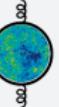


WWU
MÜNSTER



Graduiertenkolleg 2149
Research Training Group

DM@NLO

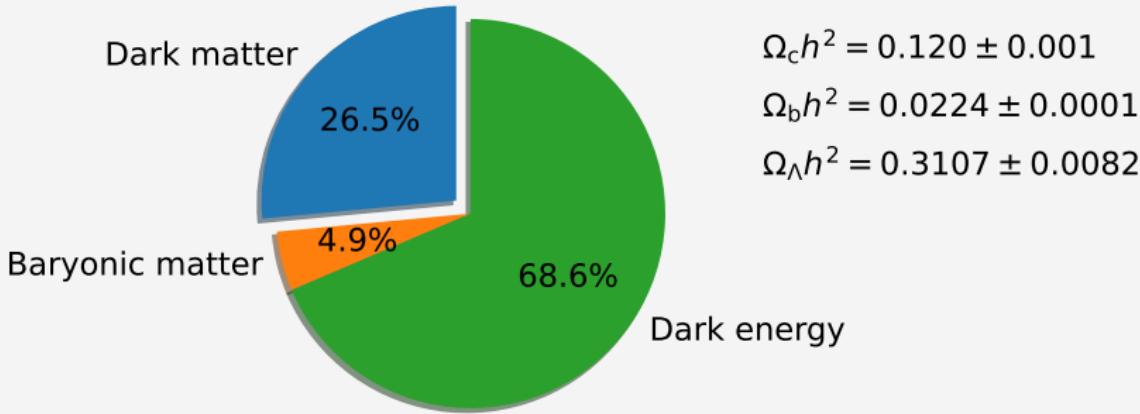


SUSY-QCD corrections to squark annihilation into gluons and light quarks

L. Wiggering for the DM@NLO collaboration

Intro - Dark matter and the MSSM

- Energy distribution of the universe:



Aghanim, N. et al. arXiv: 1807.06209 [astro-ph.CO] (2021)

- The R -symmetric MSSM provides a suitable DM candidate: the lightest neutralino $\tilde{\chi}_1^0$

Intro - Theoretical prediction of the DM relic density

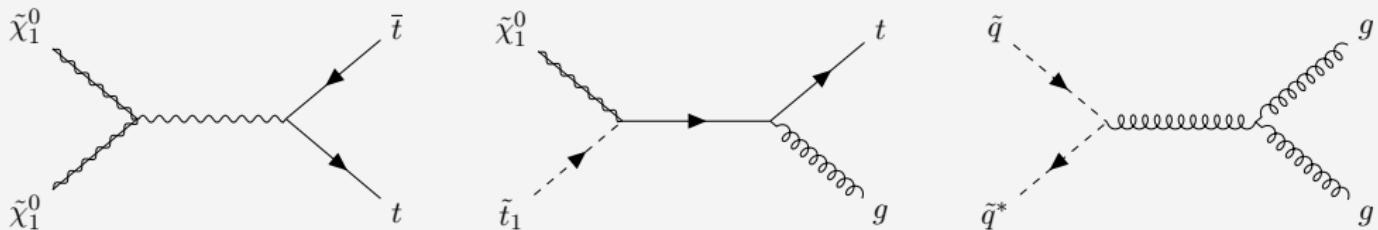
- Under the assumption of kinetic equilibrium the evolution of the neutralino number density is described by the Boltzmann eq.

$$\dot{n}_\chi = -3Hn_\chi - \langle \sigma_{\text{eff}} v \rangle (n_\chi^2 - (n_\chi^{\text{eq}})^2) \rightarrow \Omega_c = \frac{m_\chi n_\chi}{\rho_c}$$

- Thermally averaged effective cross section

$$\langle \sigma_{\text{eff}} v \rangle = \sum_{i,j=1}^N \langle \sigma_{ij} v_{ij} \rangle \frac{n_i^{\text{eq}}}{n_\chi^{\text{eq}}} \frac{n_j^{\text{eq}}}{n_\chi^{\text{eq}}} \text{ with } \frac{n_i^{\text{eq}}}{n_\chi^{\text{eq}}} \sim \exp\left(-\frac{m_i - m_\chi}{T}\right)$$

- The effective cross section contains all possible SM final states, e.g.



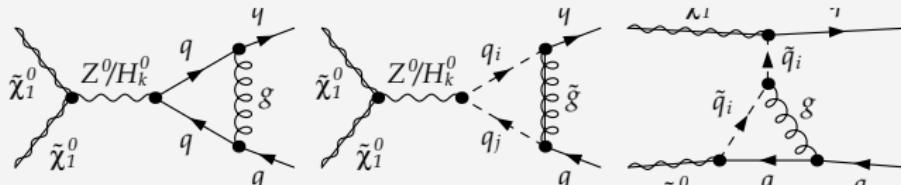
Motivation for higher-order corrections

► Public tools such as

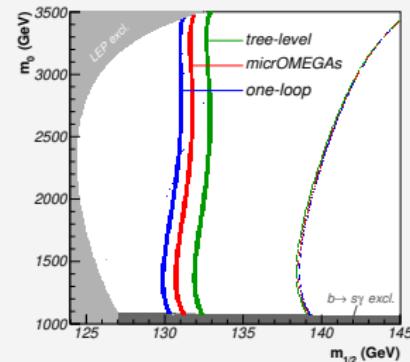
- MicrOMEGAs Belanger, G. et al. arXiv: hep-ph/0112278 (2002)
- DarkSUSY Gondolo, P. et al. arXiv: astro-ph/0406204 (2004)
- MadDM Backovic, M. et al. arXiv: 1308.4955 [hep-ph] (2014)

perform the calculation of the relic density only at an (effective) tree level

► Inclusion of SUSY-QCD corrections shifts the preferred parameter region beyond the experimental uncertainty Herrmann, B. et al. arXiv: 0901.0481 [hep-ph] (2009)



Precision of the DM relic density measurement at the %-level by Planck requires the inclusion of radiative corrections to match the theoretical and the experimental precision.



The goal of the DM@NLO project is to provide a consistent set of next-to-leading order corrections in SUSY-QCD (+resummation) for important (co-)annihilation processes within the MSSM.

Corrected cross sections are available for the following processes:

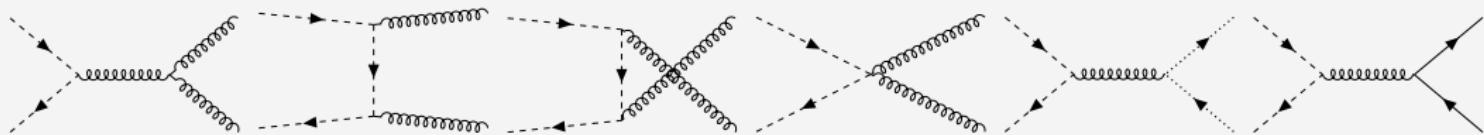
- ▶ $\tilde{\chi}\tilde{\chi}' \rightarrow qq'$ Herrmann, B. & Klasen, M. [arXiv: 0709.0043 \[hep-ph\]](#) (2007)
Herrmann, B. et al. [arXiv: 0901.0481 \[hep-ph\]](#) (2009), Herrmann, B. et al. [arXiv: 0907.0030 \[hep-ph\]](#) (2009)
Herrmann, B. et al. [arXiv: 1404.2931 \[hep-ph\]](#) (2014)
- ▶ $\tilde{\chi}\tilde{q} \rightarrow qV/qH$ Harz, J. et al. [arXiv: 1212.5241 \[hep-ph\]](#) (2013), Harz, J. et al. [arXiv: 1409.2898 \[hep-ph\]](#) (2015)
- ▶ $\tilde{q}\tilde{q}^* \rightarrow VV/HH/VH$ Harz, J. et al. [arXiv: 1410.8063 \[hep-ph\]](#) (2015)
- ▶ $\tilde{q}\tilde{q}' \rightarrow qq'$ Schmiemann, S. et al. [arXiv: 1903.10998 \[hep-ph\]](#) (2019)
- ▶ $\tilde{\tau}\tilde{\tau}^* \rightarrow q\bar{q}$ Branahl, J. et al. [arXiv: 1909.09527 \[hep-ph\]](#) (2019)
- ▶ $\tilde{t}_1\tilde{t}_1^* \rightarrow gg, q\bar{q}$ to be published in a few weeks
- ▶ $\tilde{g}\tilde{g} \rightarrow gg, q\bar{q}$ work in progress

Ultimate goal: use of DM@NLO within GAMBIT studies, make code public ...

Stop-antistop annihilation into gluons and light quarks @ NLO

- Relevant processes: $\tilde{t}_1 \tilde{t}_1^* \rightarrow gg$ and $\tilde{t}_1 \tilde{t}_1^* \rightarrow q\bar{q}$ with $q \in \{u, d, c, s\}$ being an effectively massless quark

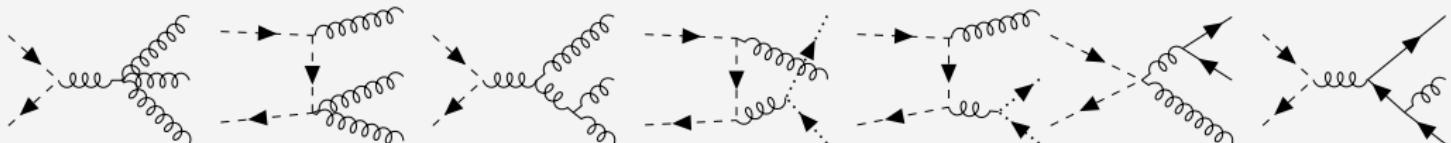
Tree level:



Virtual one-loop corrections (a few examples)



Real corrections (a few examples)



Some technical details

- ▶ Regularization of UV/IR divergences in the SUSY preserving four-dimensional helicity scheme (variant of dimensional regularization) Signer, A. & Stöckinger, D. [arXiv: 0807.4424 \[hep-ph\] \(2009\)](#)
- ▶ Renormalization of the MSSM through a hybrid on-shell/ \overline{DR} scheme
 - ▶ Input parameters: $A_t^{\overline{DR}}$, $A_b^{\overline{DR}}$, $m_{\tilde{t}_1}^{\text{OS}}$, $m_{\tilde{b}_1}^{\text{OS}}$, $m_{\tilde{b}_2}^{\text{OS}}$, m_t^{OS} , $m_b^{\overline{DR}}$
 - ▶ Output parameters: $\theta_{\tilde{t}_1}$, $\theta_{\tilde{t}_2}$, $m_{\tilde{t}_2}$
- ▶ Gluons and ghosts are both renormalized in the on-shell scheme
- ▶ $\alpha_s^{\text{MSSM}, \overline{DR}}(\mu_R)$ and $m_b^{\text{MSSM}, \overline{DR}}(\mu_R)$ are determined using the 4-loop QCD β -function and 2-loop threshold corrections to include the full MSSM particle spectrum ≠ treatment in CalcHEP Vermaseren, J. A. M. et al. [arXiv: hep-ph/9703284 \(1997\)](#)
- ▶ Infrared treatment with the help of the Catani-Seymour dipole subtraction method for massive initial states [to be published in a few weeks](#)

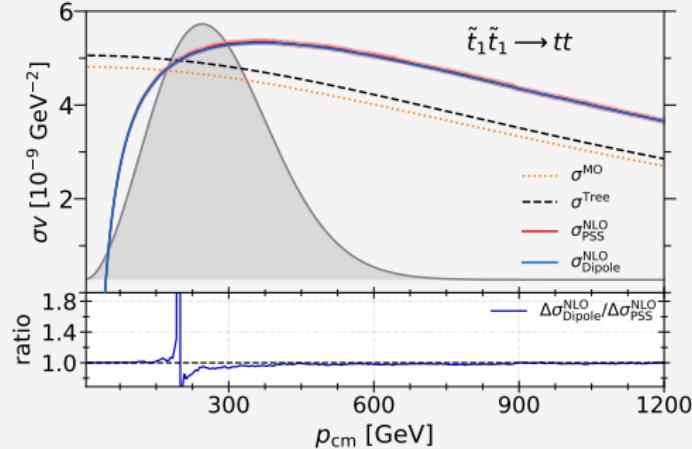
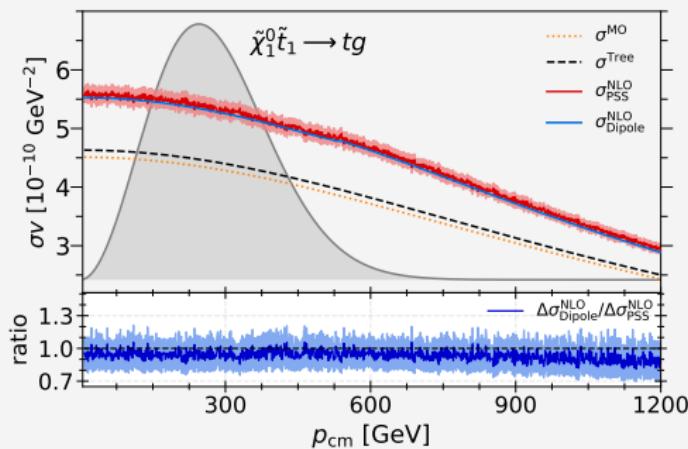
$$\Delta\sigma^{\text{NLO}} = \int_3 \left[d\sigma_{\varepsilon=0}^R - d\sigma_{\varepsilon=0}^A \right] + \int_2 \left[d\sigma^V + \int_1 d\sigma^A \right]_{\varepsilon=0}$$

Dipole subtraction for massive initial states

- Phase space slicing Harris, B. W. & Owens, J. F. arXiv: [hep-ph/0102128](https://arxiv.org/abs/hep-ph/0102128) (2002)

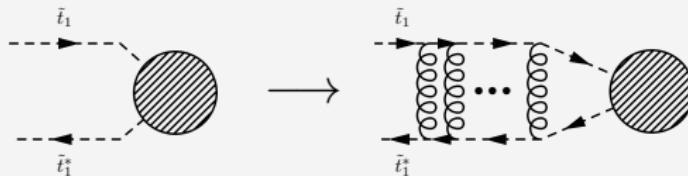
$$\sigma^R = \sigma_{\text{coll}}^{\text{hard}}(\delta_s, \delta_c) + \sigma_{\text{non-coll}}^{\text{hard}}(\delta_s, \delta_c) + \sigma^{\text{soft}}(\delta_s)$$

- Advantages of the dipole subtraction method: no cutoff dependence, no separation of squared diagrams into collinear, soft and soft-collinear divergent contributions, easy to automatize (e.g. MadDipole Frederix, R. et al. arXiv: [0808.2128 \[hep-ph\]](https://arxiv.org/abs/0808.2128) (2008)), ...



Sommerfeld enhancement

- ▶ For small relative velocities v between the incoming stop-antistop pair the annihilation cross section grows as $(\alpha_s/v)^n$ for the exchange of n potential gluons
Sommerfeld, A. *Annalen Phys.* **403**, 257–330 (1931)
→ all order resummation within the framework of NRQCD



- ▶ Resummation requires distinction between attractive and repulsive color potentials
Kiyo, Y. et al. arXiv: 0812.0919 [hep-ph] (2009)

$$\tilde{V}^{[R]}(\vec{q}) = -C^{[R]} \frac{4\pi\alpha_s(\mu_C)}{\vec{q}^2} \left\{ 1 + \frac{\alpha_s(\mu_C)}{4\pi} \left[\beta_0 \ln \left(\frac{\mu_C^2}{\vec{q}^2} \right) + a_1 \right] \right\}$$

- ▶ Sommerfeld factor S_0 is a solution of the Schrödinger eq.

$$[H^{[\mathbf{R}]} - (\sqrt{s} + i\Gamma_{\tilde{t}_1})] \mathcal{G}^{[\mathbf{R}]}(\vec{r}; \sqrt{s} + i\Gamma_{\tilde{t}_1}) = \delta^{(3)}(\vec{r}) \rightarrow S_{0,[\mathbf{R}]} = \frac{\text{Im} \mathcal{G}^{\mathbf{R}}(\vec{r} = 0, \sqrt{s} + i\Gamma_{\tilde{t}_1})}{\text{Im} \mathcal{G}_0(\vec{r} = 0, \sqrt{s} + i\Gamma_{\tilde{t}_1})}$$

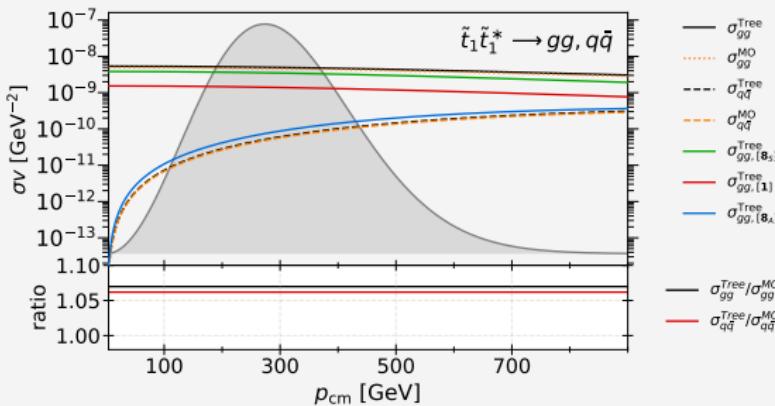
Color decomposition and resummation

► Decomposition of initial and final state colors:

- Initial: $\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$
- Final: $\mathbf{8} \otimes \mathbf{8} = \mathbf{1} \oplus \mathbf{8}_S \oplus \mathbf{8}_A \oplus \overline{\mathbf{10}} \oplus \mathbf{10} \oplus \mathbf{27}$

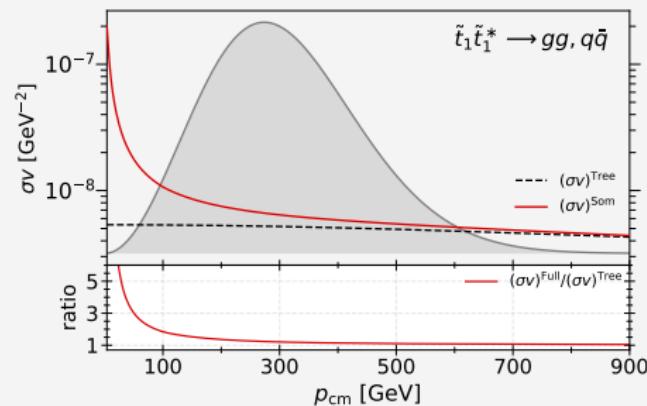
► Sommerfeld enhanced cross section:

$$(\sigma v)^{\text{Som}} = S_{0,[8]} \left((\sigma v)_{gg,[8_S]}^{\text{Tree}} + (\sigma v)_{gg,[8_A]}^{\text{Tree}} + N_f (\sigma v)_{q\bar{q},[8]}^{\text{Tree}} \right) + S_{0,[1]} (\sigma v)_{gg,[1]}^{\text{Tree}}$$



► Quadratic Casimirs:

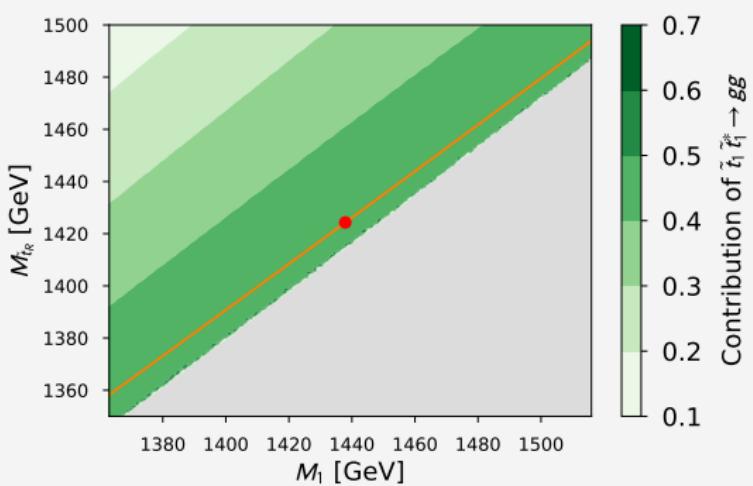
- Singlet: $C^{[1]} = C_F$ (attractive)
- Octet: $C^{[8]} = -\frac{1}{2N_c}$ (repulsive)



Relevant scenario

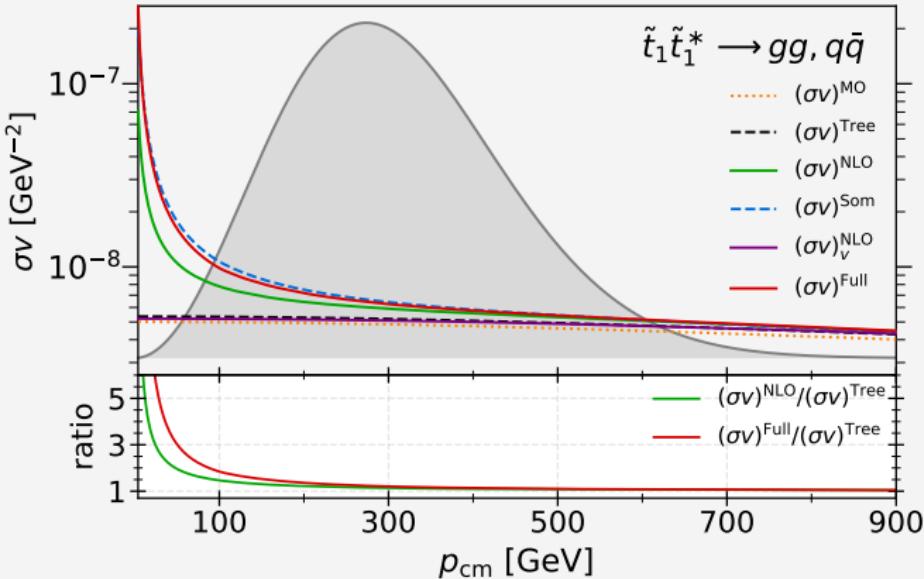
► Viable pMSSM-19 scenario:

M_1	M_2	M_3	$M_{\tilde{l}_L}$	$M_{\tilde{\tau}_L}$	$M_{\tilde{l}_R}$	$M_{\tilde{\tau}_R}$	$M_{\tilde{q}_L}$	$M_{\tilde{q}_{3L}}$	$M_{\tilde{u}_R}$
1437.9	2739.6	3079.5	4034.1	3620.2	4075.12	2605.9	1773.2	2172.7	1816.1
$M_{\tilde{t}_R}$	$M_{\tilde{d}_R}$	$M_{\tilde{b}_R}$	A_t	A_b	A_τ	μ	m_{A^0}	$\tan \beta$	Q_{SUSY}
1424.3	1926.8	2913.0	2965.3	3050.7	2880.3	-1880.8	3742.2	34.9	1756.4
$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{g}}$	$m_{\tilde{\tau}_1}$	m_{h^0}	m_{H^0}	Z_{11}
1435.7	1884.4	1882.9	1446.3	2248.0	3059.3	2613.5	124.0	3742.9	0.9976
									$\Omega_{\tilde{\chi}_1^0} h^2$
									0.1201



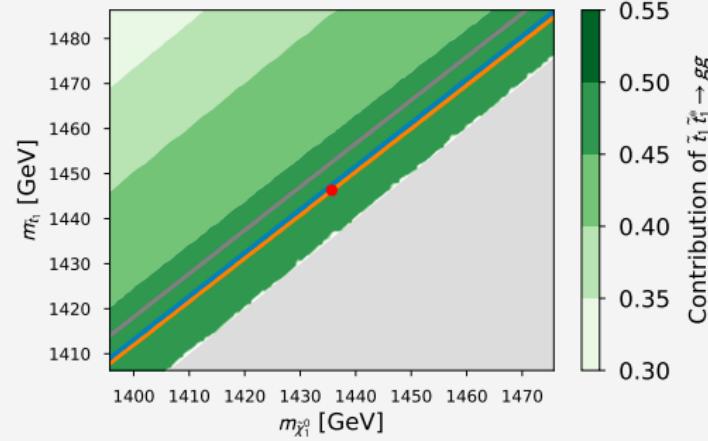
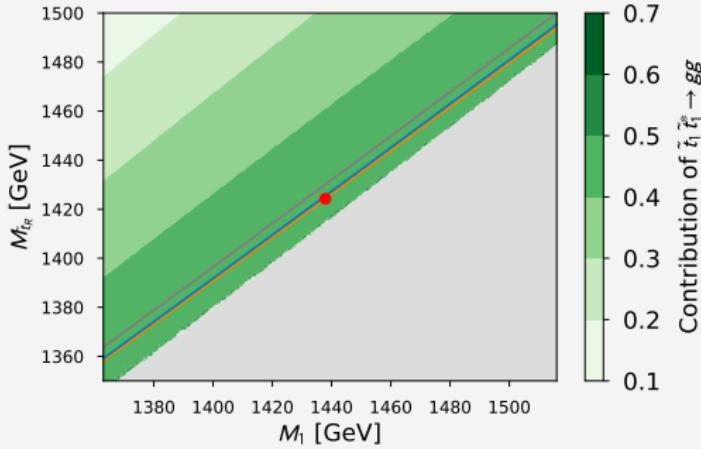
Channel	Contribution
$\tilde{t}_1 \tilde{t}_1^* \rightarrow gg$	47 %
$\tilde{t}_1 \tilde{t}_1 \rightarrow t t$	23 %
$\tilde{\chi}_1^0 \tilde{t}_1 \rightarrow g t$	7 %
$\tilde{t}_1 \tilde{t}_1^* \rightarrow \gamma g$	7 %
$\tilde{t}_1 \tilde{t}_1^* \rightarrow t \bar{t}$	5 %
$\tilde{t}_1 \tilde{t}_1^* \rightarrow Z^0 g$	2 %
DM@NLO total	77 %

Impact on the annihilation cross section



- ▶ “Pure” NLO correction is lower than $\pm 3\%$ of the tree-level cross section
- ▶ $(\sigma v)^{\text{Full}}$ is in very good approximation given by the Sommerfeld enhancement only

Impact on the relic density



- ▶ Stop masses consistent with the measured relic density are increased by 6.1 GeV through the inclusion of the radiative corrections

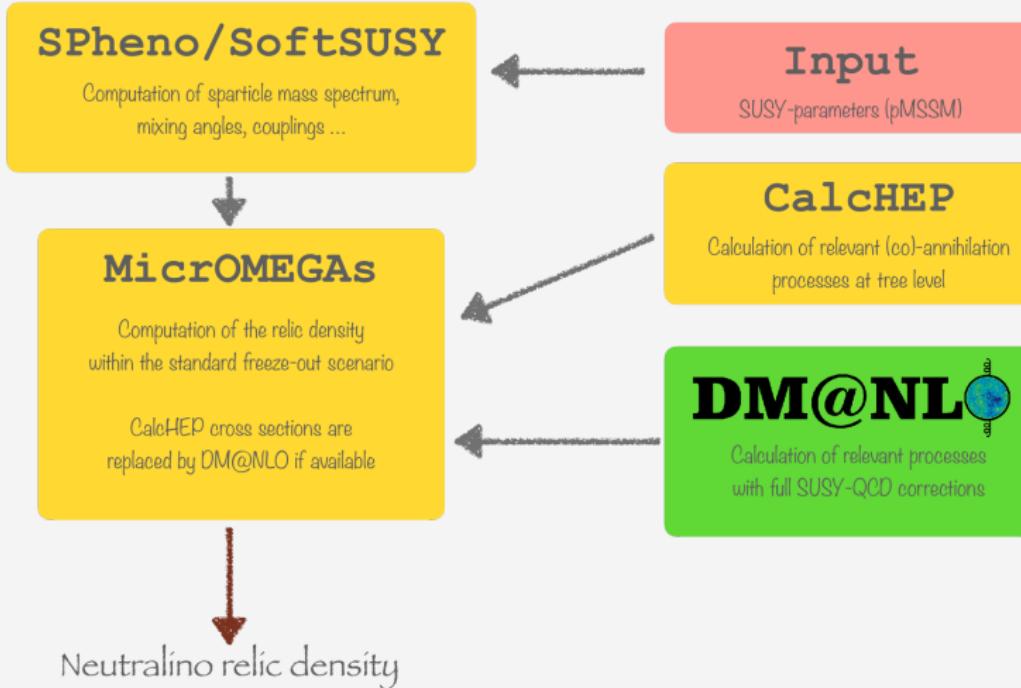
Conclusion

- ▶ $\tilde{t}_1 \tilde{t}_1^* \rightarrow gg$ is an important process for scenarios with nearly mass degenerate stops and neutralinos
- ▶ $(\sigma v)^{\text{Full}} \approx (\sigma v)^{\text{Som}}$ for $\tilde{t}_1 \tilde{t}_1^* \rightarrow gg$ and $\tilde{t}_1 \tilde{t}_1^* \rightarrow q\bar{q}$
→ confident that this result extends to simplified dark matter models containing colored scalars
- ▶ Dipole subtraction method is now available for dark matter calculations with colored massive initial states
- ▶ SUSY-QCD corrections are important
 - ▶ Shift the cosmologically preferred parameter region beyond the current experimental uncertainty
 - ▶ Give a realistic estimate on the theoretical uncertainty



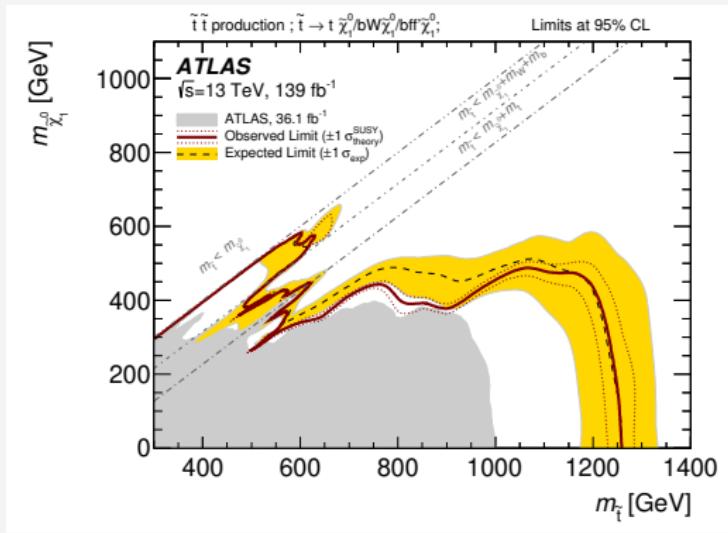
Thank you!

Backup - DM@NLO Setup

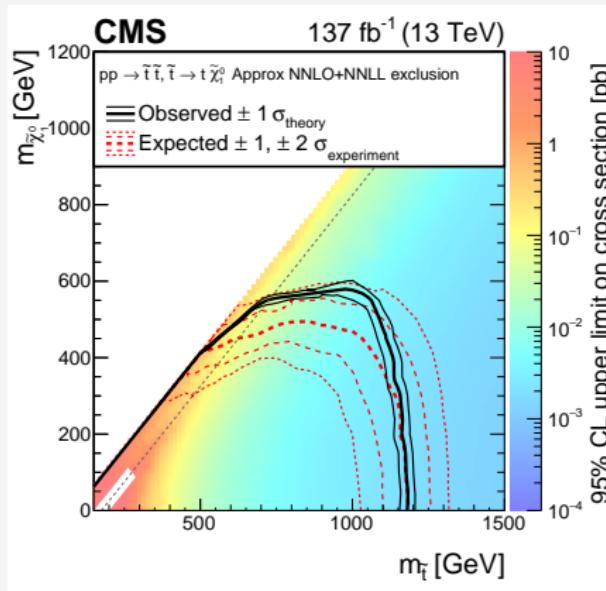


Backup - Motivation for a light stop/co-annihilation

- ▶ Large mass splitting in the stop sector is consistent with the observation of a 125 GeV Higgs boson [Arbey, A. et al. arXiv: 1211.4004 \[hep-ph\] \(2013\)](#)
- ▶ Light stops allow for heavier neutralino masses by avoiding a too early freeze-out
- ▶ Compressed spectra (difficult to exclude)

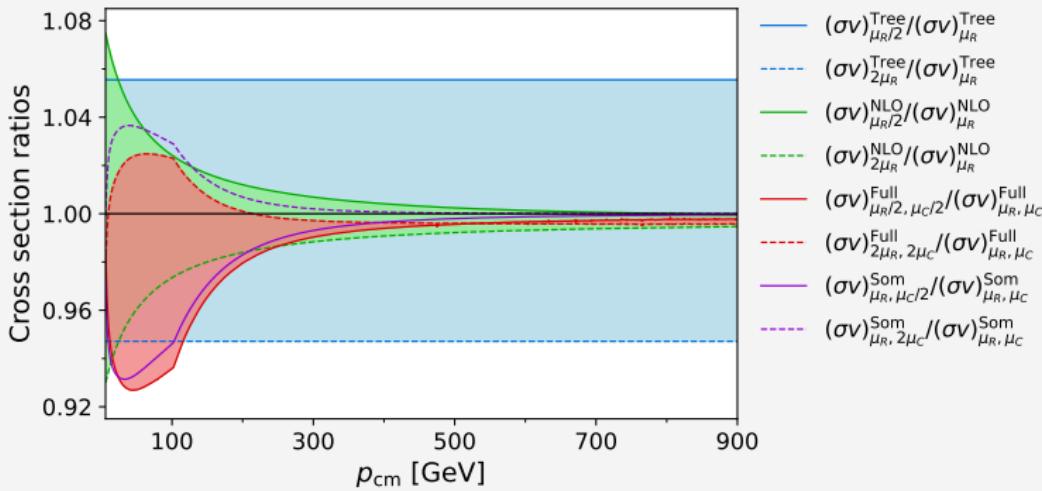


Aad, G. et al. [arXiv: 2004.14060 \[hep-ex\] \(2020\)](#)



Sirunyan, A. M. et al. [arXiv: 1908.04722 \[hep-ex\] \(2019\)](#)

Backup - Theoretical uncertainty from scale variations



- ▶ Reduction of scale uncertainties from $\pm 5.5\%$ to below $\pm 2\%$ in the perturbative regime