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Graduiertenkolleg 2149
Research Training Group

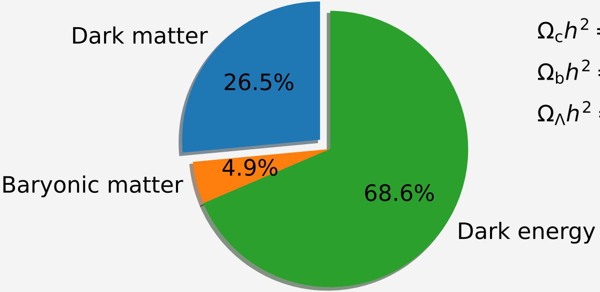
DM@NLO

Radiative corrections to stop-antistop annihilation

Based on:
Wiggering, L. P. et al. Phys. Rev. D **106,** 115032. arXiv: `2210.05260 [hep-ph]` (2022)
in collaboration with Michael Klasen and Karol Kovařík

Intro - Dark Matter

- Energy distribution of the universe:



$$\Omega_c h^2 = 0.120 \pm 0.001$$

$$\Omega_b h^2 = 0.0224 \pm 0.0001$$

$$\Omega_\Lambda h^2 = 0.3107 \pm 0.0082$$

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

- Does the theoretical precision match the experimental one?

Intro - the MSSM

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

Superfield	Particle	Spin	Superpartner	Spin
$\hat{V}_1$	B_μ	1	$\tilde{B}$	$\frac{1}{2}$
$\hat{V}_2$	W^i_μ	1	$\tilde{W}^i$	$\frac{1}{2}$
$\hat{V}_3$	G^a_μ	1	$\tilde{g}^a$	$\frac{1}{2}$
$\hat{Q}$	$Q = (u_L, d_L)$	$\frac{1}{2}$	$\tilde{Q} = (\tilde{u}_L, \tilde{d}_L)$	0
$\hat{U}^c$	$U^c = \bar{u}_R$	$\frac{1}{2}$	$\tilde{U}^c = \tilde{u}^*_R$	0
$\hat{D}^c$	$D^c = \bar{d}_R$	$\frac{1}{2}$	$\tilde{D}^c = \tilde{d}^*_R$	0
$\hat{L}$	$L = (\nu_L, e_L)$	$\frac{1}{2}$	$\tilde{L} = (\tilde{\nu}_L, \tilde{e}_L)$	0
$\hat{E}^c$	$E^c = \bar{e}_R$	$\frac{1}{2}$	$\tilde{E}^c = \tilde{e}^*_R$	0
$\hat{H}_1$	$H_1 = (H^0_1, H^-_1)$	0	$\tilde{H}_1 = (\tilde{H}^0_1, \tilde{H}^-_1)$	$\frac{1}{2}$
$\hat{H}_2$	$H_2 = (H^+_2, H^0_2)$	0	$\tilde{H}_2 = (\tilde{H}^+_2, \tilde{H}^0_2)$	$\frac{1}{2}$

Intro - Theoretical prediction of the DM relic density

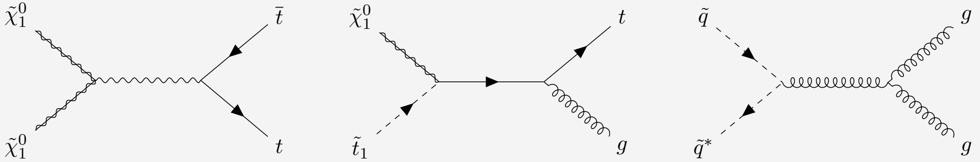
- Under the assumption of kinetic equilibrium the evolution of the neutralino number density is described by the Boltzmann eq.

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

- Thermally averaged effective cross section

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

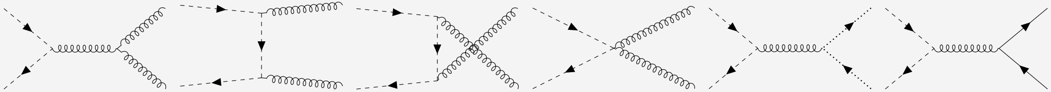
- The effective cross section contains all possible SM final states, e.g.



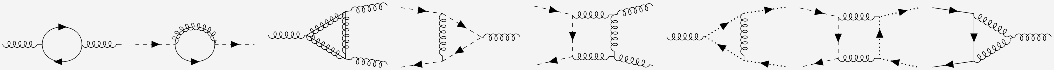
Stop-antistop annihilation into gluons and light quarks @ NLO

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

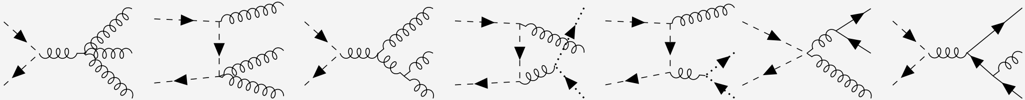
Tree level:



Virtual one-loop corrections (a few examples)



Real corrections (a few examples)

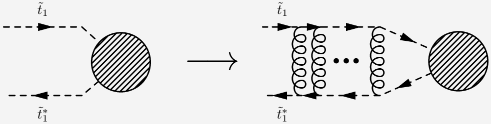


Sommerfeld enhancement

- 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)

  $\longrightarrow$ 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.

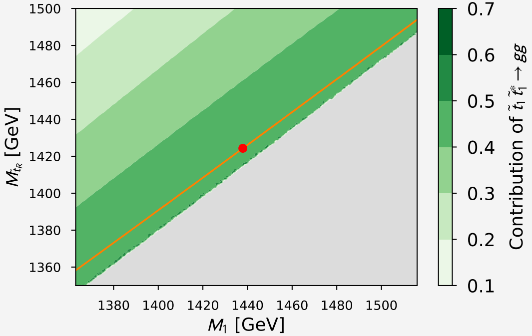
$$\left[H^{[\mathbf{R}]}-(\sqrt{s}+i\Gamma_{\tilde{t}_1})\right]\mathcal{G}^{[\mathbf{R}]}(\vec{r};\sqrt{s}+i\Gamma_{\tilde{t}_1}) = \delta^{(3)}(\vec{r}) \longrightarrow S_{0,[\mathbf{R}]} = \frac{\operatorname{Im}\mathcal{G}^{\mathbf{R}}(\vec{r}=0,\sqrt{s}+i\Gamma_{\tilde{t}_1})}{\operatorname{Im}\mathcal{G}_0(\vec{r}=0,\sqrt{s}+i\Gamma_{\tilde{t}_1})}$$

Relevant scenario

- Viable pMSSM-19 scenario:

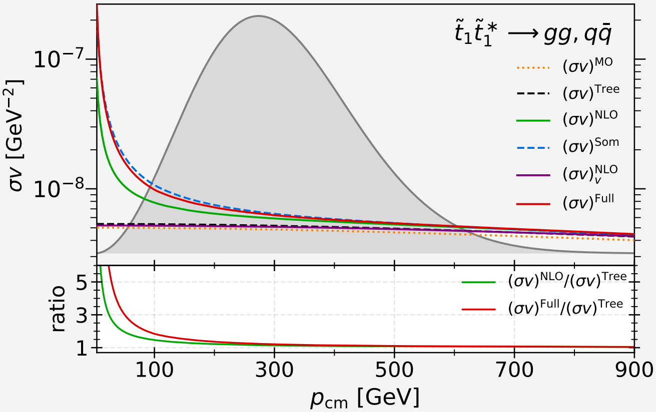
M_1	M_2	M_3	$M_{\tilde{l}_L}$	$M_{\tilde{\tau}_L}$	$M_{\tilde{l}_R}$	$M_{\tilde{\tau}_R}$	$M_{\tilde{q}_L}$	$M_{\tilde{q}_{3L}}$	$M_{\tilde{u}_R}$
1437.9	2739.6	3079.5	4034.1	3620.2	4075.12	2605.9	1773.2	2172.7	1816.1
$M_{\tilde{t}_R}$	$M_{\tilde{d}_R}$	$M_{\tilde{b}_R}$	A_t	A_b	A_τ	μ	m_{A^0}	$\tan\beta$	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}	$\Omega_{\tilde{\chi}_1^0} h^2$
1435.7	1884.4	1882.9	1446.3	2248.0	3059.3	2613.5	124.0	3742.9	0.9976	0.1201



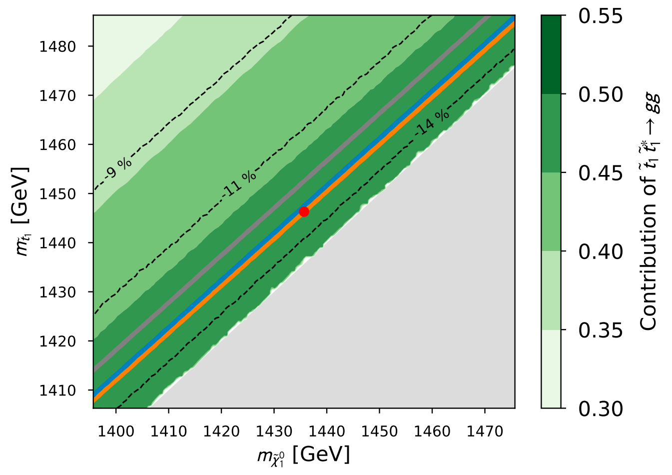
Channel	Contribution
$\tilde{t}_1\,\tilde{t}_1^* \to g\,g$	$47\,\%$
$\tilde{t}_1\,\tilde{t}_1 \to t\,t$	$23\,\%$
$\tilde{\chi}_1^0\,\tilde{t}_1 \to g\,t$	$7\,\%$
$\tilde{t}_1\,\tilde{t}_1^* \to \gamma\,g$	$7\,\%$
$\tilde{t}_1\,\tilde{t}_1^* \to t\,\bar{t}$	$5\,\%$
$\tilde{t}_1\,\tilde{t}_1^* \to Z^0\,g$	$2\,\%$
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

DM@NLO

Computer package that provides a consistent set of NLO corrections in SUSY-QCD (+resummation) for the following processes (so far):

- $\tilde\chi\tilde\chi' \to qq'$ Herrmann, B. et al. 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)
- $\tilde\chi\tilde q \to qV/qH$ Harz, J. et al. arXiv: `1212.5241 [hep-ph]` (2013), Harz, J. et al. arXiv: `1409.2898 [hep-ph]` (2015)
- $\tilde q\tilde q^* \to VV/HH/VH$ Harz, J. et al. arXiv: `1410.8063 [hep-ph]` (2015)
- $\tilde q\tilde q' \to qq'$ Schmiemann, S. et al. arXiv: `1903.10998 [hep-ph]` (2019)
- $N + \tilde\chi \to N + \tilde\chi$ Klasen, M. et al. arXiv: `1607.06396 [hep-ph]` (2016)
- $\tilde\tau\tilde\tau^* \to q\bar q$ Branahl, J. et al. arXiv: `1909.09527 [hep-ph]` (2019)
- $\underline{\tilde t_1\tilde t_1^* \to gg, q\bar q}$ Wiggering, L. P. et al. arXiv: `2210.05260 [hep-ph]` (2022)

Public release is now under construction: `https://dmnlo.hepforge.org/`

Main messages

- experimental uncertainty ‹ theoretical uncertainty for the standard relic density calculation (e.g. `MicrOMEGAs`)
  $\longrightarrow$ %-level theoretical error is too strict

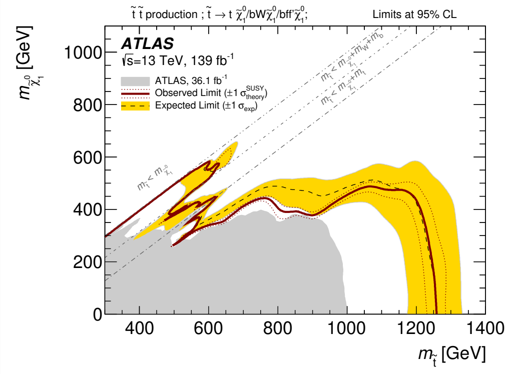
- $\tilde{t}_1\tilde{t}_1^* \to gg$ is an important process for scenarios with nearly mass degenerate stops and neutralinos

- $(\sigma v)^{\text{Full}} \approx (\sigma v)^{\text{Som}}$ for $\tilde{t}_1\tilde{t}_1^* \to gg$ and $\tilde{t}_1\tilde{t}_1^* \to q\bar{q}$
  $\longrightarrow$ confident that this result extends to simplified dark matter models containing colored scalars

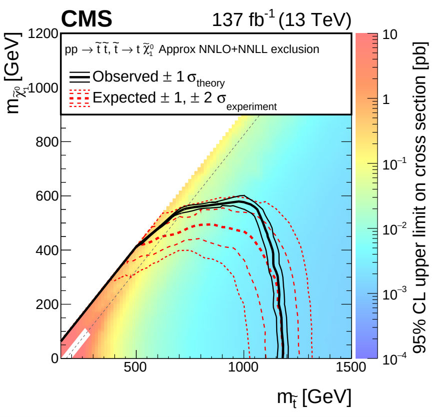
Thank you!

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)

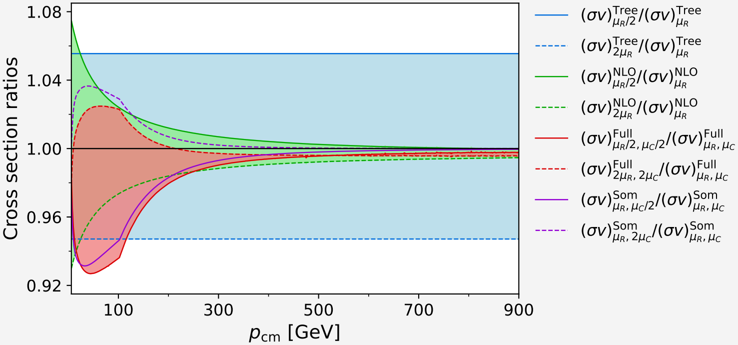


Aad, G. et al. arXiv: `2004.14060 [hep-ex]` (2020)



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