Neutralino-Stop Coannihilation at One-Loop

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Neutralino-Stop Coannihilation at One-Loop

- Motivations for one-loop QCD calculation
- Virtual corrections: renormalization scheme
- Real corrections: phase space slicing
- Impact of corrections on the relic density
- Conclusion

Motivations for a one-loop QCD calculation

Introduction: relic density

- Relic density of Dark Matter is a very constraining observable for New Physics models:

$$\Omega_{\mathrm{CDM}} h^2 = 0.1126 \pm 0.0036$$

- Precision of future experimental values (Planck) will require a high precision calculation.

- Its calculation requires the computation of thermally averaged (co)annihilation cross-section of the Dark Matter particle:

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

- Significant coannihilation contribution when masses of coannihilating particles are close to each other.

Neutralino-Stop coanihilation

- Neutralino-Stop coannihilation is one of the processes which can reduce relic density down to the experimental value.
- Implies that Neutralino and Stop are nearly degenerated.
    - Need large mixing: possibly compatible with Higgs mass.
    - Light Stop: interesting for collider signatures.
- Very thin region in parameter space: will be shifed by corrections.
- QCD corrections expected to be significant. A. Freitas [Phys. Let. B 652 (2007)]

Neutralino-Stop coanihilation

- Differences with Freitas calculation:
  - Not only bottom-W and top-gluon but all possible final states (top-Z, top-photon, top-Higgs, bottom-Higgs).
  - Neutralino not a pure bino, stop 1 not a pure stop right.
  - Very general: any neutralino with any sfermion.
  - Code to be public and interfaced with MicrOmegas and DarkSUSY.

State of the art

- MicrOmegas already include some effective corrections.
- However the full one loop corrections are not included, and known to be important:
  - Electroweak corrections studied by «SLOOPS» collaboration.

    N. Baro, F. Boudjema, A. Semenov [Phys. Rev. D 78 (2008)]
    N. Baro, F. Boudjema [Phys. Rev. D 80 (2009)]
    N. Baro, F. Boudjema, G. Chalons, S. Hao [Phys. Rev. D 81 (2010)]

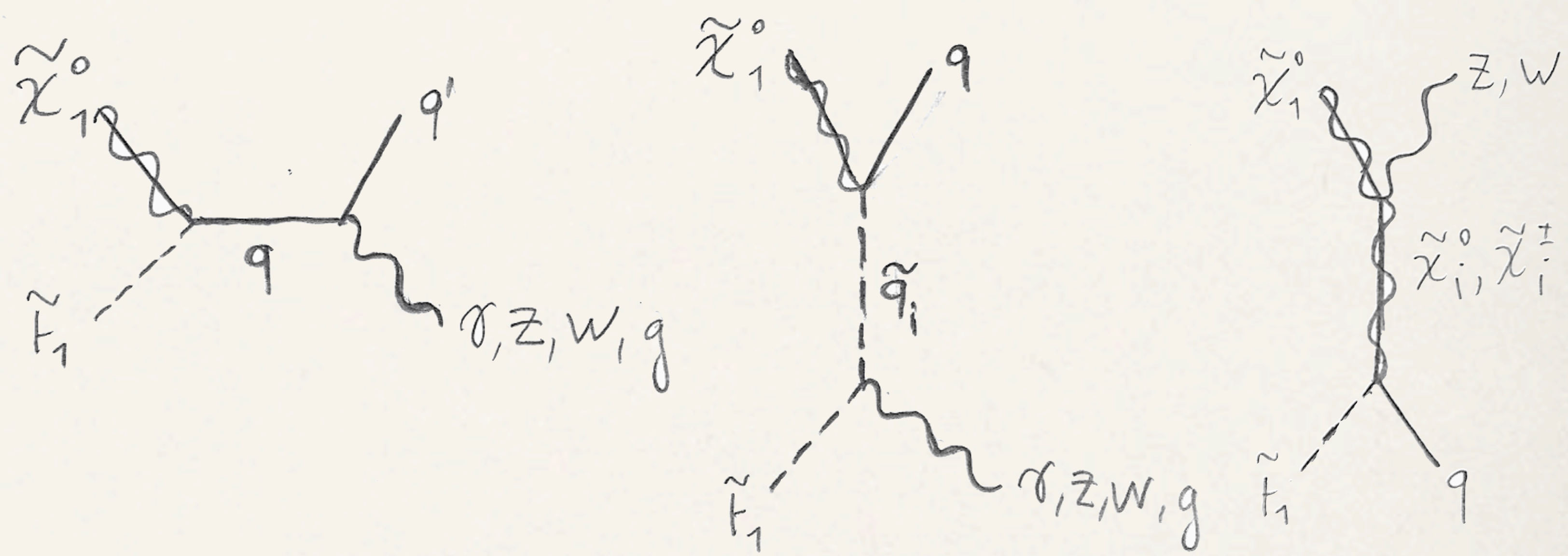
  - QCD corrections studied by «DM@NLO» collaboration for annihilation into quarks.

    B. Herrman, M. Klasen [Phys. Rev. D 76, (2007)]
    B. Herrman, M. Klasen, K. Kovařík [Phys. Rev. D 79, (2009)]
    B. Herrman, M. Klasen, K. Kovařík [Phys. Rev. D 80, (2009)]

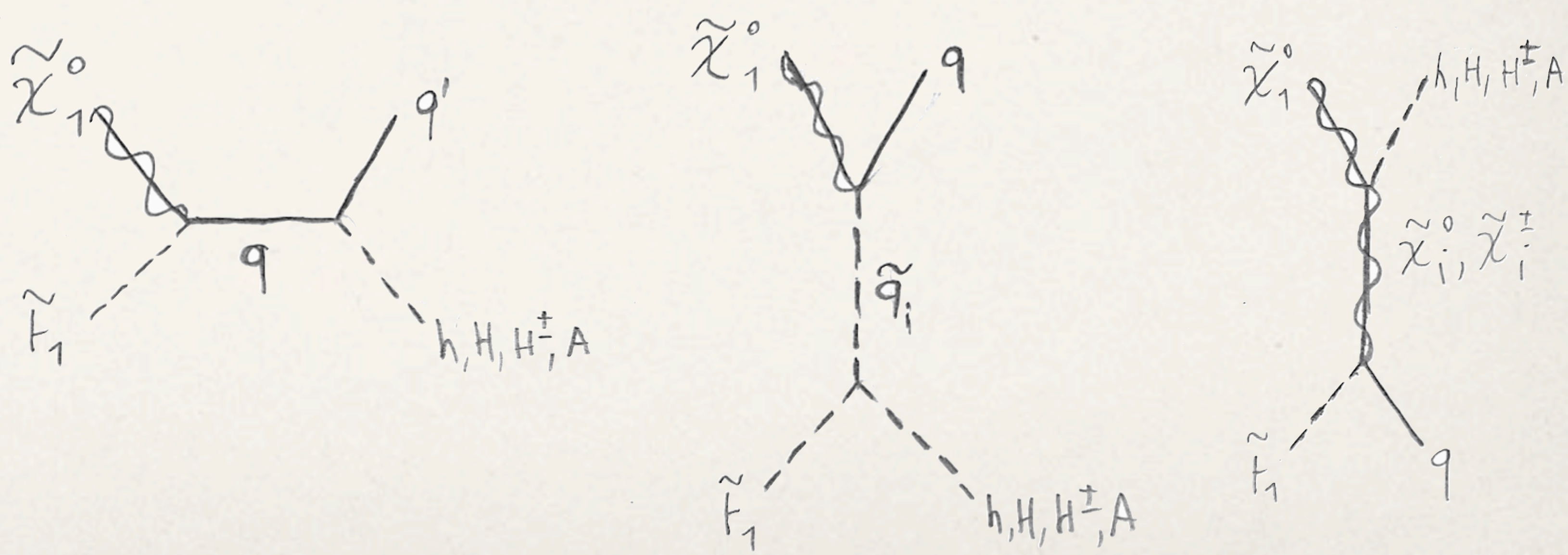
Virtual Corrections: Renormalization scheme

Neutralino-Stop coanihilation

- Tree-level diagrams (8 possible final states):
  - Vector final states

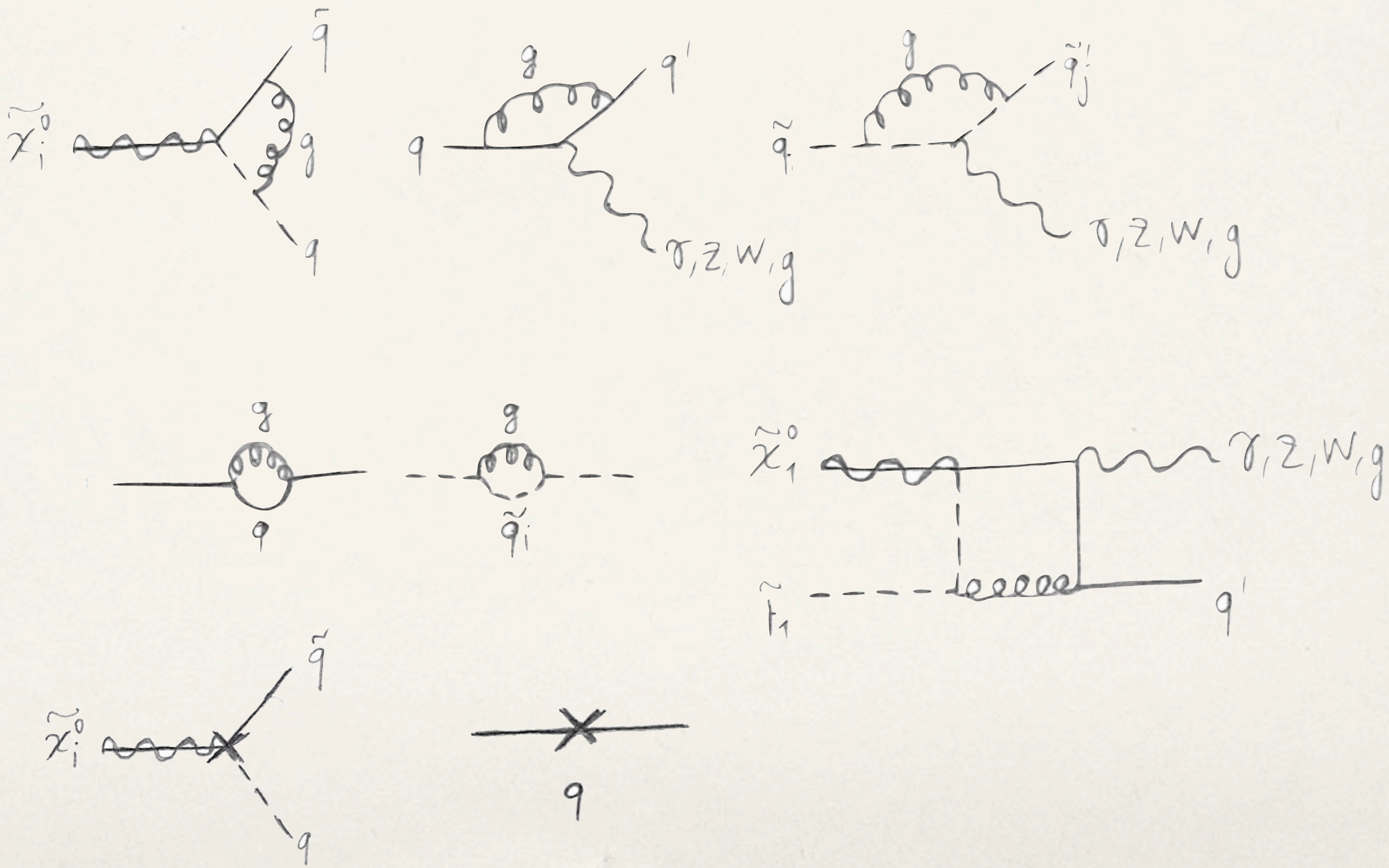


  - Higgs final states



Virtual corrections diagrams

- Some vertex corrections, self-energies and boxes diagrams:



Renormalization scheme

- Renormalization of MSSM (QCD) implies renormalization of the sfermions.
- As they mix together, the mixing angles have to be renormalized.
- Here mixing matrix is renormalized before rotation to physical (1,2) basis. Hence counter-terms for mixing angles appear.
- Due to SU(2) invariance stop and sbottom sector have to be renormalized together:

$$\mathcal{M}^2_{\tilde{q}} = \begin{pmatrix} \mathcal{M}^2_{\tilde{q},\mathrm{LL}} & \mathcal{M}^2_{\tilde{q},\mathrm{LR}} \\ \mathcal{M}^2_{\tilde{q},\mathrm{RL}} & \mathcal{M}^2_{\tilde{q},\mathrm{RR}} \end{pmatrix}$$ contains 5 parameters: $M^2_{\tilde{q}_L}, M^2_{\tilde{b}_R}, M^2_{\tilde{t}_R}, A_b, A_t$

But 6 in the physical basis: $m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}, m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}$

One is expressed in function of the others and will be shifted at one-loop: $m_{\tilde{t}_2}$

Renormalization scheme

- Mixed $\overline{\mathrm{DR}}$/OS scheme: m_b, A_b, A_t in $\overline{\mathrm{DR}}$
  $m_t, m_{\tilde{t}_1}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$ in $\overline{\mathrm{OS}}$
  $\theta_{\tilde{t}}, \theta_{\tilde{b}}, m_{\tilde{t}_2}$ dependant parameters

- When inversing the relation $(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}) \Leftrightarrow (M^2_{\tilde{q}_L}, M^2_{\tilde{b}_R})$, one obtains 2 solutions

$(M^2_{\tilde{q}_L} < M^2_{\tilde{b}_R}, M^2_{\tilde{q}_L} > M^2_{\tilde{b}_R})$ corresponding to different $m_{\tilde{t}_2}$ and $\theta_{\tilde{t}}$. One choose the most stable one, i.e.:

  - $\theta_{\tilde{t}}, \theta_{\tilde{b}}$ not too small
  - $\theta_{\tilde{t}}, \theta_{\tilde{b}}$ not too close to $\pi/4$

to avoid large mixing angle counterterm: $\delta\theta \sim \dfrac{1}{\cos^2\theta - \sin^2\theta} \times \dfrac{1}{\cos\theta.\sin\theta}$

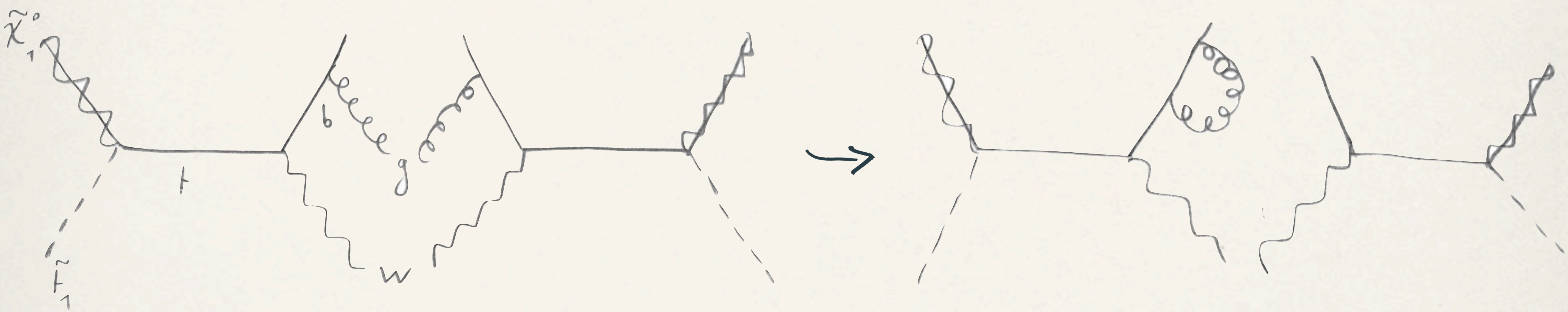
Renormalization scheme

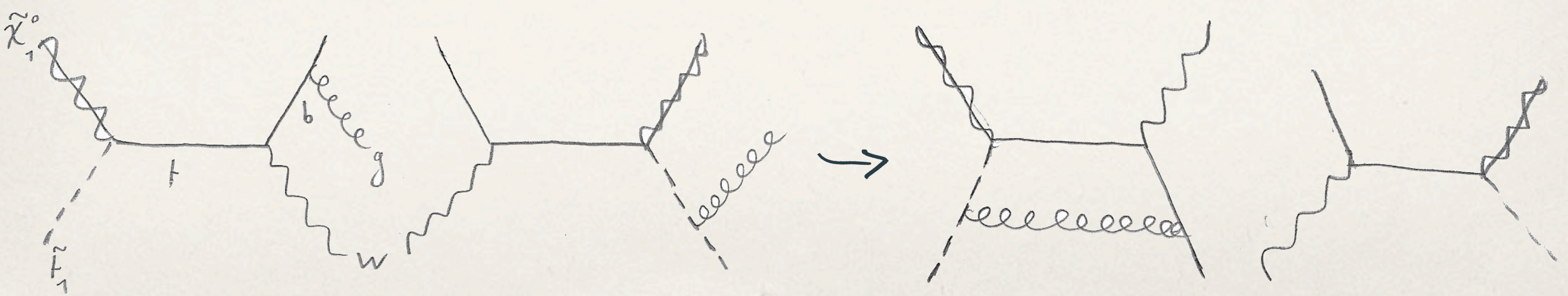
- Then use appropriate counterterms:
  - δm_b in $\overline{\mathrm{DR}}$, δm_t in OS
  - $\delta m_{\tilde{t}_1}, \delta m_{\tilde{b}_1}, \delta m_{\tilde{b}_2}$ in OS
  - $\delta m_{\tilde{t}_2}$ expressed in function of $\delta m_{\tilde{t}_1},\ \delta m_{\tilde{b}_1},\ \delta m_{\tilde{b}_2}$ (OS) and $\delta m_b,\ \delta A_b$ ($\overline{\mathrm{DR}}$)
  - etc.
- When all counterterms are calculated, we can cancel UV divergence of virtual corrections.

Real Corrections

Cancellation of IR divergencies

- Squarks and quarks can emit real gluons, which can be soft.
- The IR divergences cancel with opposite divergences in the virtual corrections:





The Phase Space Slicing method

- Divergences have completely different origins:
  - In the real emission, they come from the 3 body phase space integration.
  - In the virtual corrections, they come from the integration over the internal gluon momenta.
- To perform the cancellation the divergent term has to be analytically extracted .
- Use the Phase Space Slicing method which make use of the soft gluon approximation:
  - In the hard part of the phase space the cross-section is treated «as usual», i.e. numerically integrated over the 3 final states.

The Phase Space Slicing method

- In the soft part, thanks to the very low gluon energy the cross-section is factorized into tree-level cross-section and a universal factor:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{soft}} = F \times \left(\frac{d\sigma}{d\Omega}\right)_{\text{tree-level}}$$

- The universal factor contains integrals I_{ab} of the form:

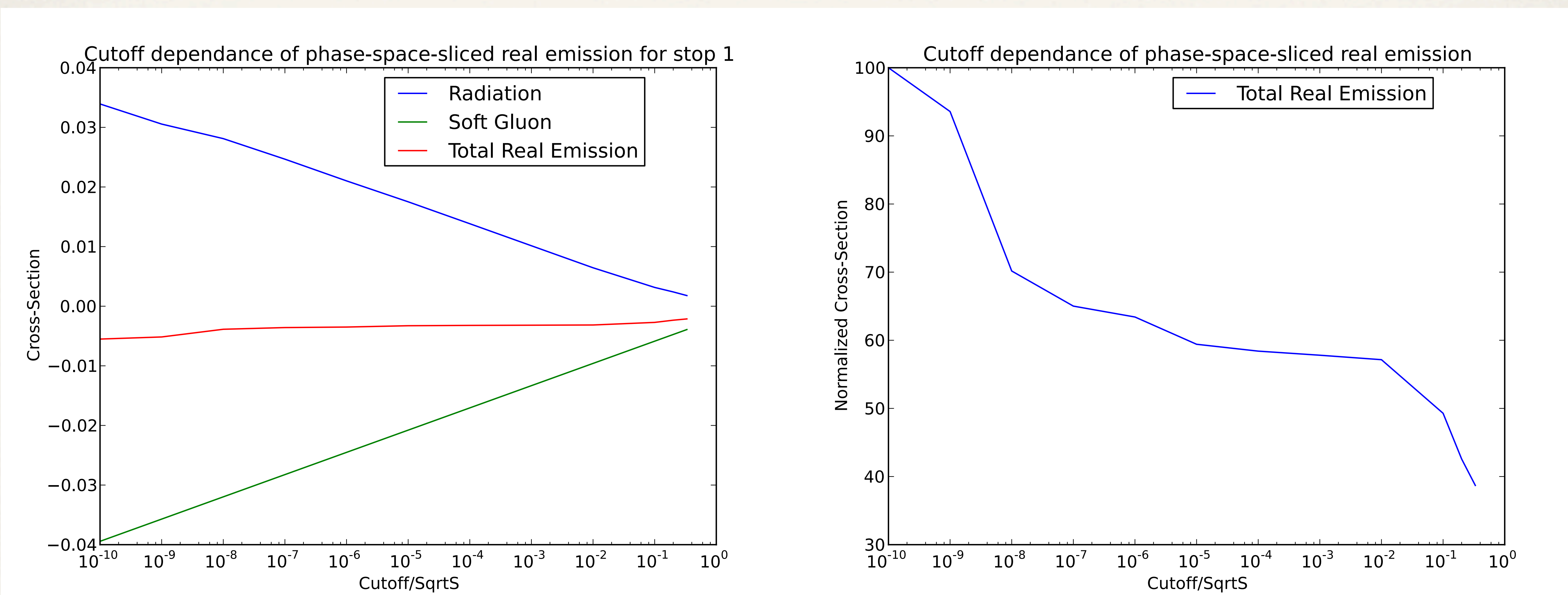
$$I_{ab} = (a.b) \int_{0 \leq |\overrightarrow{k}| \leq \Delta} \frac{d^3 k}{k^0} \frac{1}{(k.a)(k.b)}$$

which can be calculated analytically and contains explicit IR divergence.

- Δ is an unphysical cutoff which separate hard and soft part. Total result should not depend (too much) on this parameter.

Dependance on the cutoff

- Low cutoff: phase space integration is less accurate close to the divergence.
- High cutoff: soft gluon approximation is not valid anymore.
- Medium cutoff: sum of both contribution does not depend on the cutoff value.



Impact of corrections on the relic density

pMSSM Benchmark point

We choose a coannihilation test point in the pMSSM:

$\tan\beta = 39$
$m_A = 2259$
$\mu = 1263$
$M_1 = 495.5$
$M_2 = 1000$
$M_3 = 2965$
$M_{l,r} = 1000$
$M_{q1,2} = M_{u1,2} = M_{d1,2} = 1043$
$M_{q3} = 950$
$M_{d3} = 2403$
$M_{u3} = 1250$
$A_t = 2000$

$$m_{\chi_1^0} = 495 \text{ GeV}, \; m_{\tilde{t}_1} = 538 \text{ GeV}, m_{h^0} = 124 \text{ GeV}$$

Obtained with SPheno [W. Porod, arXiv:hep-ph/0301101]

$$\Omega_{\mathrm{CDM}} h^2 = 0.13797$$

$$\tilde{\chi}_1^0 \; \tilde{t}_1 \to t \; h^0 \; (22\%)$$

$$\tilde{t}_1 \; \bar{\tilde{t}}_1 \to g \; g \; (17\%)$$

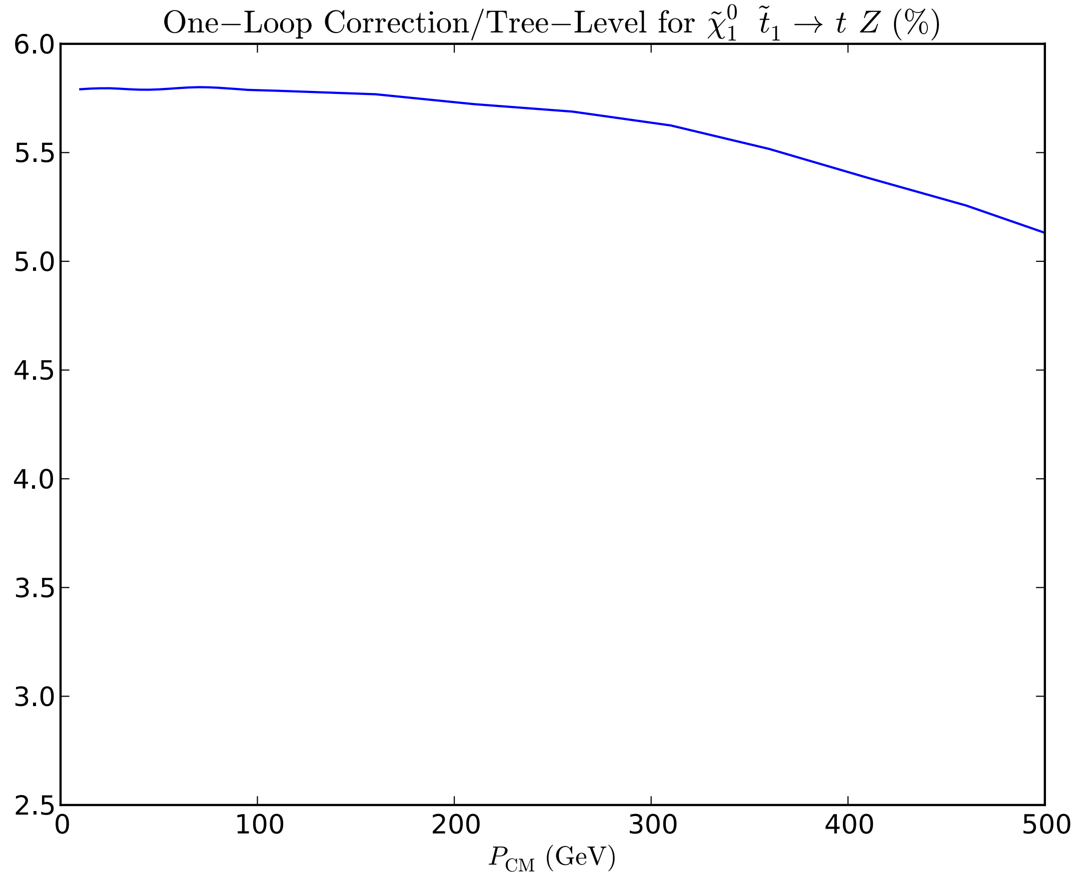
$$\tilde{\chi}_1^0 \; \tilde{t}_1 \to t \; Z \; (12\%)$$

$$\tilde{t}_1 \; \bar{\tilde{t}}_1 \to h^0 \; h^0 \; (11\%)$$

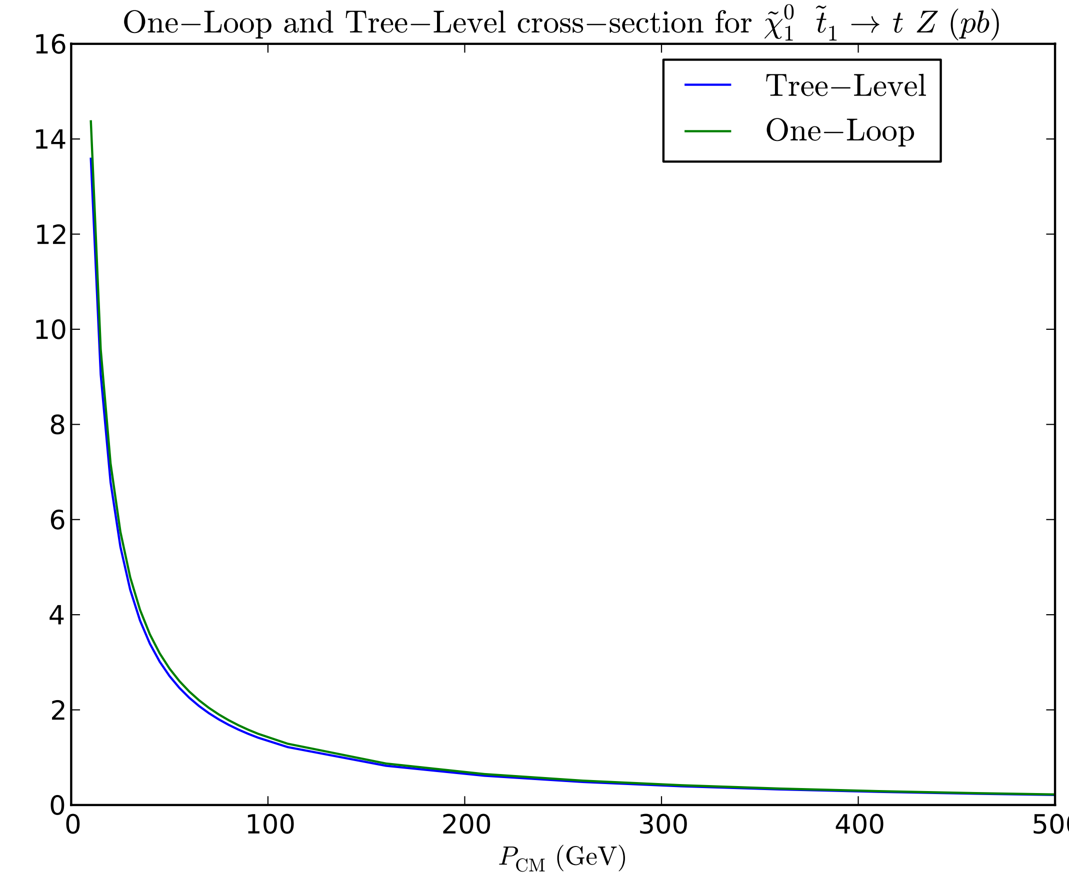
Obtained with MicrOmegas
[G. Belanger, F. Boudjema, A. Pukhov, A. Semenov, arXiv:hep-ph/1005.4133]

Total correction for Top-Z final state

Relative correction (%) un function of momenta



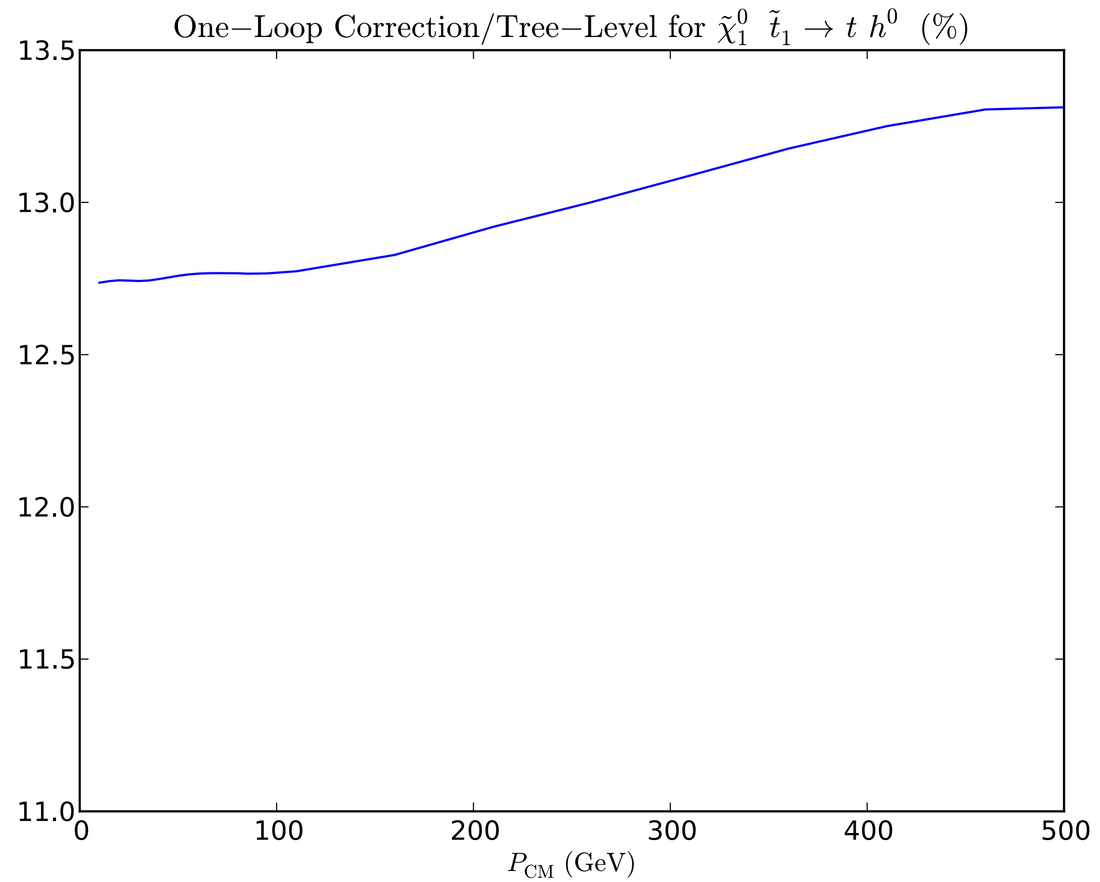
Tree-level and one-loop cross-sections (pb) un function of momenta



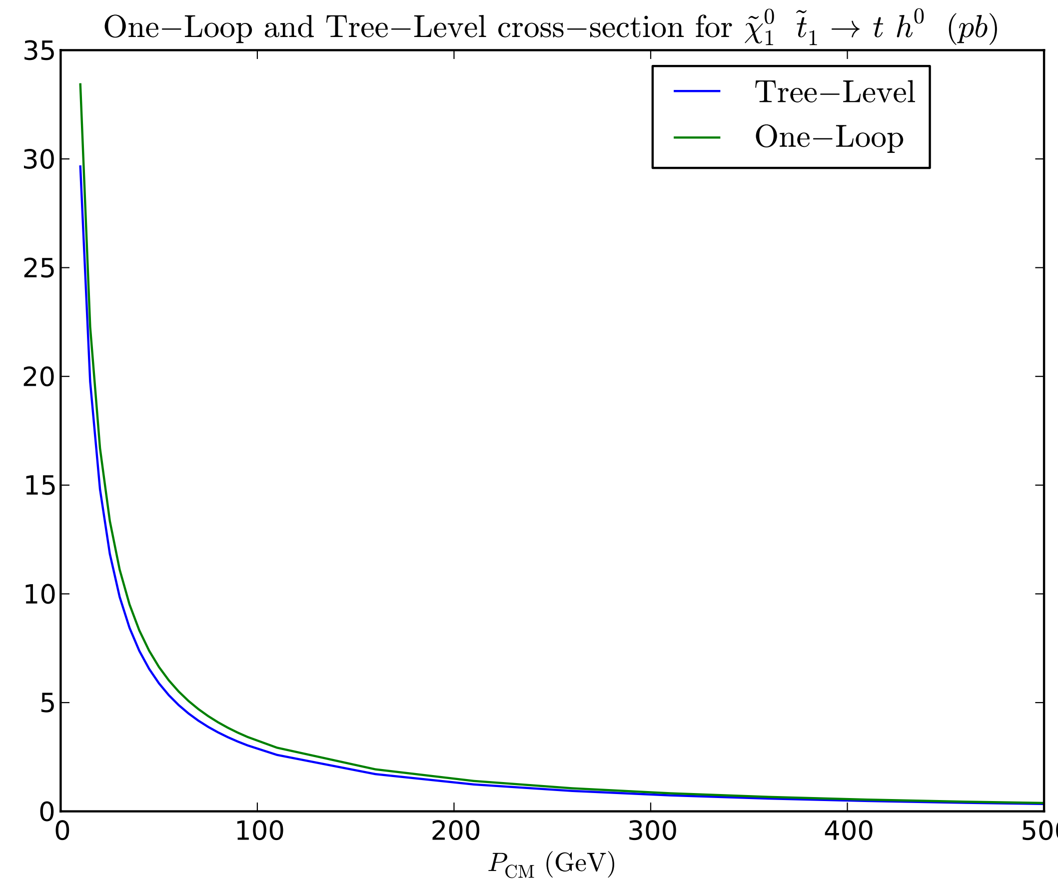
→ Moderate correction ~ 5%

Total correction for Top-Higgs final state

Relative correction (%) un function of momenta



Tree-level and one-loop cross-sections (pb) un function of momenta

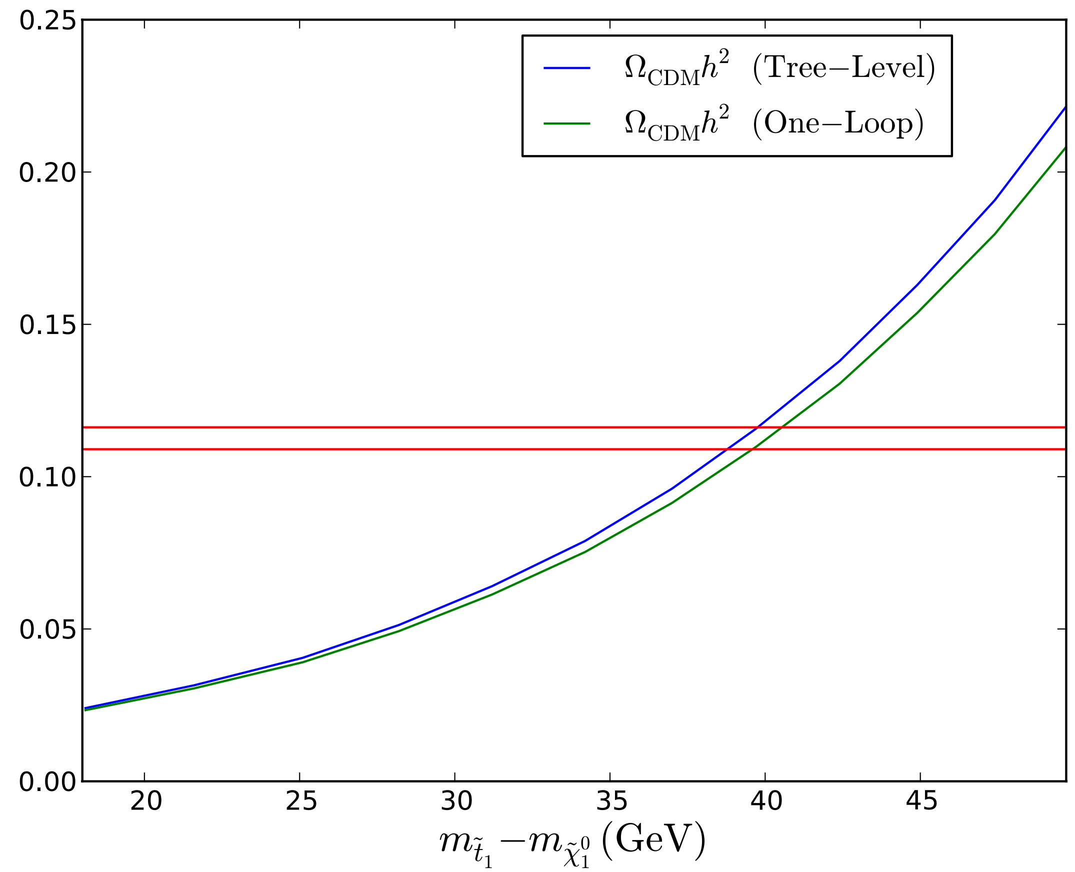


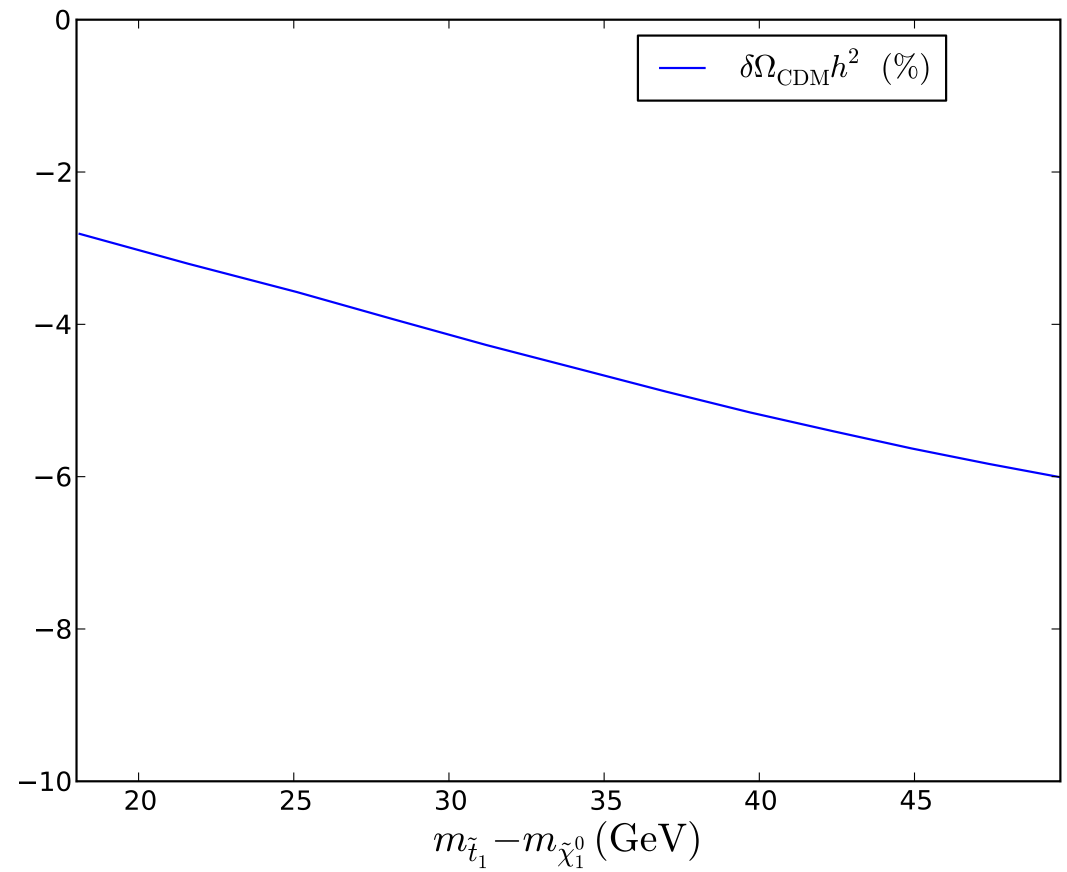
→ Larger correction ~ 13%

Impact on relic density

Relic density for tree-level and one-loop in function of the neutralino-stop mass difference

Relative correction on the relic density in function of the neutralino-stop mass difference

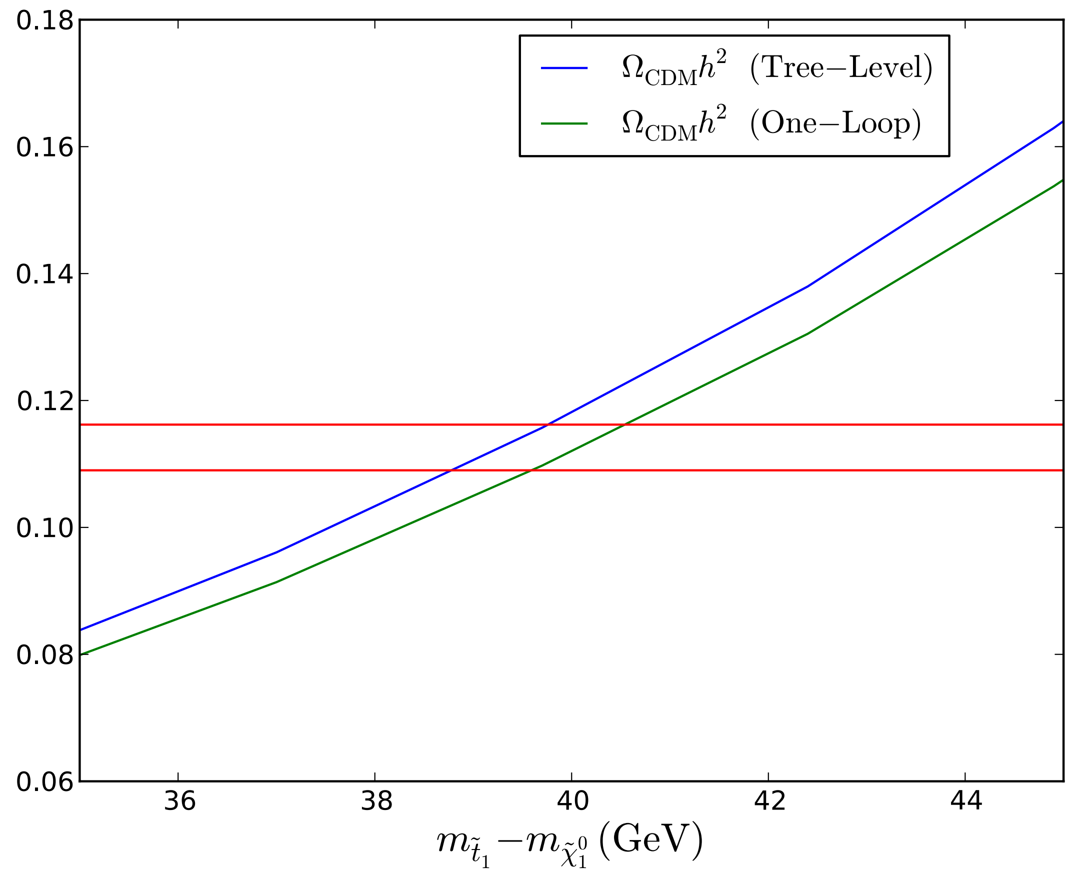




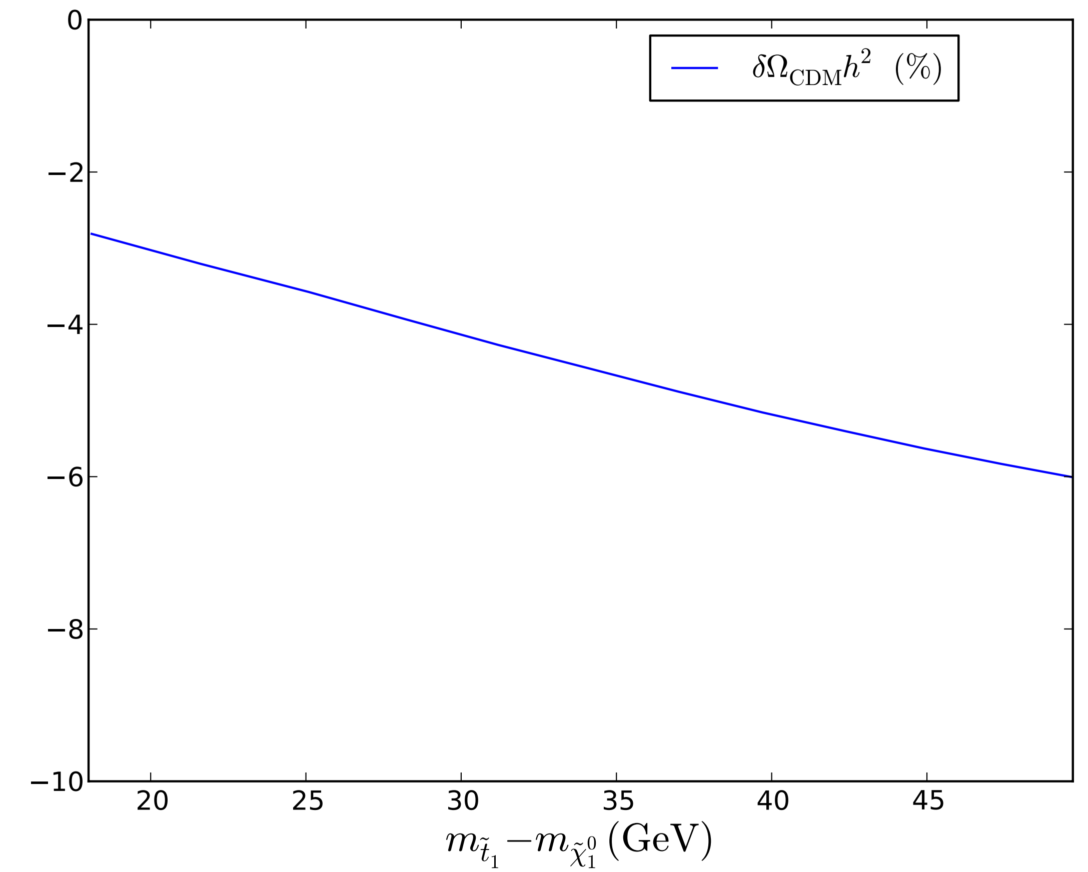
→ Correction ~ 5% on the relic density

Impact on relic density

Relic density for tree-level and one-loop in function of the neutralino-stop mass difference



Relative correction on the relic density in function of the neutralino-stop mass difference



→ Correction of the same order as experimental uncertainty

Conclusion

Conclusion

- Correction on the relic density is shown to be here as large as the experimental uncertainty.
- More detailed study to come with different processes contributions, different pMSSM scenarios, impact of renormalization scheme, etc.
- Coannihilation was contributing for only ~40% here. Stop annihilation was also important. This process is expected to receive large corrections + Sommerfeld enhancement.
- Top - gluon final state is also important in large regions of parameter space, because always kinematically allowed, provided that Neutralino and Stop are reasonnably heavy.
    - Larger QCD corrections are also expected. Non abelian corrections are being calculated. Collinear divergence: two cutoff Phase Space Slicing needed.