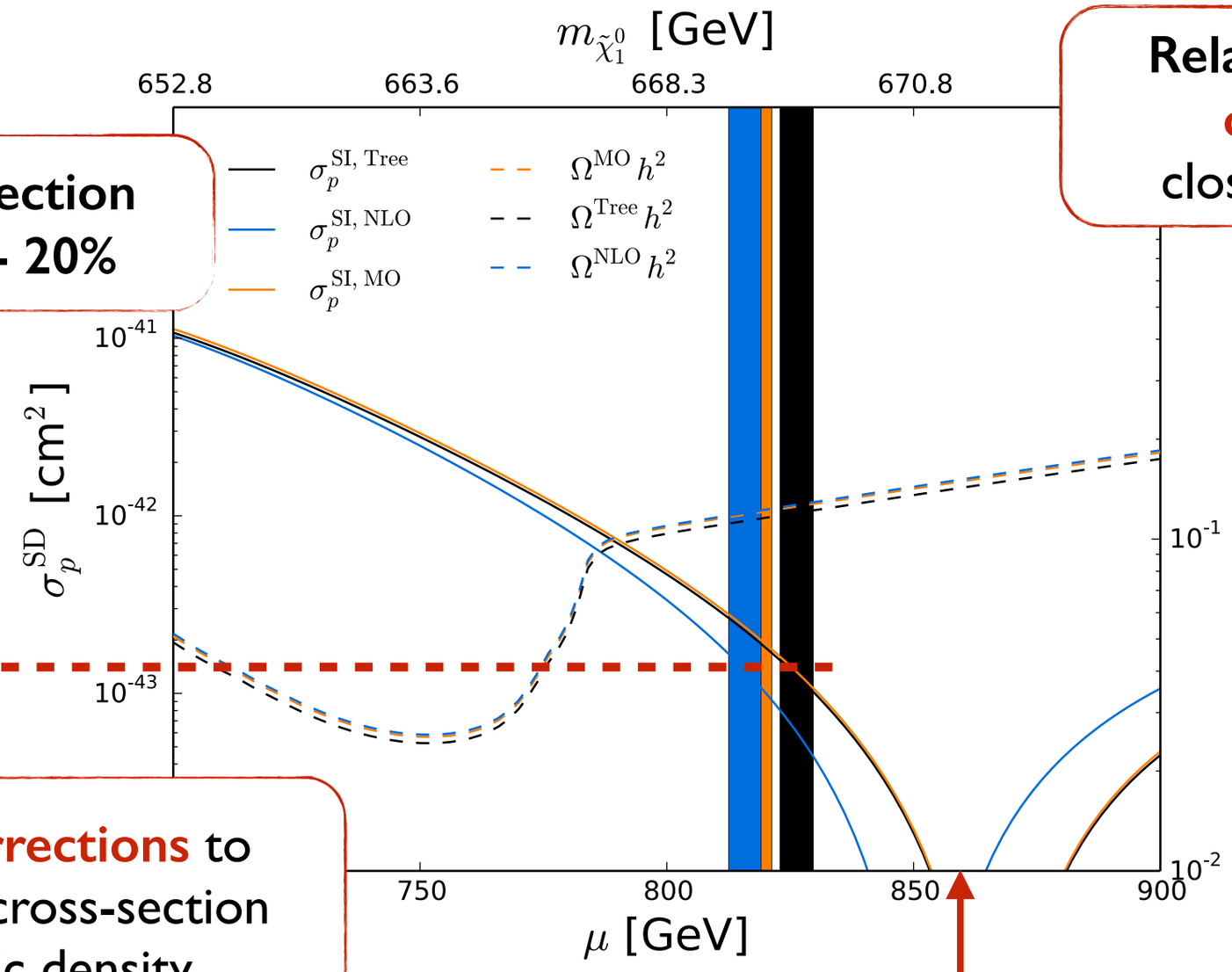
**Renormalization group running** of effective theory from Q~1 TeV to Q~5 GeV

Klasen, Kovařík, Steppeler — arXiv:1607.06396 [hep-ph]

# Corrections to direct dark matter detection

**Relative correction of about 10 - 20%**

**Relative correction of up to 50%** close to the "drop"




**Effect of corrections** to DM-nucleon cross-section and to relic density **may compensate each other**

Destructive interference "higgsino-bino switch"

Klasen, Kovařík, Steppeler — arXiv:1607.06396 [hep-ph]

# Scale dependence and theoretical uncertainty

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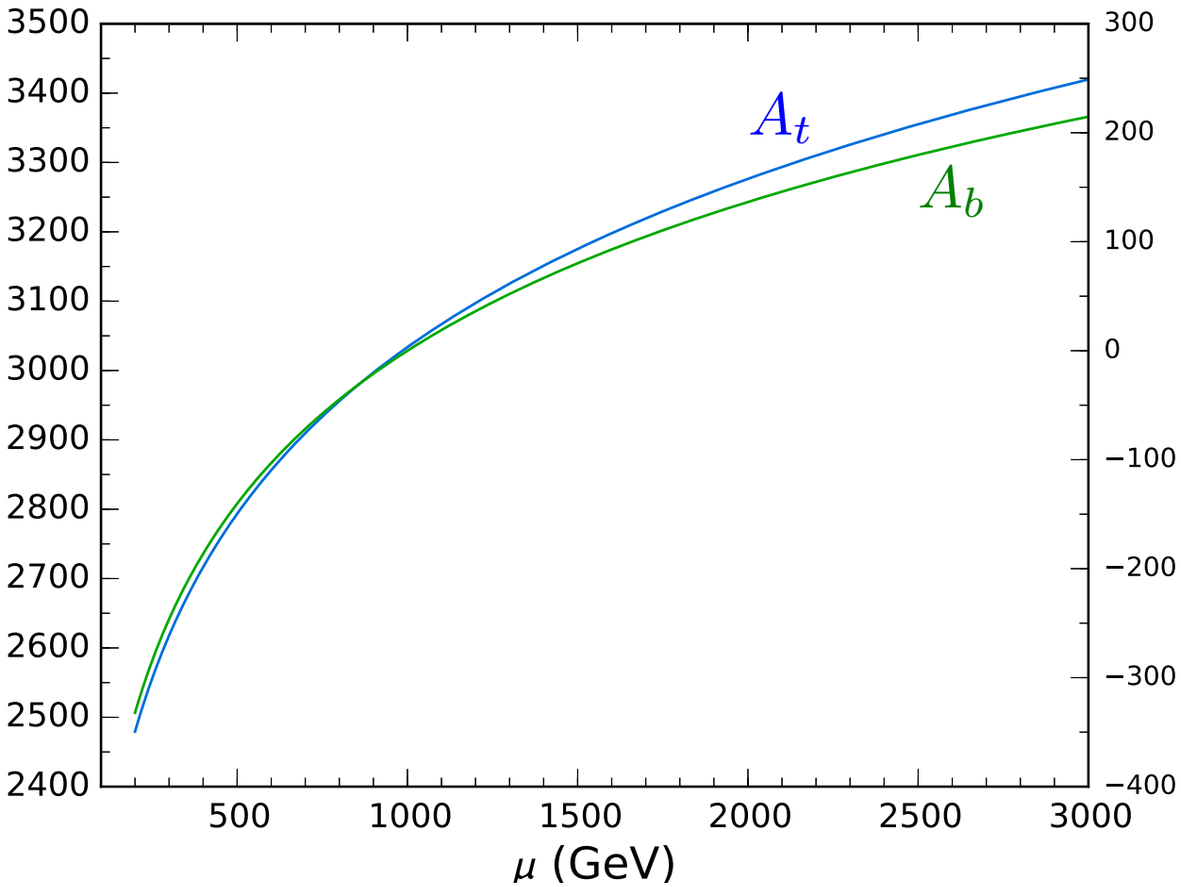
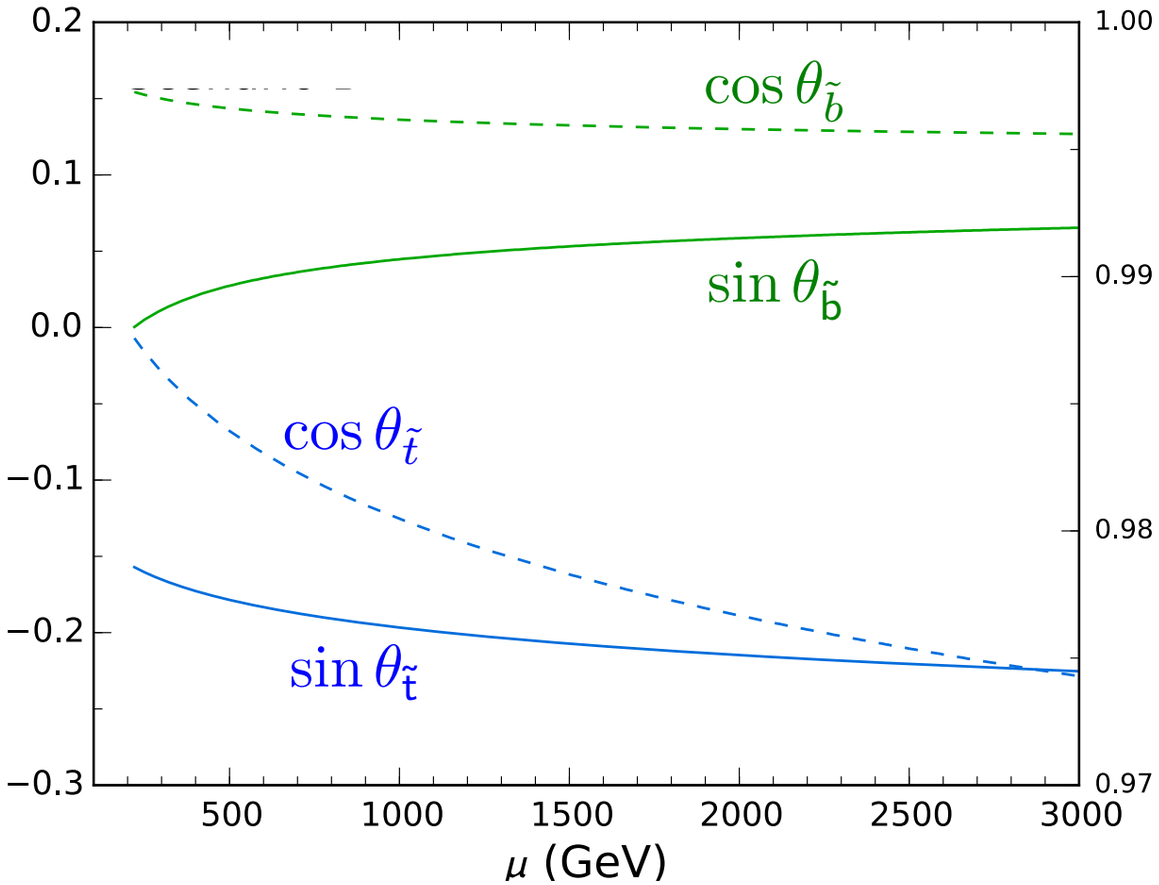
Evaluation of theoretical uncertainty by **varying** (unphysical) **renormalization scale**
— hybrid on-shell / DRbar renormalization scheme designed for neutralino (co-)annihilation

$\mu_R = 500 \ldots 2000$ GeV → $A_t,\ A_b,\ \theta_{\tilde{t}},\ \theta_{\tilde{t}},\ \alpha_s,\ m_b$

scale-dependent parameters

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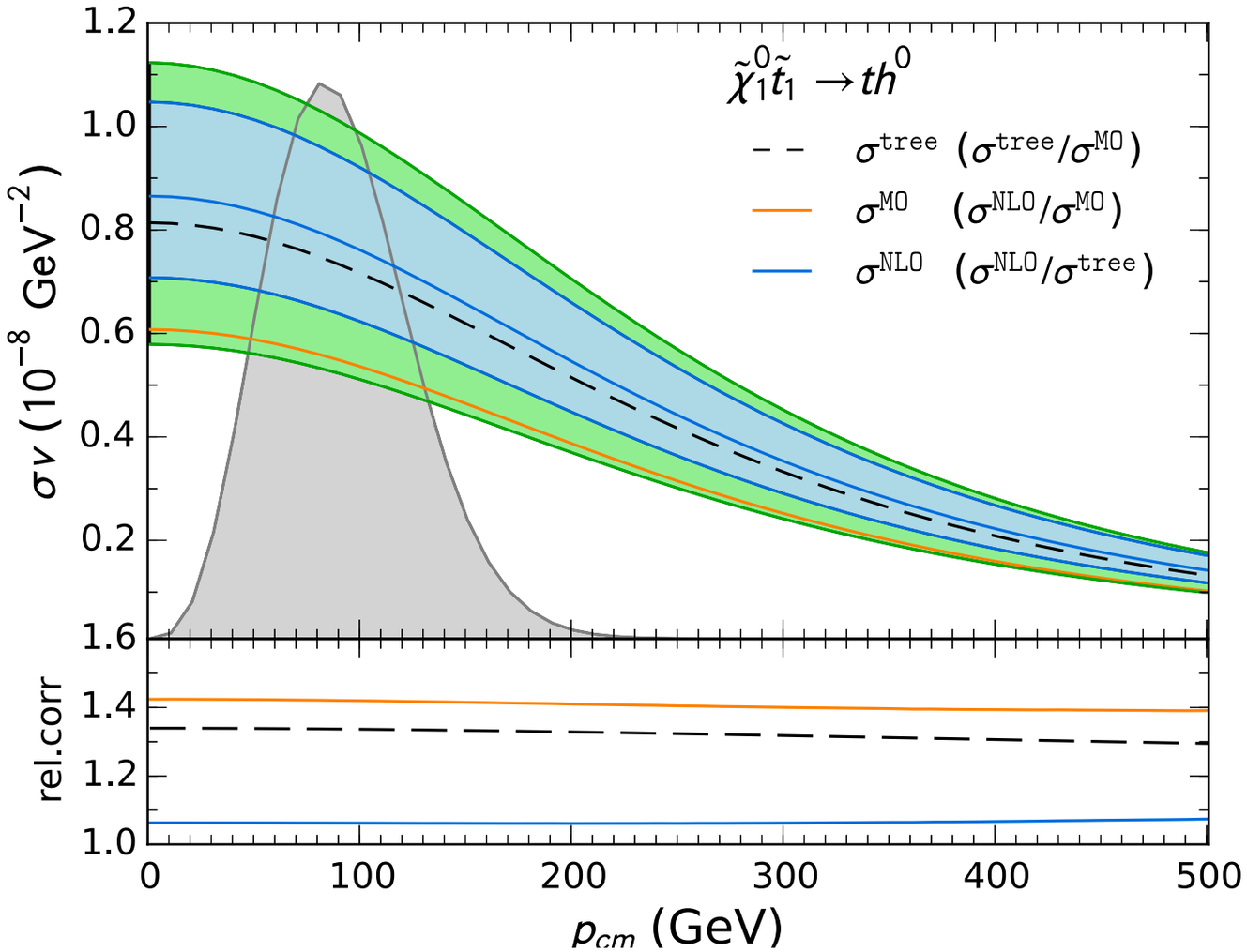
scale-dependent parameters

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 $\alpha_s$ subdominant

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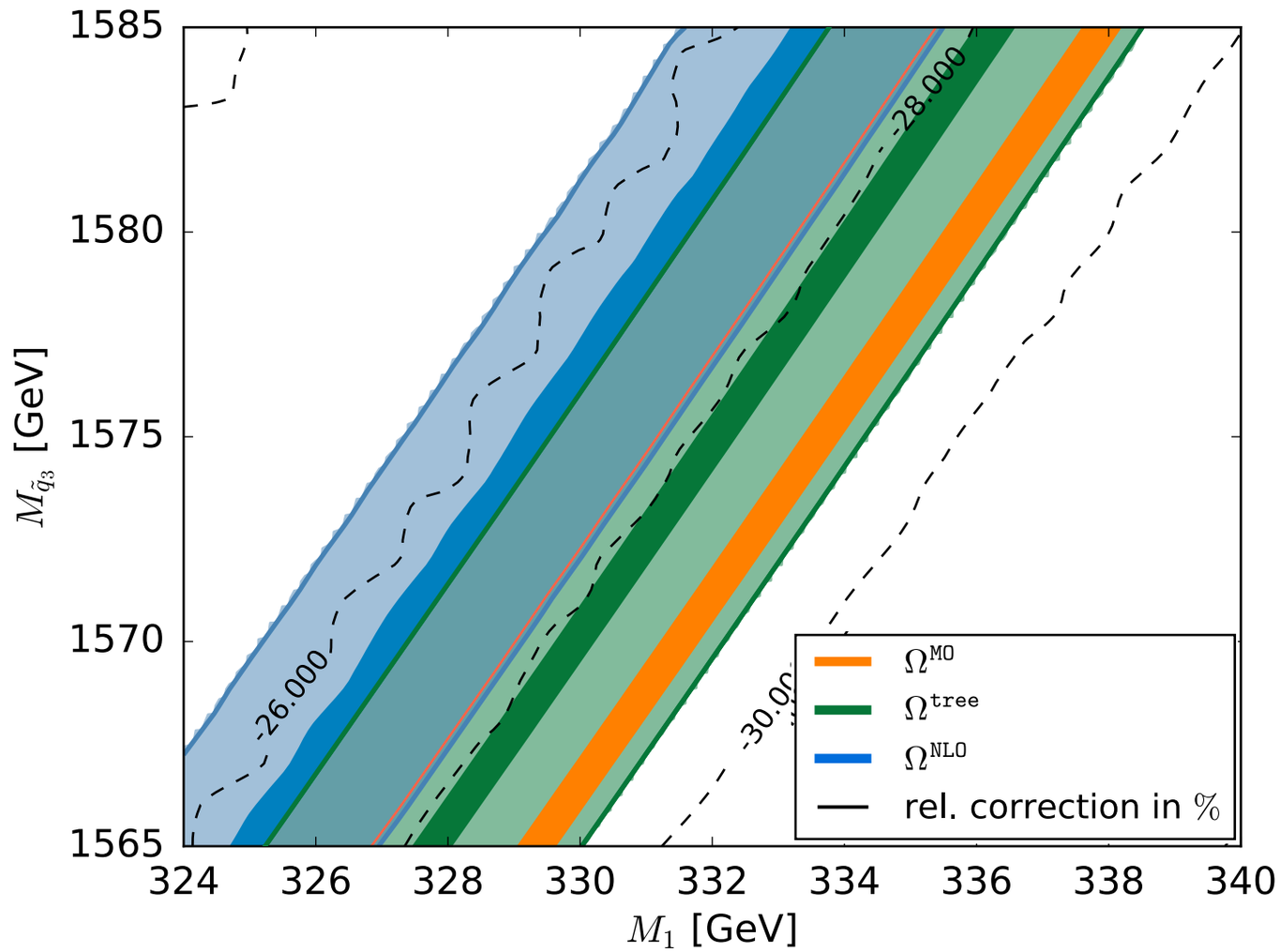


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# Conclusion

# Summary

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

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

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

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

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

numerically implemented
results published

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

$$\tilde{q}\tilde{q}^* \to q\bar{q}'/gg$$

$$\tilde{q}\tilde{q} \to qq$$

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

**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%** similarly to the experimental result

http://dmnlo.hepforge.org