DM@NLO

– a tool for a precise prediction of the relic density

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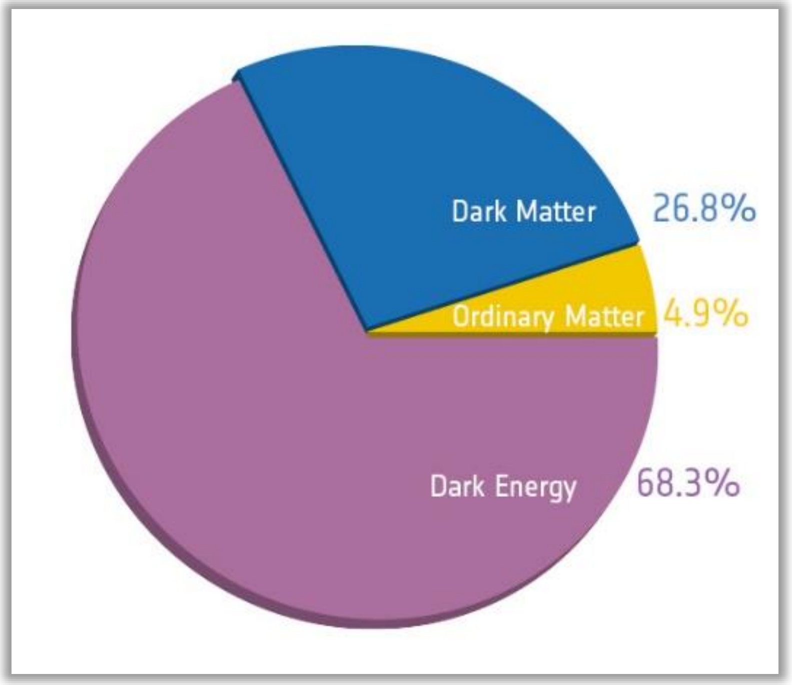
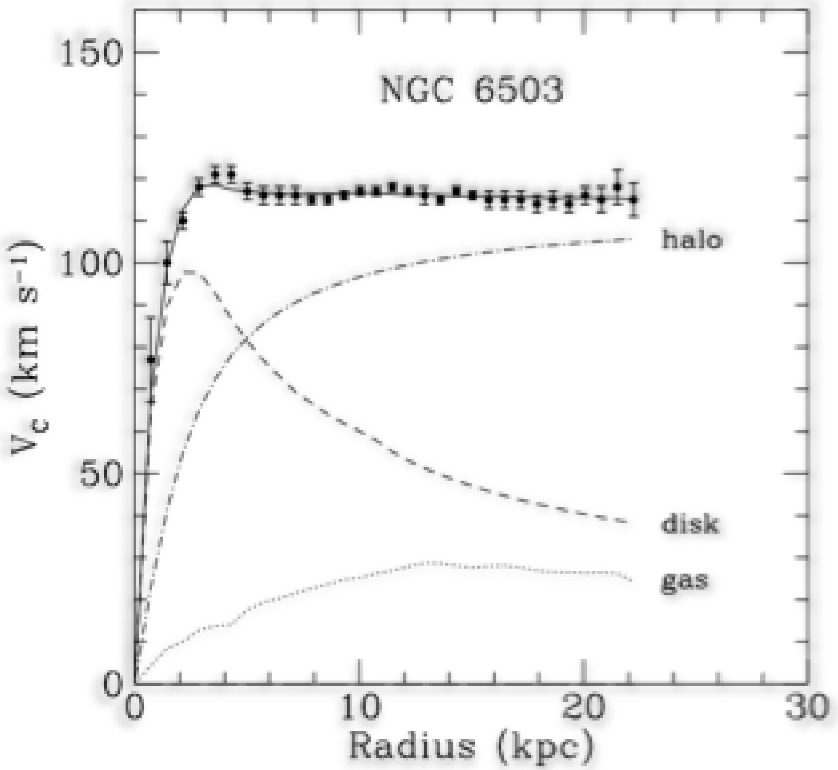
GDR Terascale 2014, Heidelberg

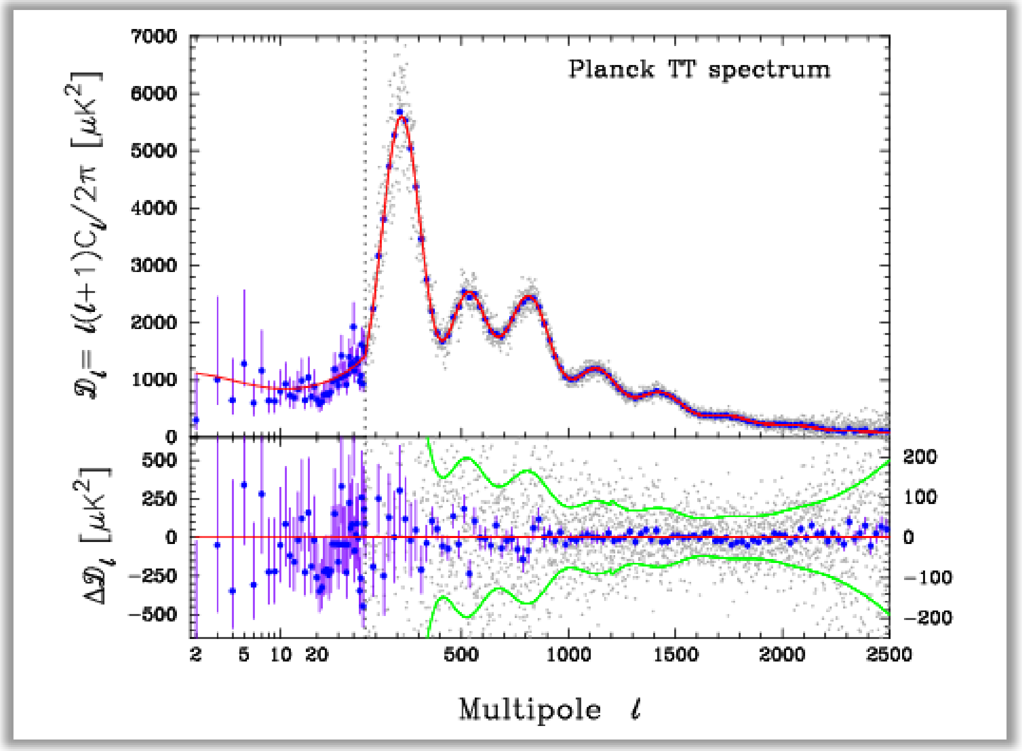
I. Motivation

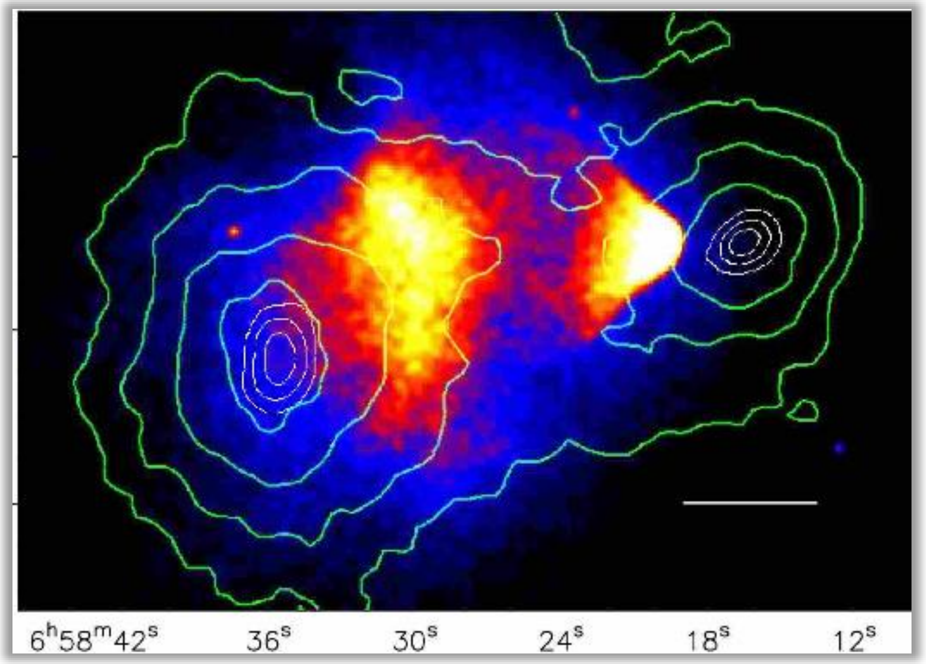
Different Evidence for Dark Matter





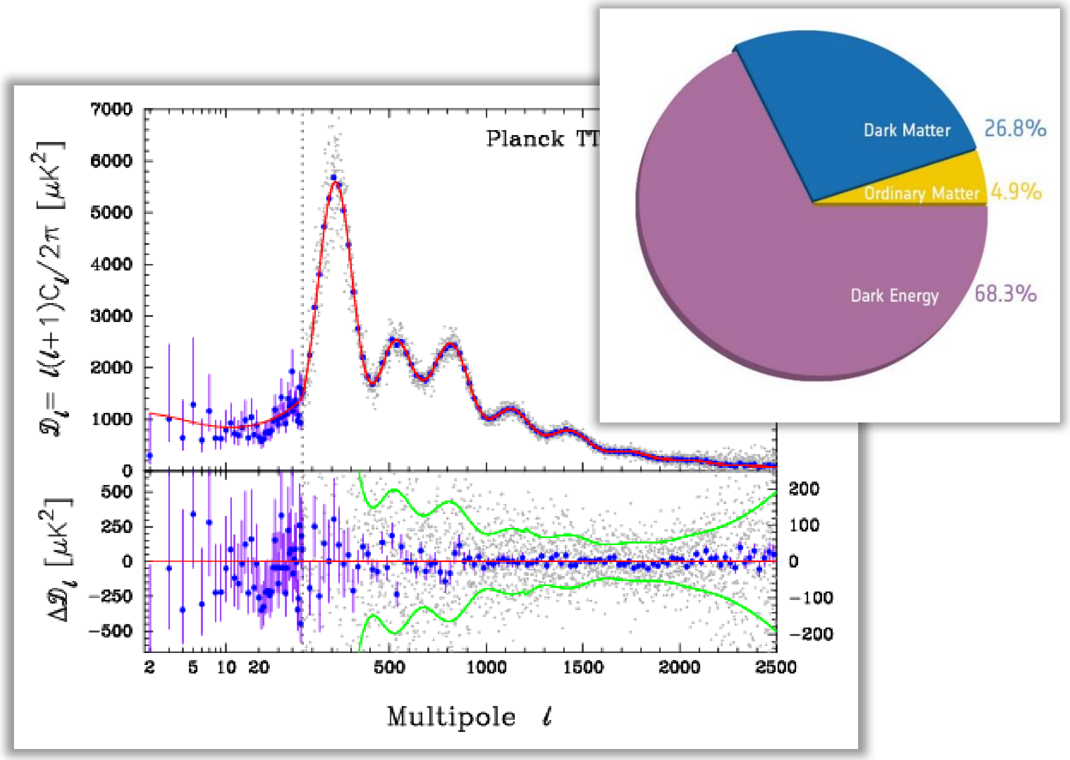
What is Dark Matter?





What is Dark Matter?

CMB Measurement

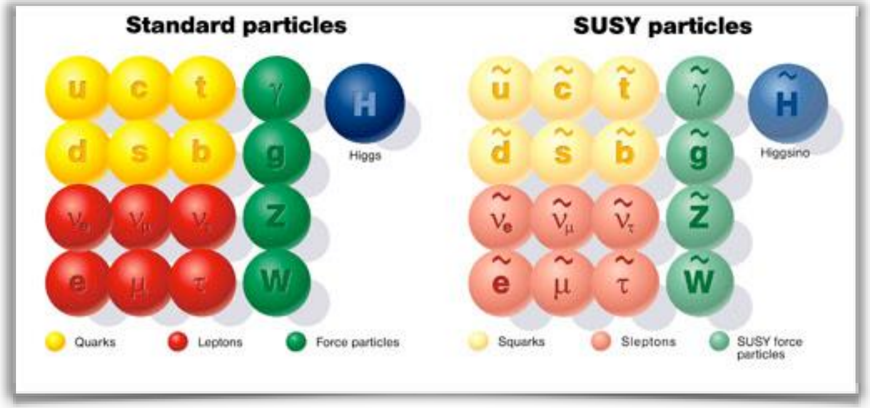


Planck Collaboration, arXiv:1303.5076

- precise determination of relic density by PLANCK to

$$\Omega_{\mathrm{CDM}}h^2 = 0.1199 \pm 0.0027$$

Particle Physics Theory



Minimal Supersymmetric Standard Model (MSSM)

- lightest neutralino $\tilde{\chi}_1^0$ is a good cold DM candidate
- theoretical prediction of relic density possible

$$\Omega_{\mathrm{CDM\,theoret.}}$$

Need of precise theoretical prediction to meet experimental precision

Theor. Prediction of DM Relic Density

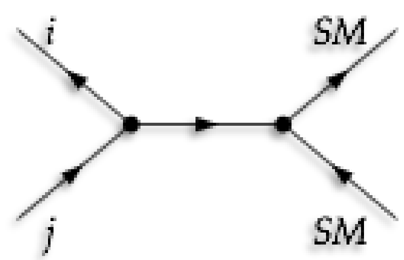
- number density of DM in the early universe can be described by the Boltzmann equation

$$\dot{n} + 3Hn = -\langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2)$$

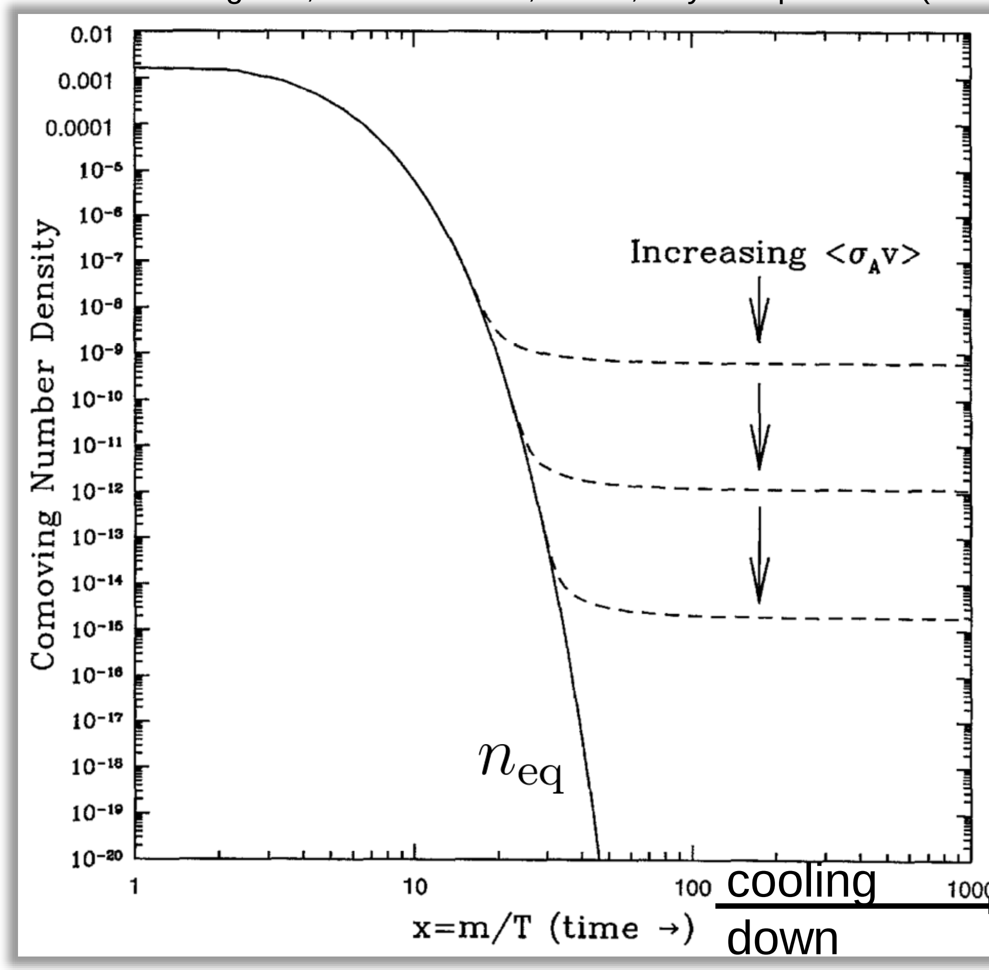
- relic density inversely proportional to cross section

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\text{eff}} v \rangle}$$

particle physics



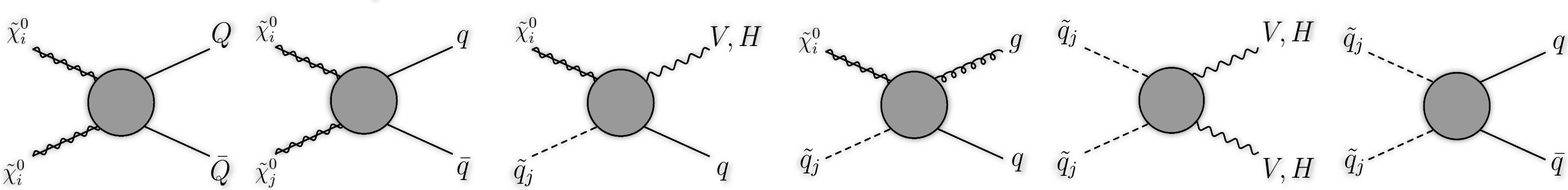
Jungman, Kamionkowski, Griest, Phys. Reports 267 (1995)



$\chi\chi \leftrightarrow \text{SM SM}$ $\quad \chi\chi \rightarrow \text{SM SM}$ $\quad \chi\chi \not\rightarrow \text{SM SM}$

- coannihilation processes can get important when particles almost mass degenerate

$$\langle \sigma_{\text{eff}} v \rangle = \sum_{ij} \langle \sigma_{ij} v_{ij} \rangle \frac{n_i^{eq}}{n^{eq}} \frac{n_j^{eq}}{n^{eq}} \quad \text{with} \quad \frac{n_i^{eq}}{n^{eq}} \propto \exp^{\frac{-(m_i - m_\chi)}{T}} = \exp^{\frac{-(m_i - m_\chi)}{x\ m_\chi}}$$



- Public tools evaluate the relic density for a specific parameter point in the MSSM

MicrOMEGAs	DarkSUSY	SuperIso Relic	MadDM
Belanger, Boudjema, et al. , CPC (2002)	Gondolo, Edsjö, et al. , JCAP (2004)	Arbey, Mamoudi, et al. , CPC (2010)	Backovic, Kong, et al. , (2013)

so far just based on (effective) tree level calculation

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\text{eff}} v \rangle}$$

particle physics

determination of (dis)favoured region of parameter space

- precise relic density determination by PLANCK

$$\Omega_{\text{CDM}} h^2 = 0.1199 \pm 0.0027$$

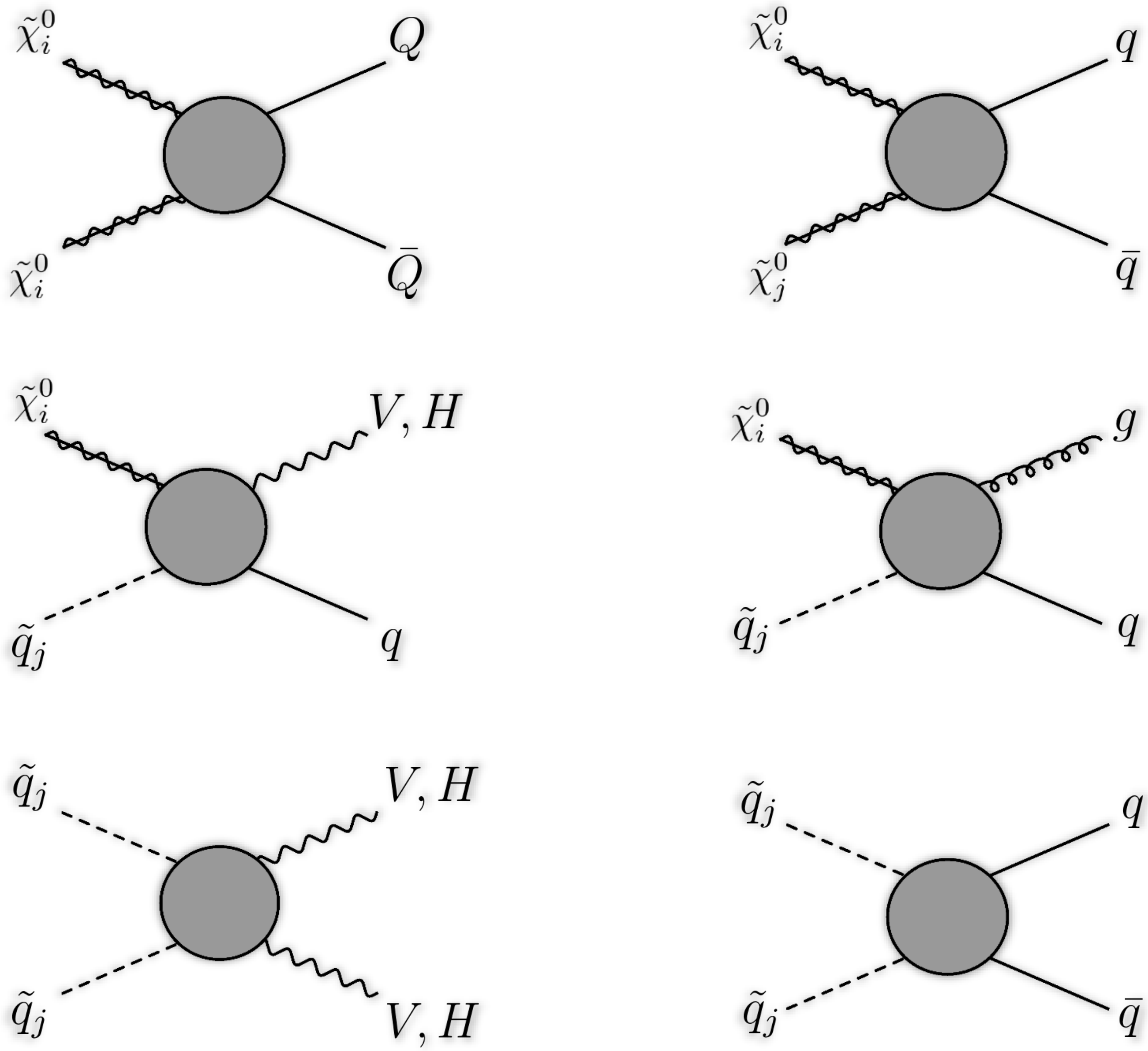
Planck Collaboration, arXiv:1303.5076

increase precision by going to NLO for cross section

II. The Tool

Our Goal

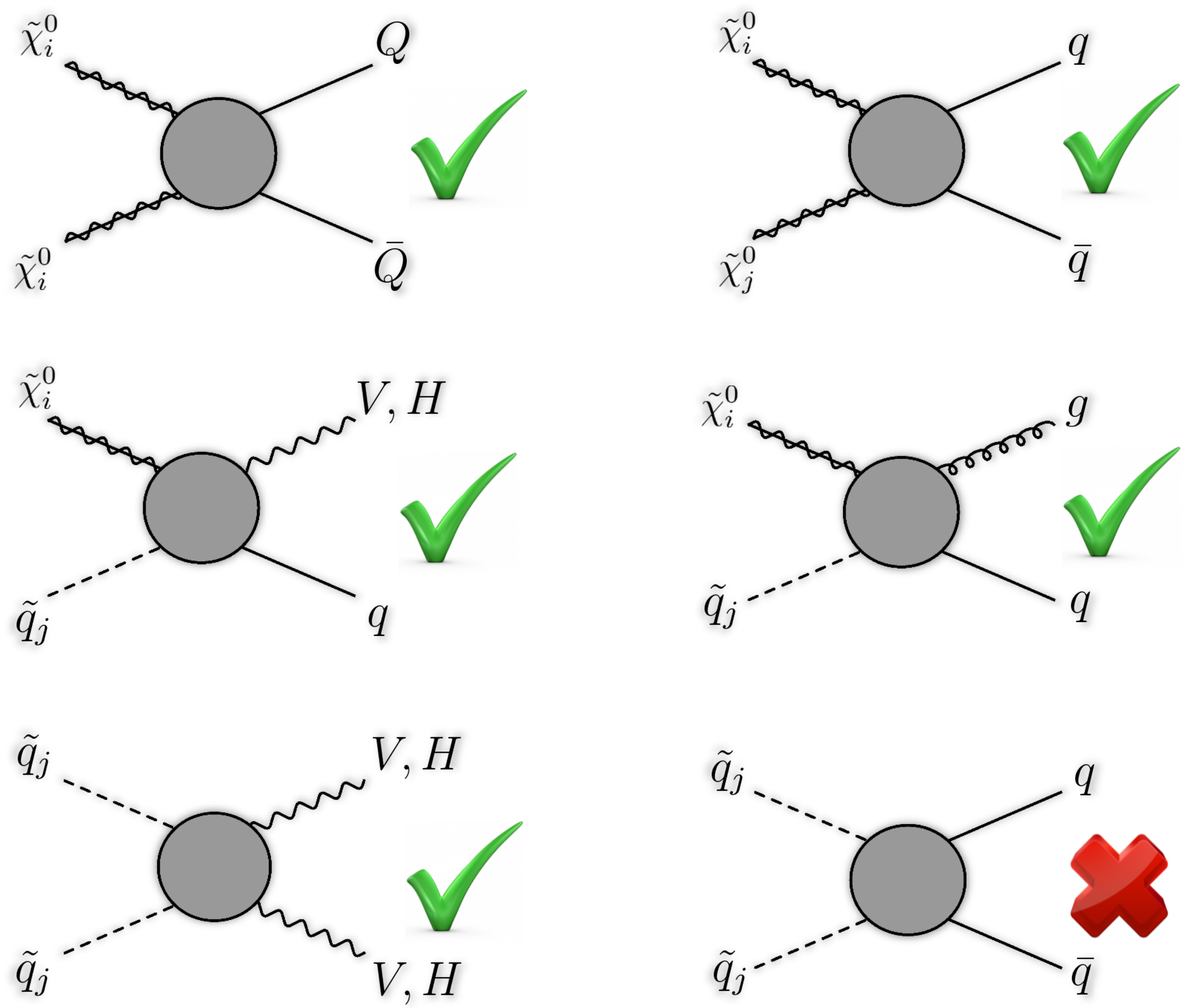
- SUSY-QCD corrections to all relevant processes for the relic density calculation



- providing a tool which extends public tools like micrOMEGAs and DarkSUSY
- allows for more precise constraints on the MSSM parameter space

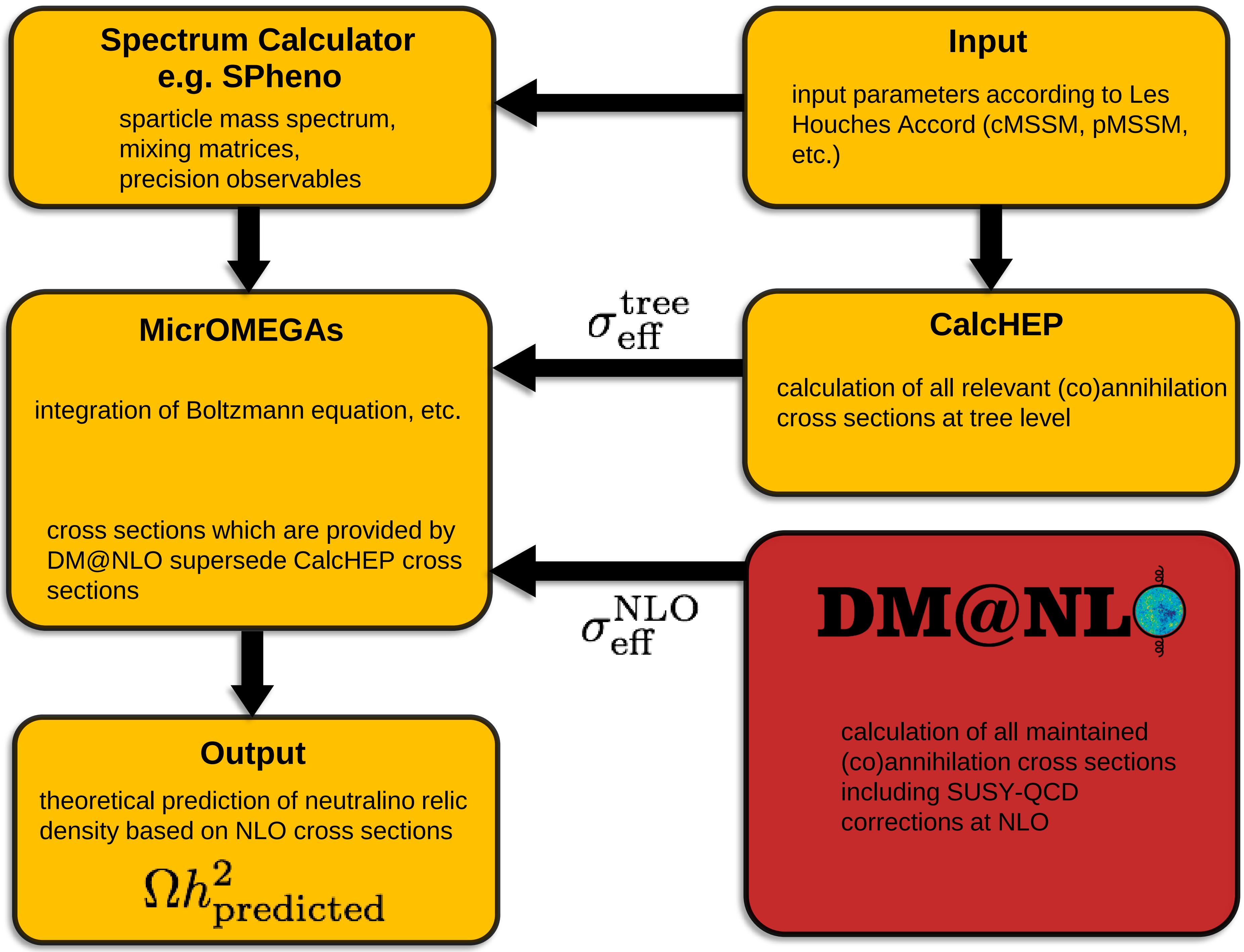
Our Goal

- SUSY-QCD corrections to all relevant processes for the relic density calculation



- providing a tool which extends public tools like micrOMEGAs and DarkSUSY
- allows for more precise constraints on the MSSM parameter space

Work flow and Implementation



The Team

Julia Harz

Björn Herrmann

Michael Klasen
Karol Kovarik
Moritz Meinecke
Patrick Steppeler

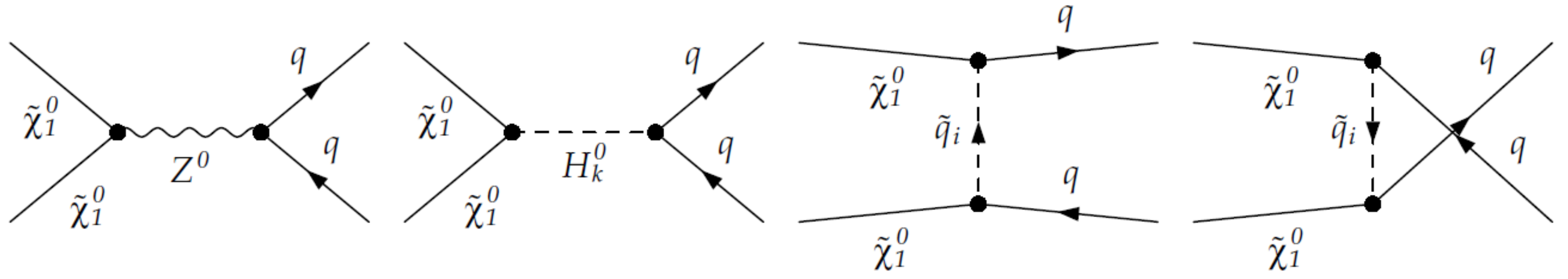
+ Saskia Schmiemann
+ Sonja Esch

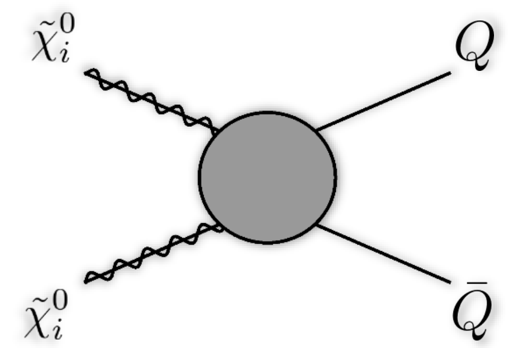
http://dmnlo.hepforge.org/

III. Results

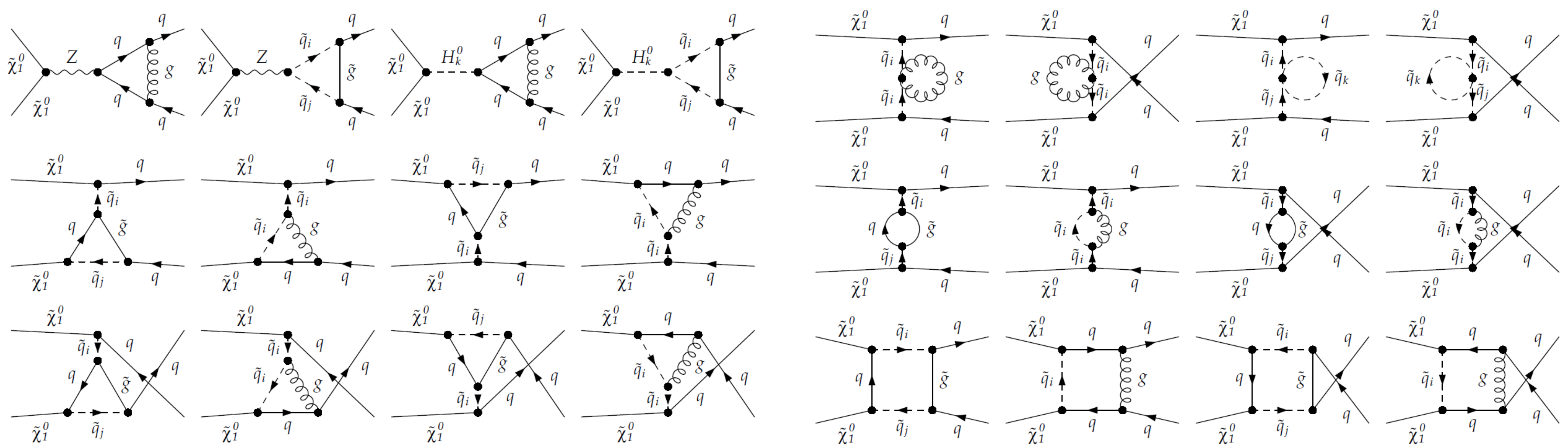
Neutralino Annihilation

Tree level

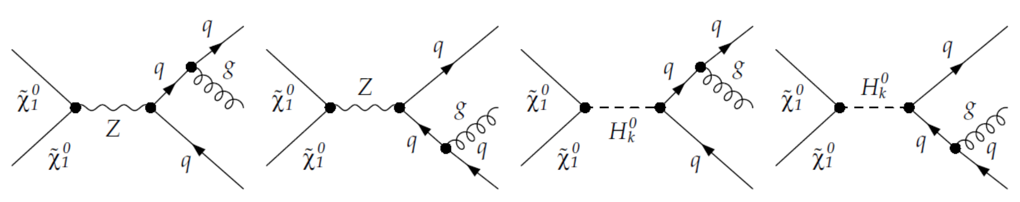


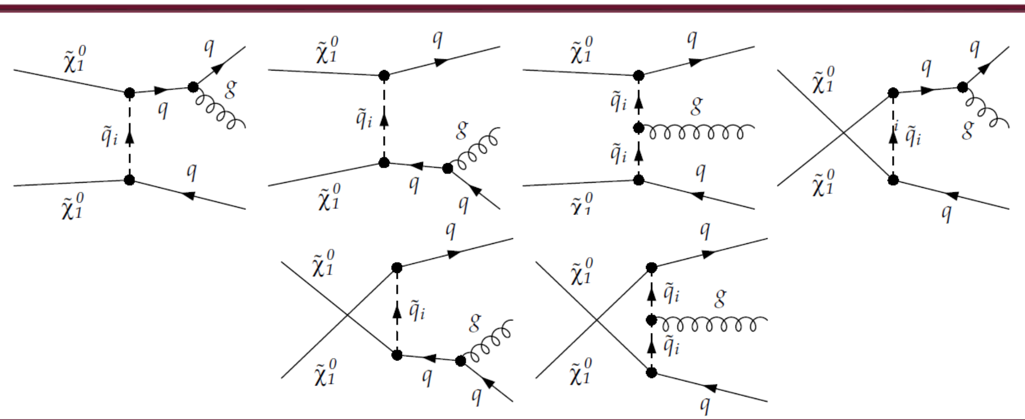


Virtual Corrections



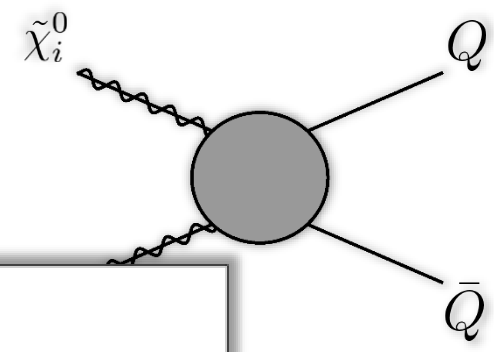
Real Emission Processes

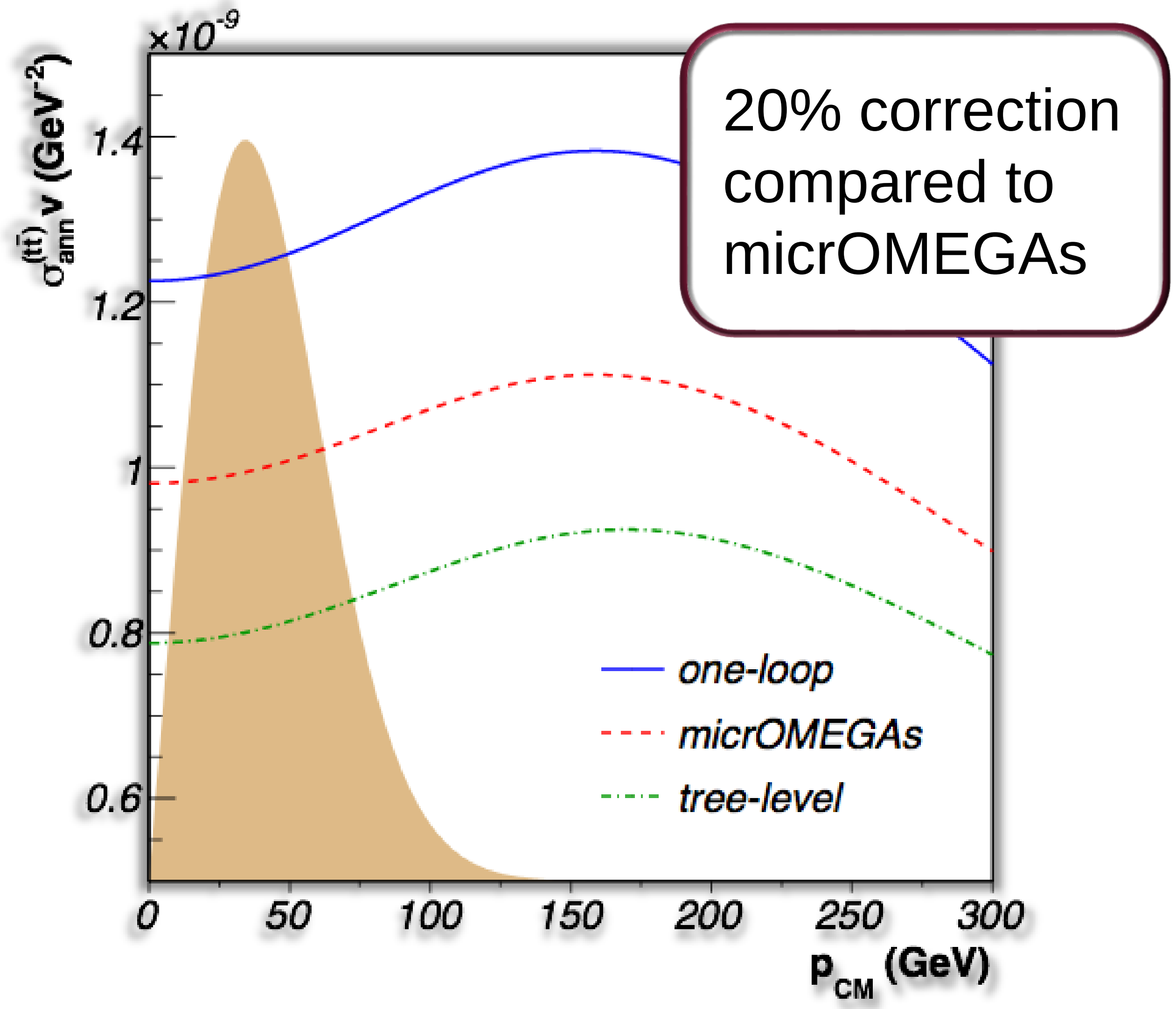


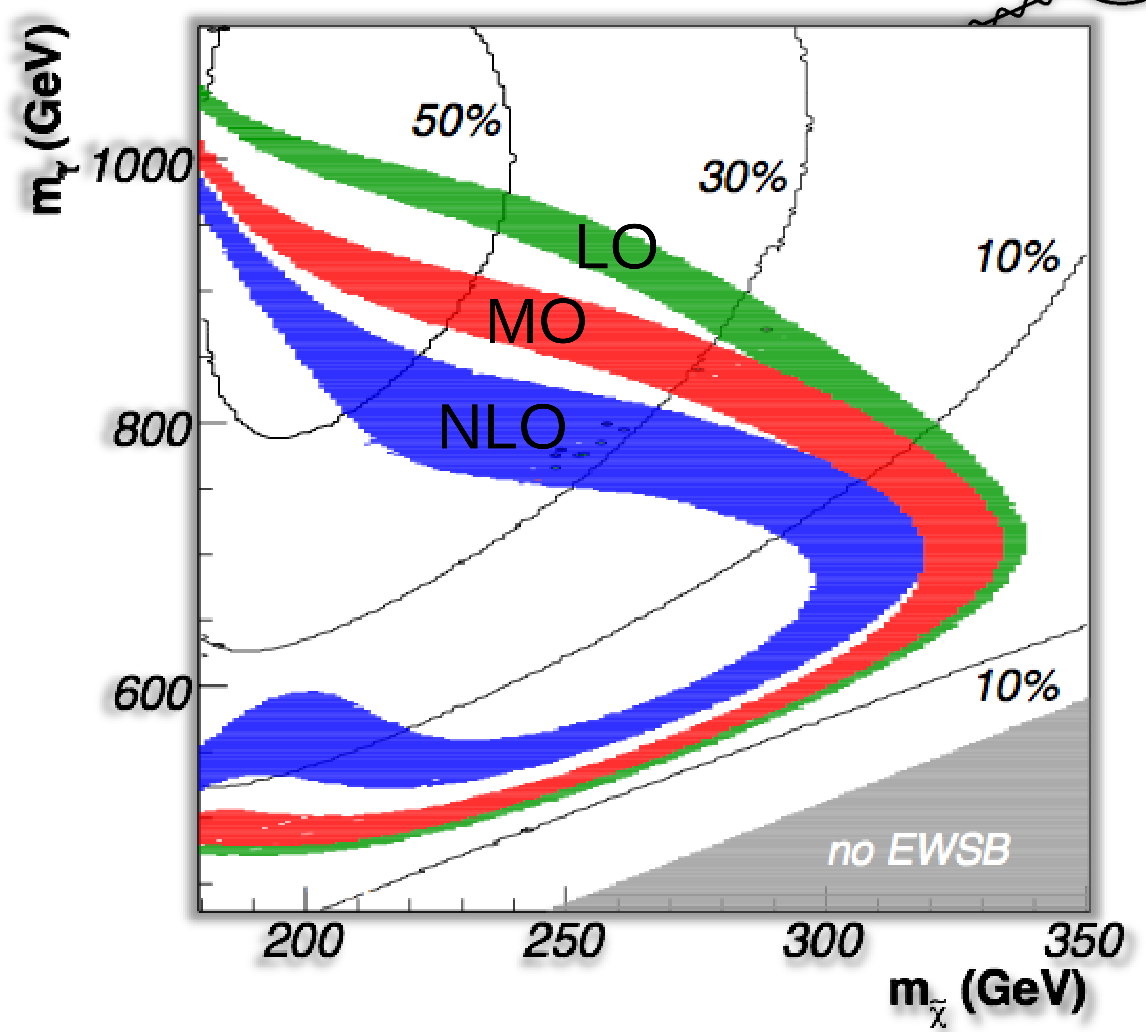


Neutralino Annihilation

- Example: Dominant Z-exchange







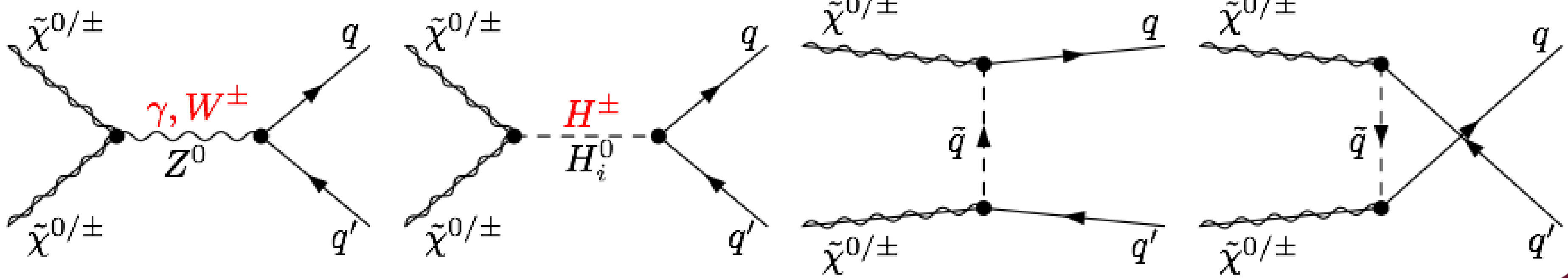
- effective Yukawa couplings not always sufficient, e.g. for dominant Z-exchange
- shift of about 100 GeV in physical mass plane

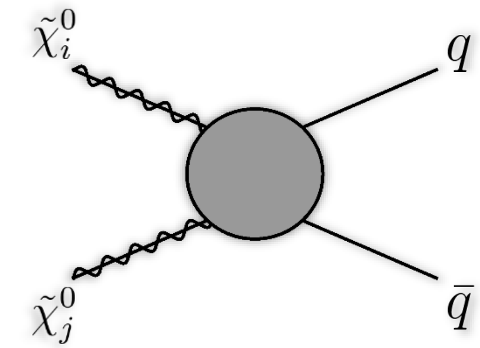
B. Herrmann, M. Klasen and K. Kovařík, Phys. Rev. D 79: 061701 (2009), arXiv:0901.0481 [hep-ph]
B. Herrmann, M. Klasen and K. Kovařík, Phys. Rev. D 80: 085025 (2009), arXiv:0907.0030 [hep-ph]

Extension to Gaugino (Co)annihilation

UCL

Tree level



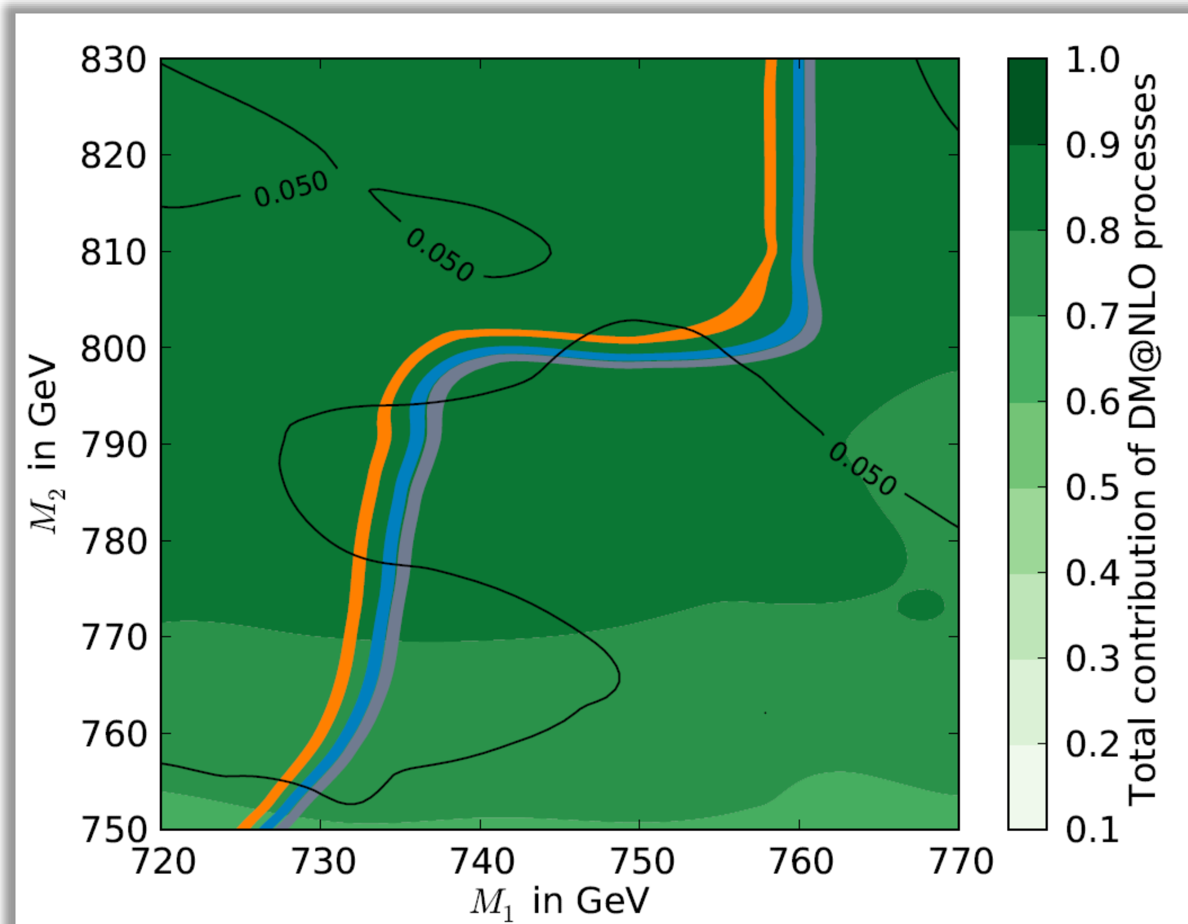


$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$Z_{1\tilde{B}}$	$Z_{1\tilde{W}}$	$Z_{1\tilde{H}_1}$	$Z_{1\tilde{H}_2}$	m_{h^0}	$\Omega_{\tilde{\chi}_1^0} h^2$	$\mathrm{BR}(b \to s\gamma)$
738.2	802.4	1288.4	1294.5	802.3	1295.1	-0.996	0.049	-0.059	0.037	126.3	0.1243	$3.0 \cdot 10^{-4}$

- pMSSM with relaxed GUT assumption

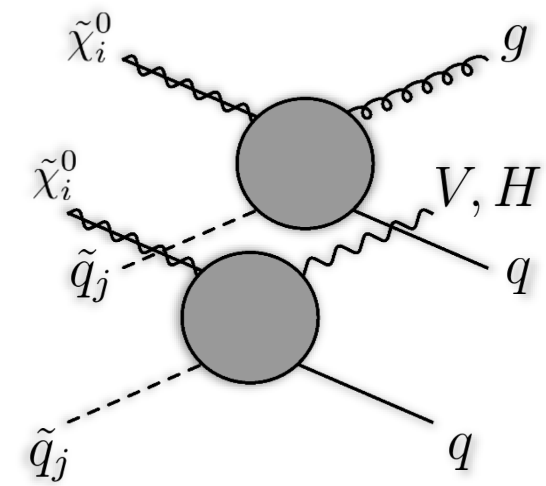
$\tilde{\chi}_1^0 \tilde{\chi}_1^\pm \to t\bar{b}$	43.0%
$\tilde{\chi}_1^0 \tilde{\chi}_2^0 \to b\bar{b}$	23.0%
$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to b\bar{b}$	9.1%

- Shift of relic density band by about 10 % with respect to micrOMEGAs



B. Herrmann, M. Klasen, K. Kovařík, M. Meinecke and P. Steppeler, Phys. Rev. D 89, 114012 (2014), arXiv:1404.2931 [hep-ph]

Neutralino-Stop Coannihilation



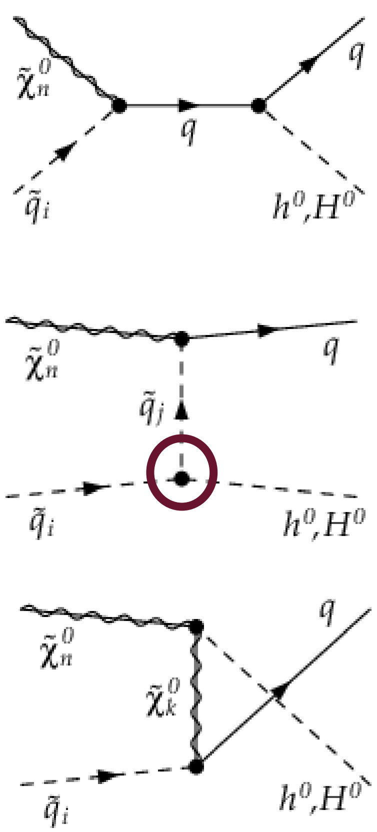
Light stop scenarios motivated by plenty of reasons:

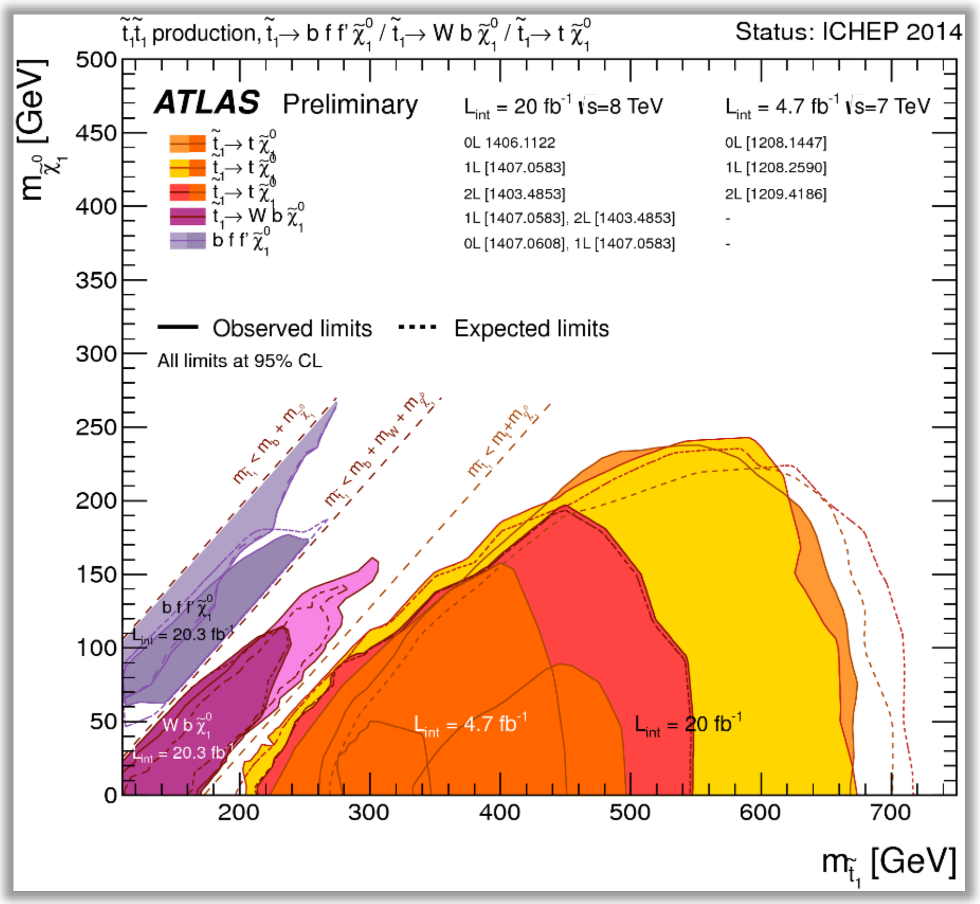
- for meeting the “right” relic density
- favoured scenario for electroweak baryogenesis
- large stop mass splitting favoured by Higgs mass

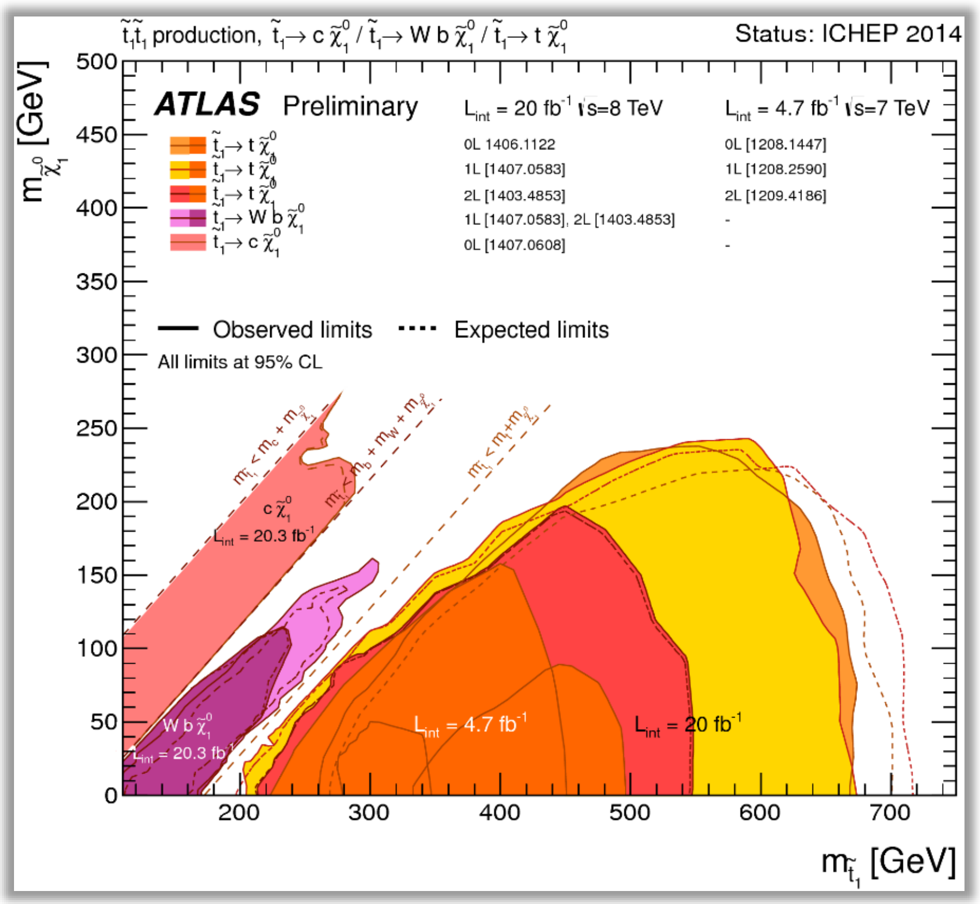
$$m_{h_0}^2 \approx m_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\frac{M_{\mathrm{SUSY}}^2}{m_t^2} + \frac{X_t^2}{M_{\mathrm{SUSY}}^2}\left(1 - \frac{X_t^2}{12 M_{\mathrm{SUSY}}^2}\right)\right]$$

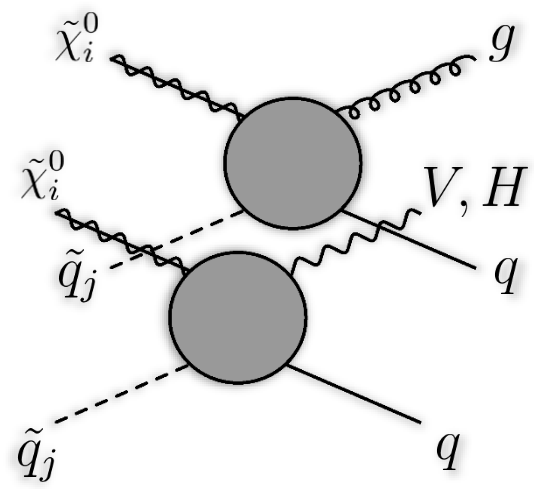
$$X_t = A_t - \mu/\tan\beta$$

$$M_{\mathrm{SUSY}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

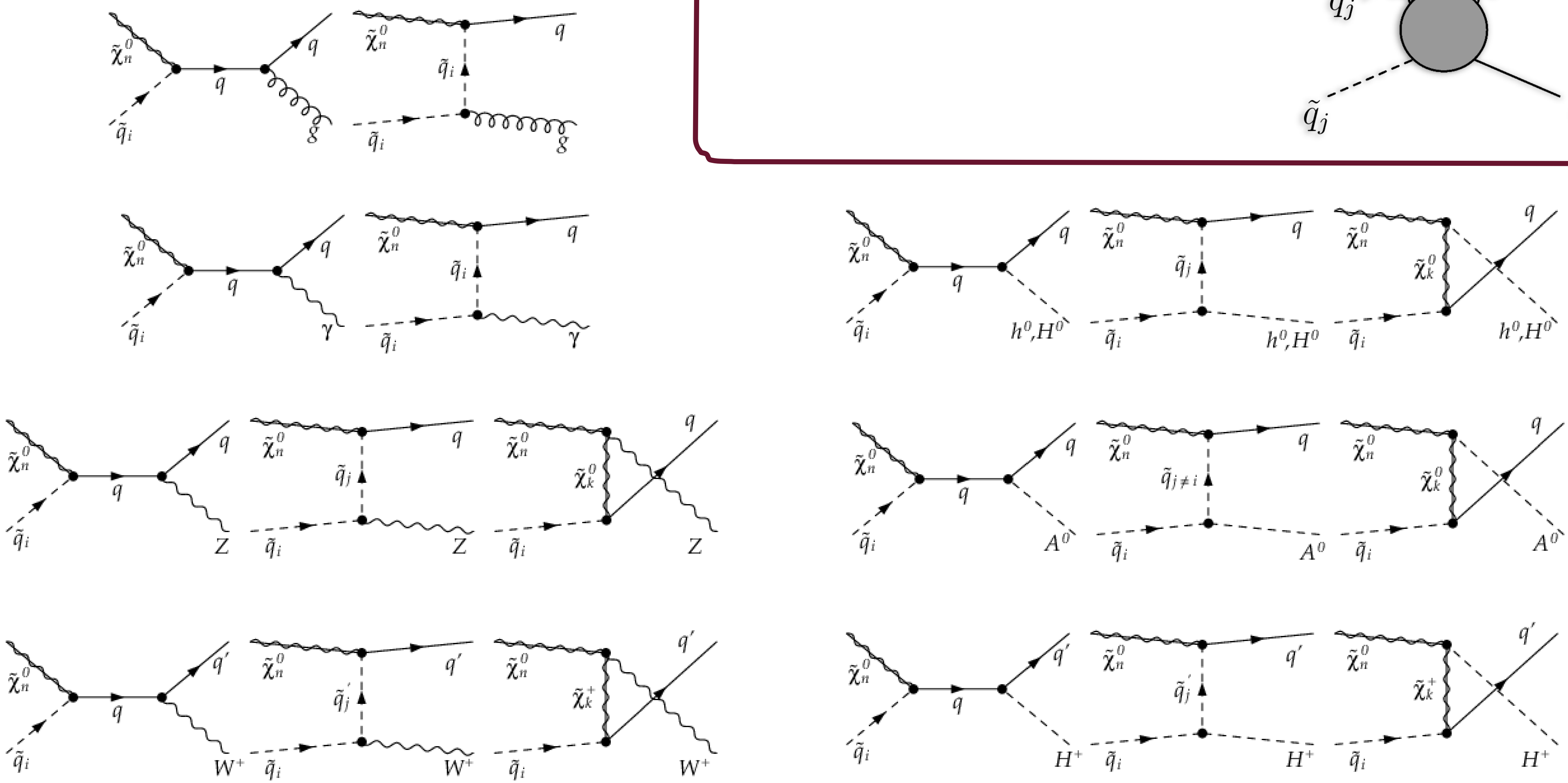








Tree level



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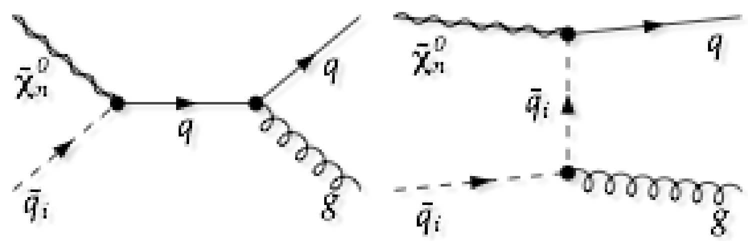
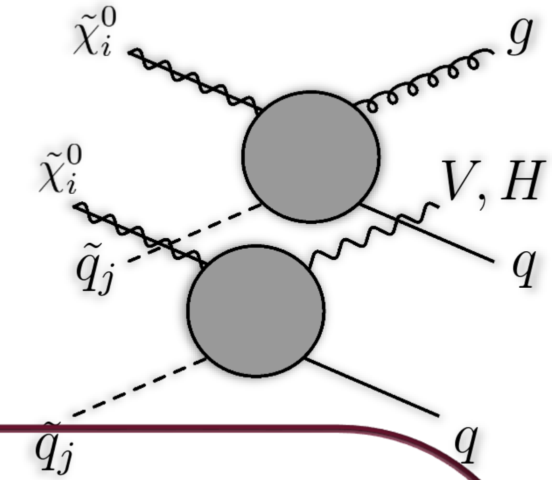
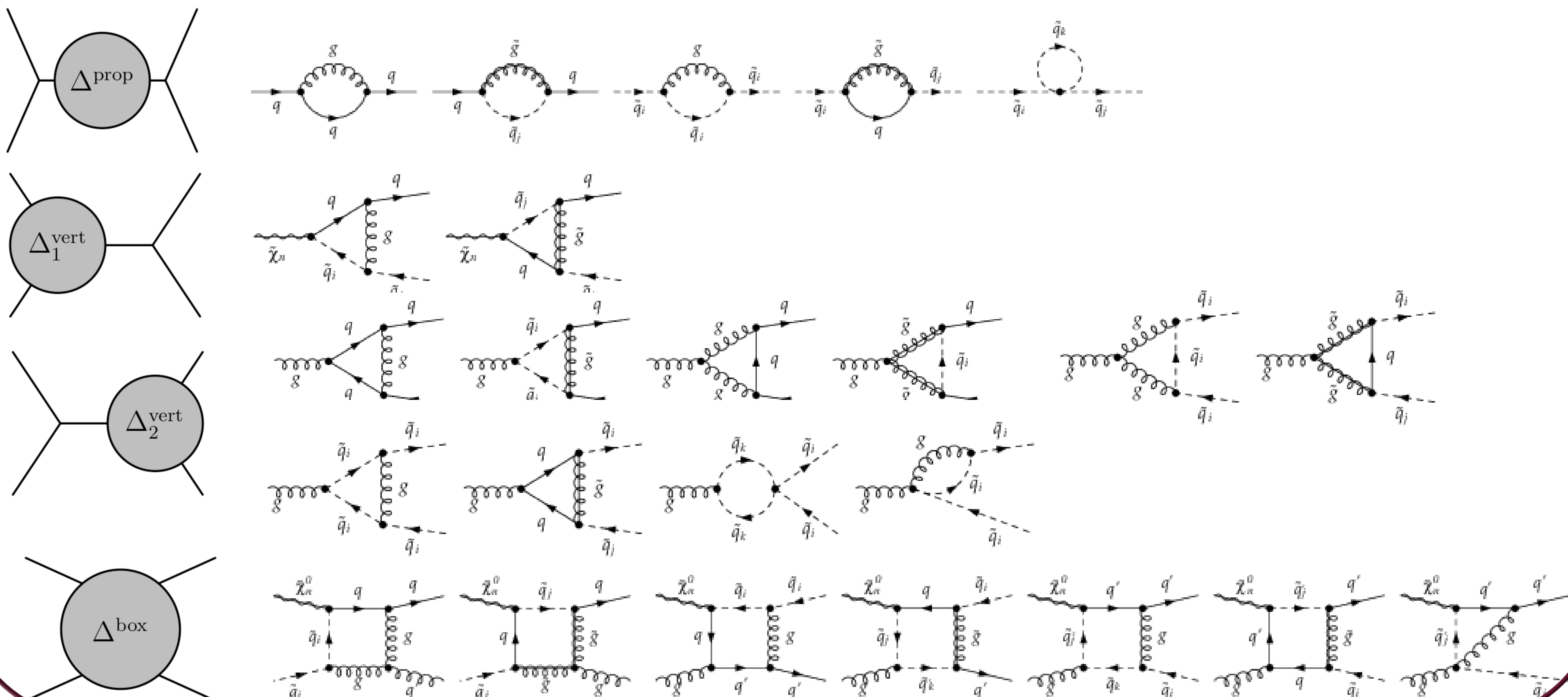
Neutralino-Stop Coannihilation

Tree level





Virtual corrections



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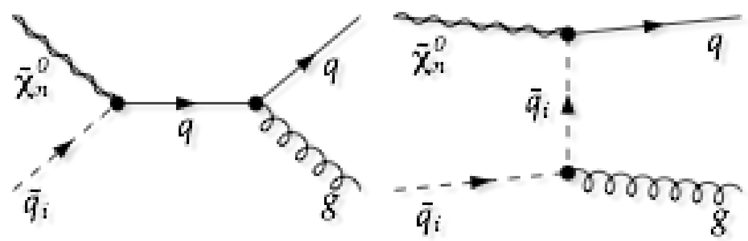
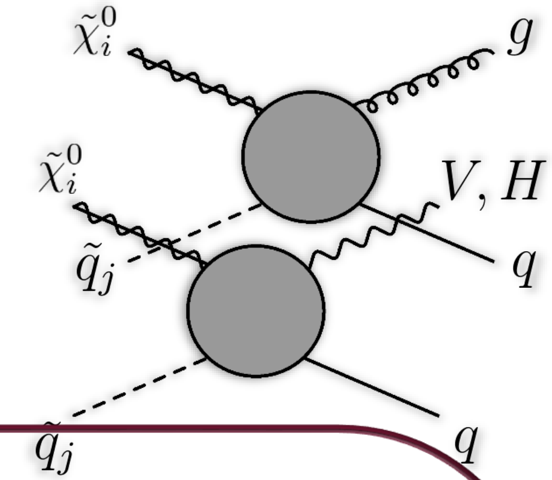
Tree level





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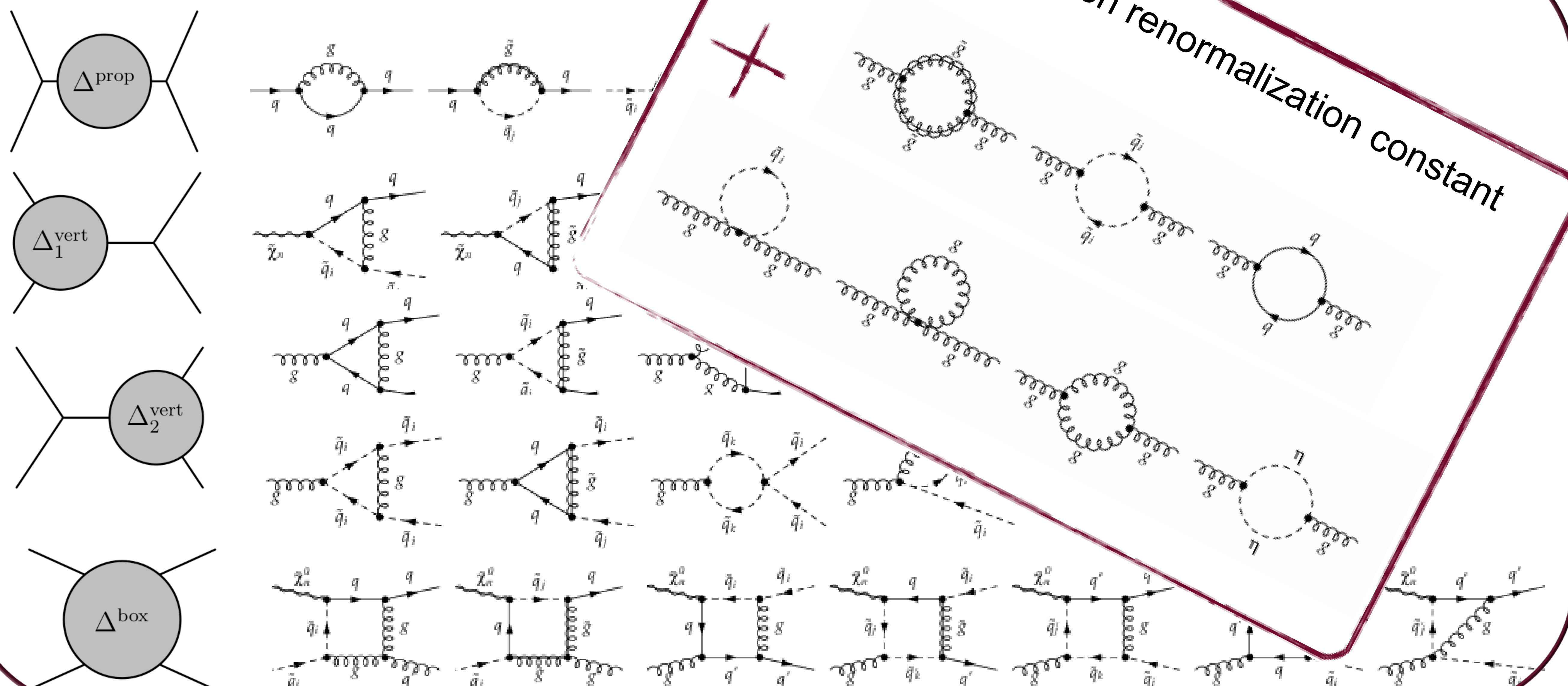

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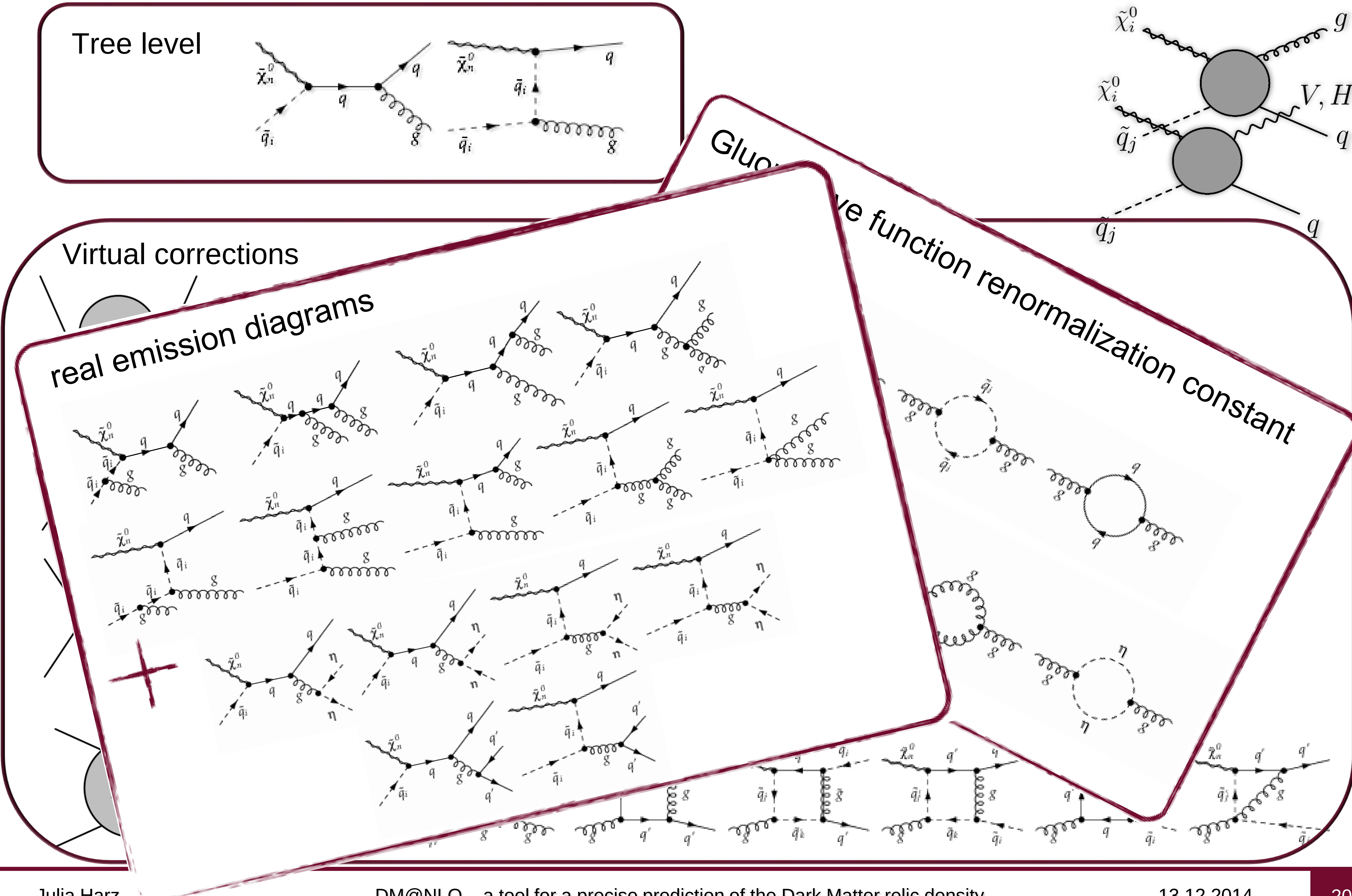
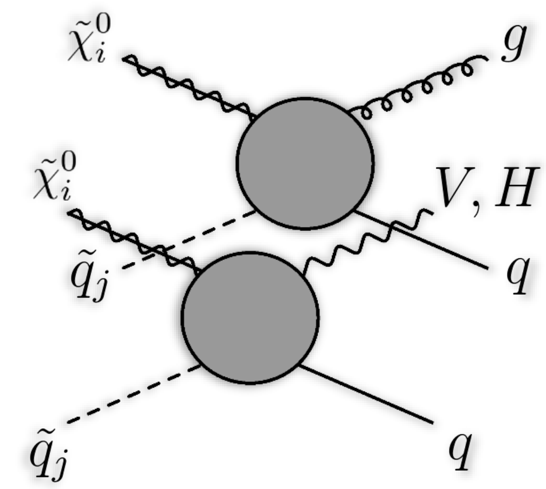


UCL

- hybrid on-shell / $\overline{\text{DR}}$ renormalisation scheme

$$m^{\text{OS}}_{\tilde{t}_1}, m^{\text{OS}}_{\tilde{b}_1}, m^{\text{OS}}_{\tilde{b}_2} \quad A^{\overline{\text{DR}}}_t, A^{\overline{\text{DR}}}_b \quad m^{\text{OS}}_t, m^{\overline{\text{DR}}}_b \;\Rightarrow\; m_{\tilde{t}_2}, \theta_{\tilde{t}}, \theta_{\tilde{b}}$$

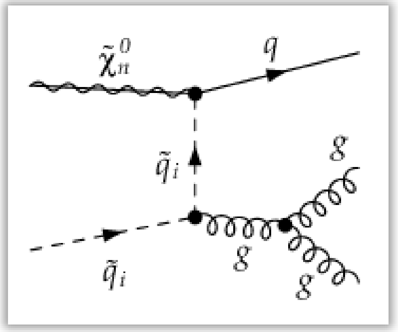
input parameters → dependent parameters

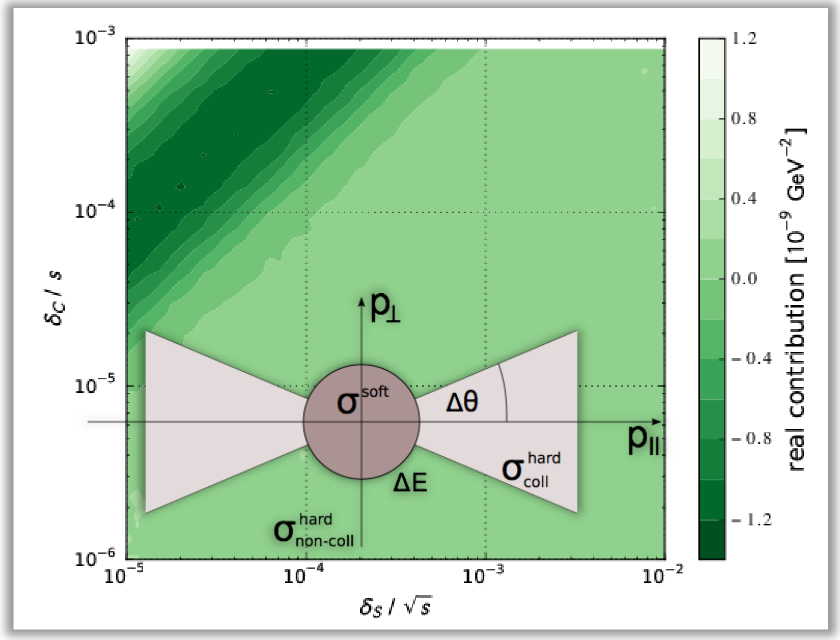


- 2-cutoff phase space slicing B. W. Harris, J. F. Owens, Phys, Rev. D65 (2002)

$$\sigma^{real} = \sigma^{\text{soft}}(\Delta E) + \sigma^{\text{hard}}_{\text{coll}}(\Delta E, \Delta\theta) + \sigma^{\text{hard}}_{\text{non-coll}}(\Delta E, \Delta\theta)$$

eikonal approximation | hard-collinear approximation | pure 2 ⟶ 3 processes



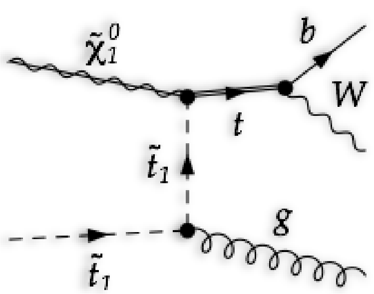


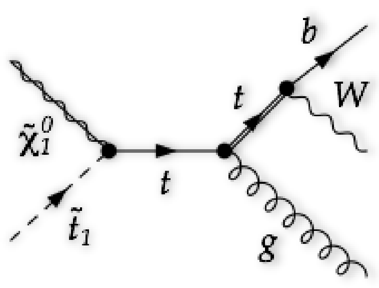
- local on-shell subtraction (DS) / "Prospino" scheme

W. Beenakker, R. Hoepker, M. Spira, P.M. Zerwas, Nuclear Physics B 492 (1997)

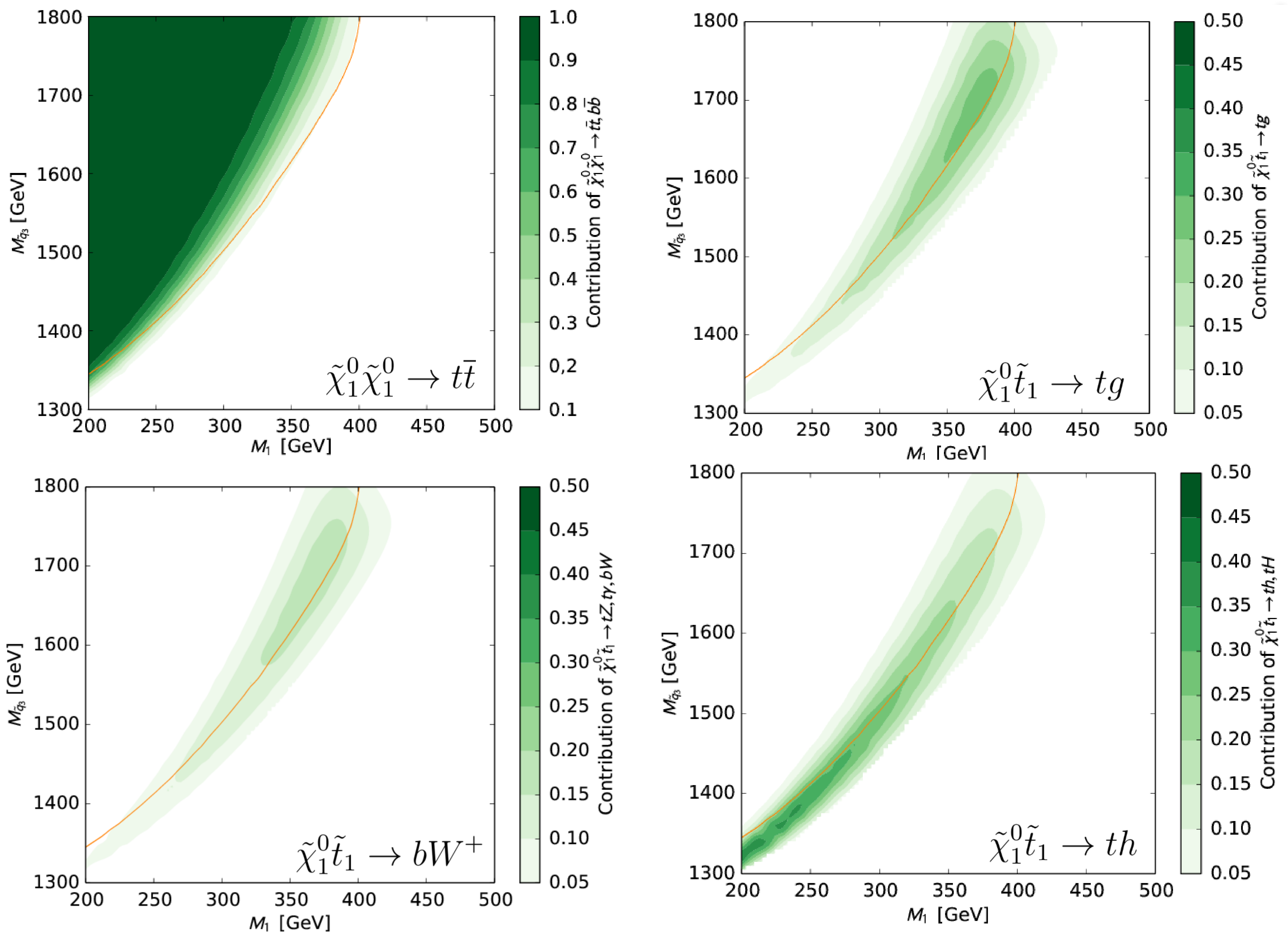
$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{res}}|^2 - |\mathcal{M}^{\text{sub}}_{\text{res}}|^2 + 2Re(\mathcal{M}^*_{\text{res}}\mathcal{M}_{\text{rem}}) + |\mathcal{M}_{\text{rem}}|^2$$

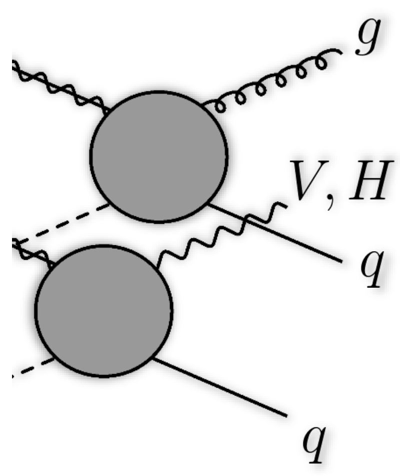
$$|\mathcal{M}^{\text{sub}}_{\text{res}}|^2 = \frac{m_t^2\Gamma_t^2}{(p_t^2 - m_t^2)^2 + m_t^2\Gamma_t^2}|\mathcal{M}_{\text{res}}|^2_{p_t^2 = m_t^2}$$





Neutralino-Stop Coannihilation





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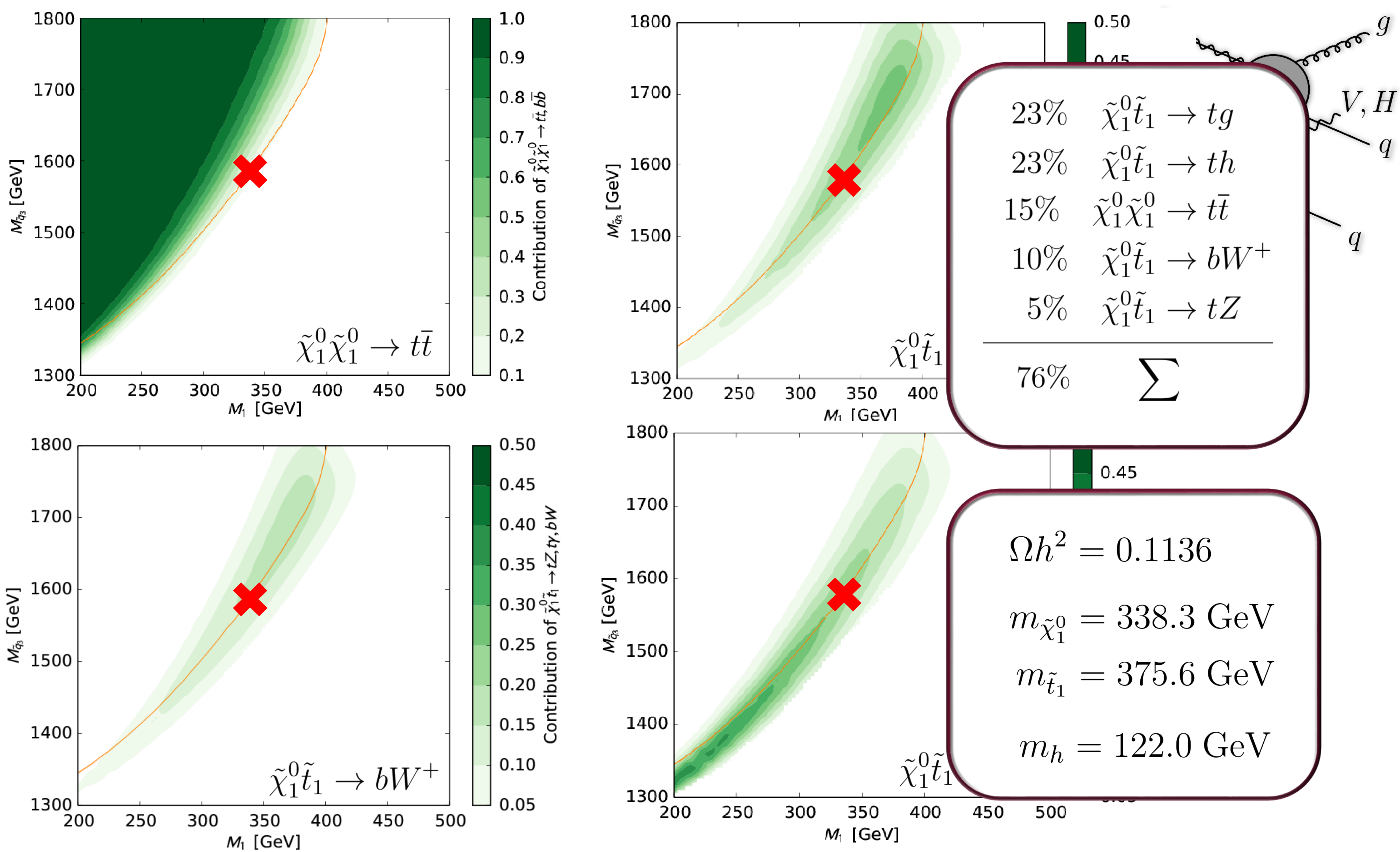

23%	$\tilde{\chi}_1^0\tilde{t}_1 \to tg$
23%	$\tilde{\chi}_1^0\tilde{t}_1 \to th$
15%	$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to t\bar{t}$
10%	$\tilde{\chi}_1^0\tilde{t}_1 \to bW^+$
5%	$\tilde{\chi}_1^0\tilde{t}_1 \to tZ$
76%	$\sum$

$$\Omega h^2 = 0.1136$$
$$m_{\tilde{\chi}_1^0} = 338.3 \text{ GeV}$$
$$m_{\tilde{t}_1} = 375.6 \text{ GeV}$$
$$m_h = 122.0 \text{ GeV}$$

J. Harz, B. Herrmann, M. Klasen, K. Kovařík and Q. Le Boulc'h, Phys. Rev. D 87: 054031 (2013), arXiv:1212.5241 [hep-ph]
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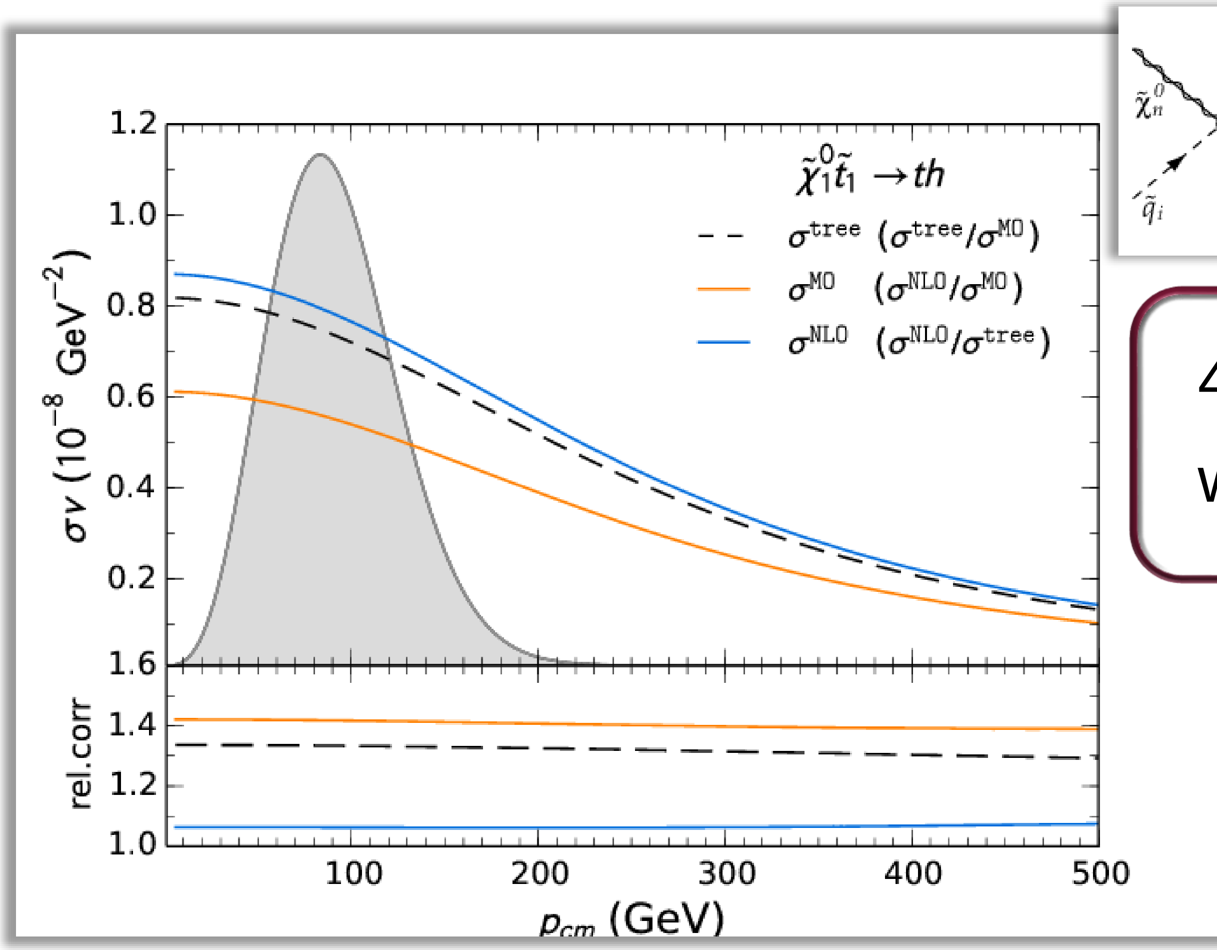
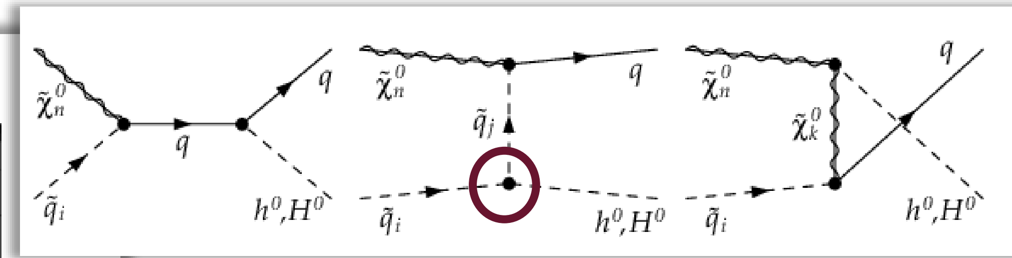
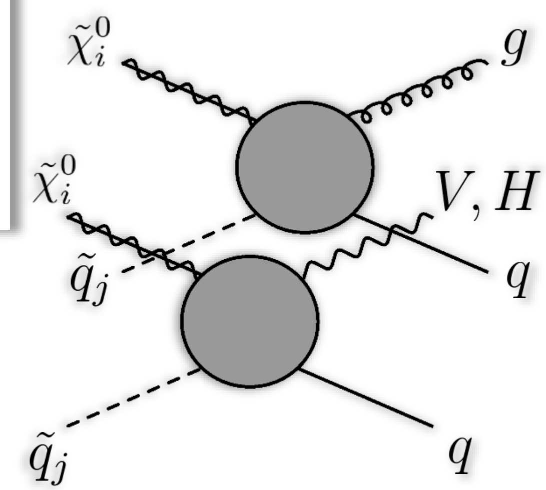
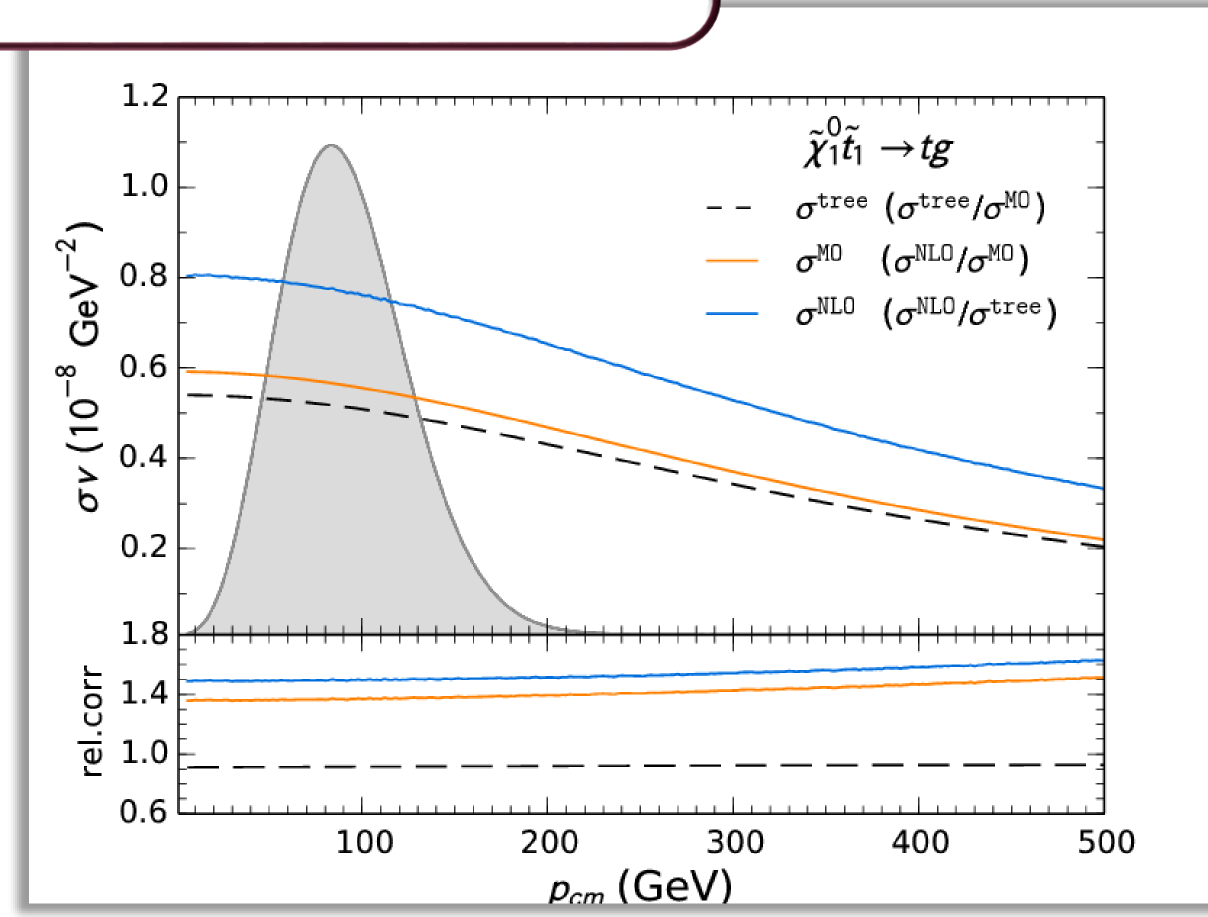






40 % correction
with respect to micrOMEGAs

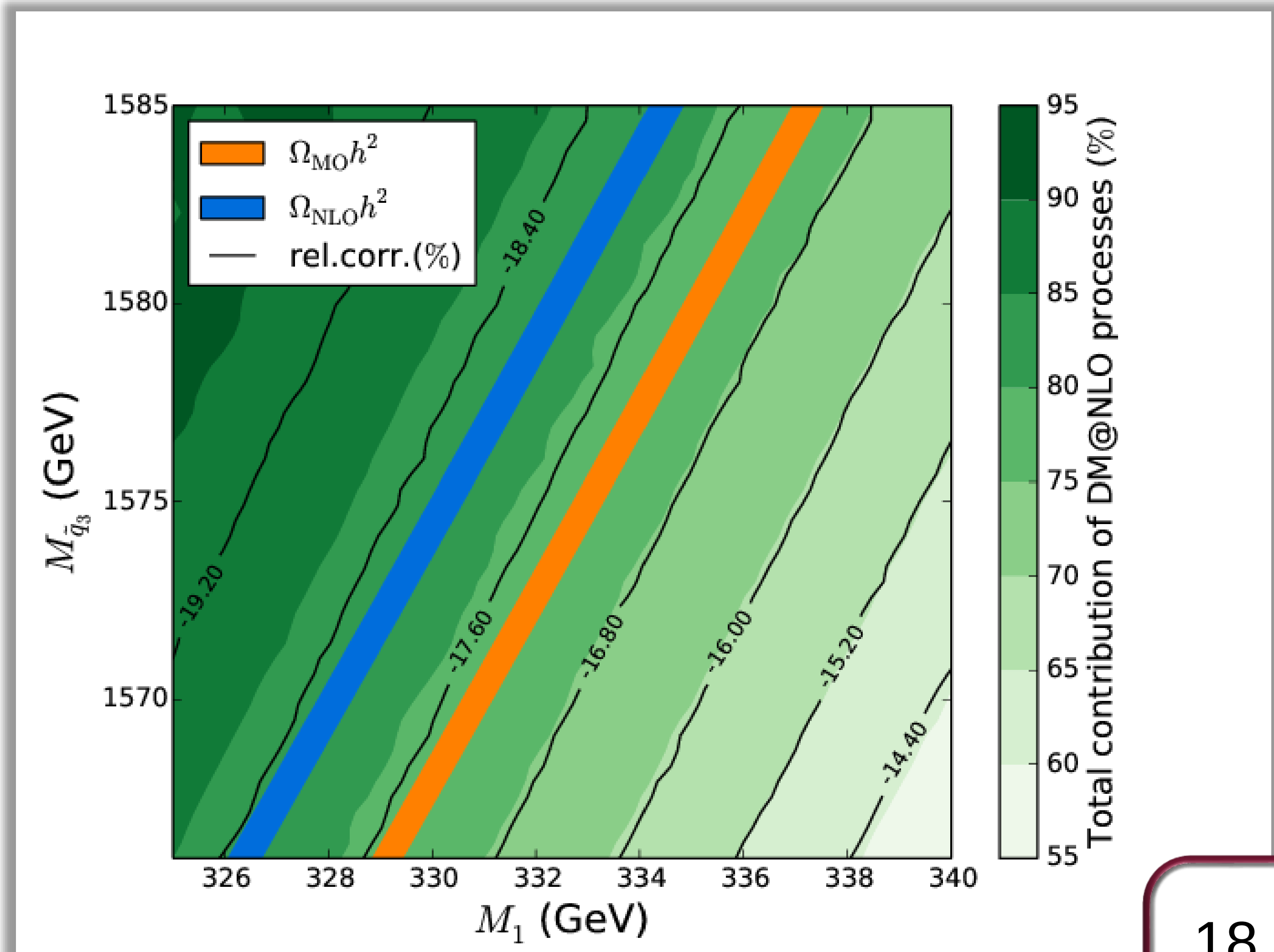
$m_{\tilde{\chi}_1^0}$	338.3 GeV
$m_{\tilde{t}_1}$	375.6 GeV
m_{h^0}	122.0 GeV
$\Omega_{\tilde{\chi}_1^0} h^2$	0.1136
$\text{BR}(b \to s\gamma)$	$3.25 \cdot 10^{-4}$



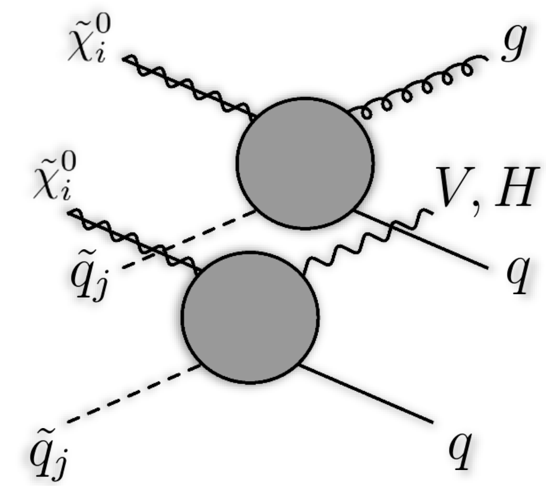
$\tan\beta$	μ	m_A	M_1	M_2	M_3	$M_{\tilde{q}_{1,2}}$	$M_{\tilde{q}_3}$	$M_{\tilde{u}_3}$	$M_{\tilde{\ell}}$	T_t
5.8	2925.8	948.8	335.0	1954.1	1945.6	3215.1	1578.0	609.2	3263.9	2704.1

J. Harz, B. Herrmann, M. Klasen, K. Kovařík and Q. Le Boulc'h, Phys. Rev. D 87: 054031 (2013), arXiv:1212.5241 [hep-ph]
J. Harz, B. Herrmann, M. Klasen, and K. Kovařík, arXiv:1409.2898 [hep-ph]

Neutralino-Stop Coannihilation



$\tilde{\chi}^0_1\tilde{t}_1 \rightarrow tg$	23%
$\tilde{\chi}^0_1\tilde{t}_1 \rightarrow th^0$	23%
$\tilde{\chi}^0_1\tilde{t}_1 \rightarrow tZ^0$	5%
$\tilde{\chi}^0_1\tilde{t}_1 \rightarrow bW^+$	10%
$\tilde{\chi}^0_1\tilde{\chi}^0_1 \rightarrow t\bar{t}$	15%
$\sum_{\rm corr}$	76%



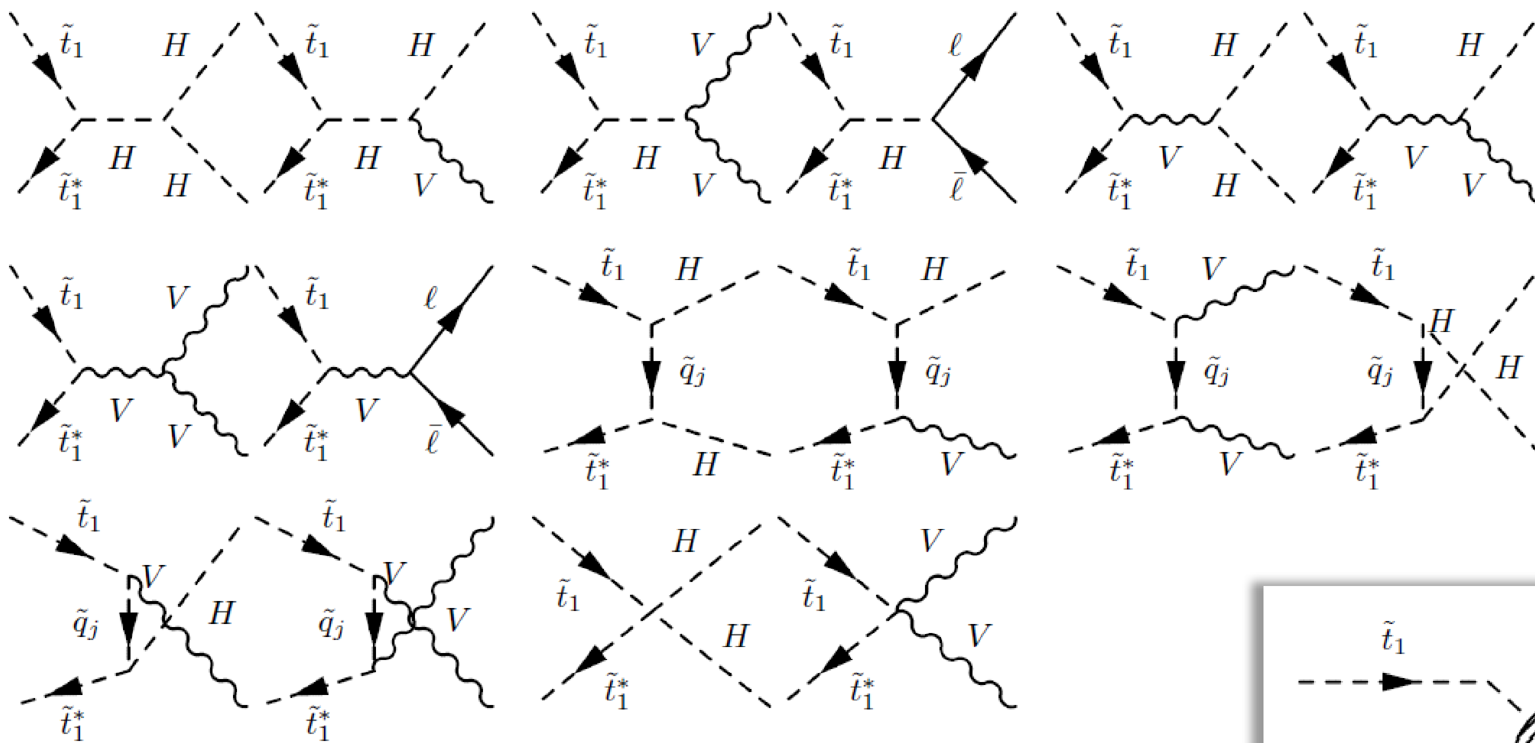
18 % correction
with respect to micrOMEGAs

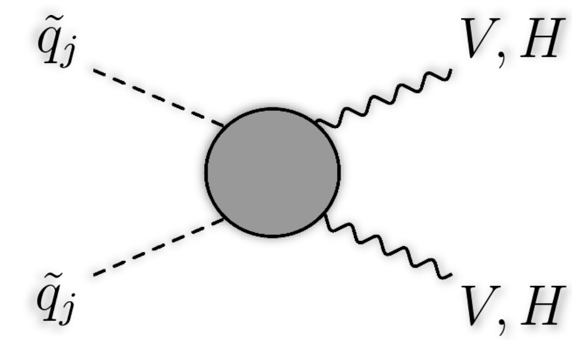
- correction of 80 % of all processes, 65% of them are coannihilation processes
- shift of the cosmologically preferred region of parameter space

J. Harz, B. Herrmann, M. Klasen, K. Kovařík and Q. Le Boulc'h, Phys. Rev. D 87: 054031 (2013), arXiv:1212.5241 [hep-ph]
J. Harz, B. Herrmann, M. Klasen, and K. Kovařík, arXiv:1409.2898 [hep-ph]

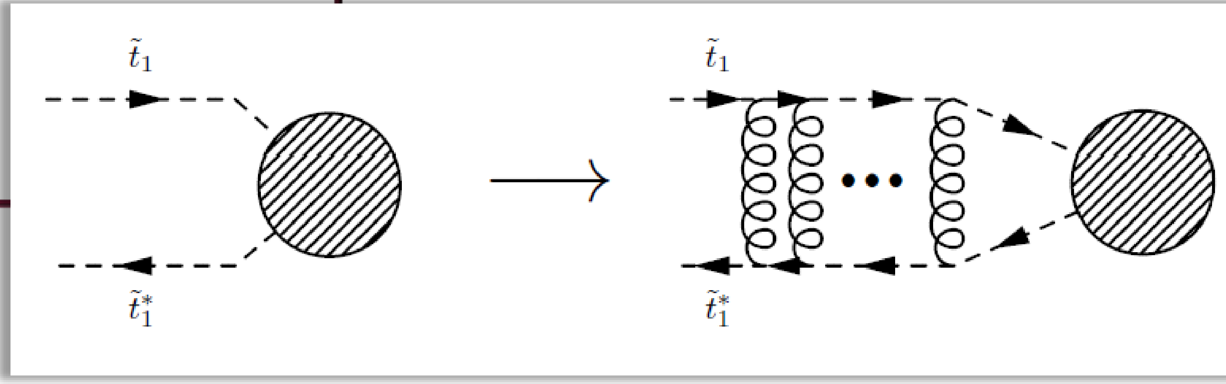
Stop Annihilation

Tree level





+ NLO corrections



+ Coulomb enhancement

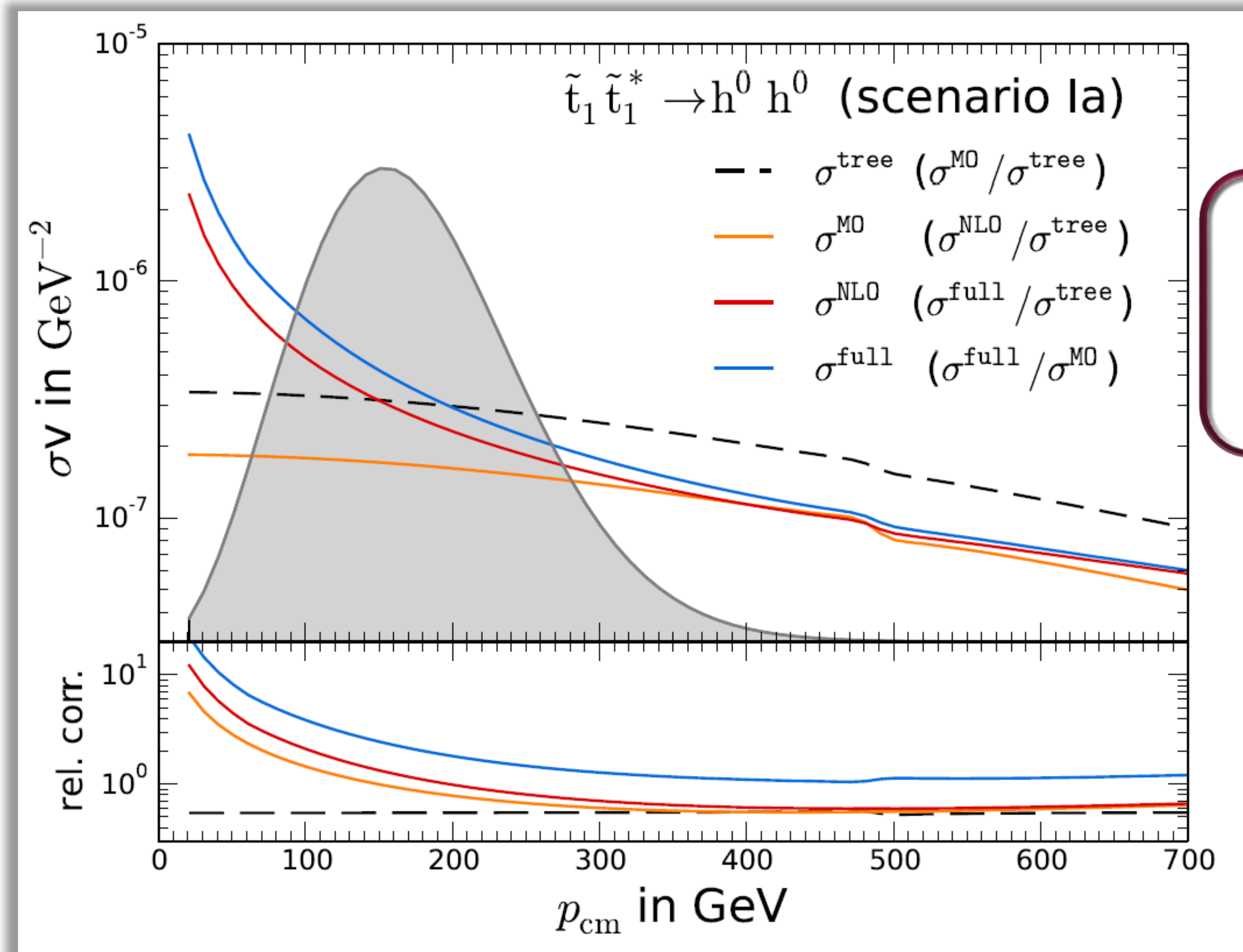
during freeze-out stops are moving slowly

⇨ contributions can become large
resummation necessary

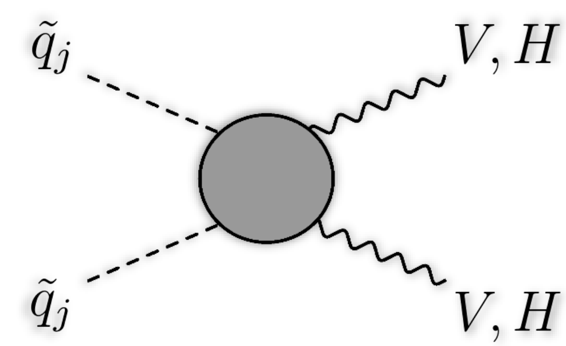
exchange of n gluons generates correction factor $\propto \left(\frac{\alpha_s}{v}\right)^n$

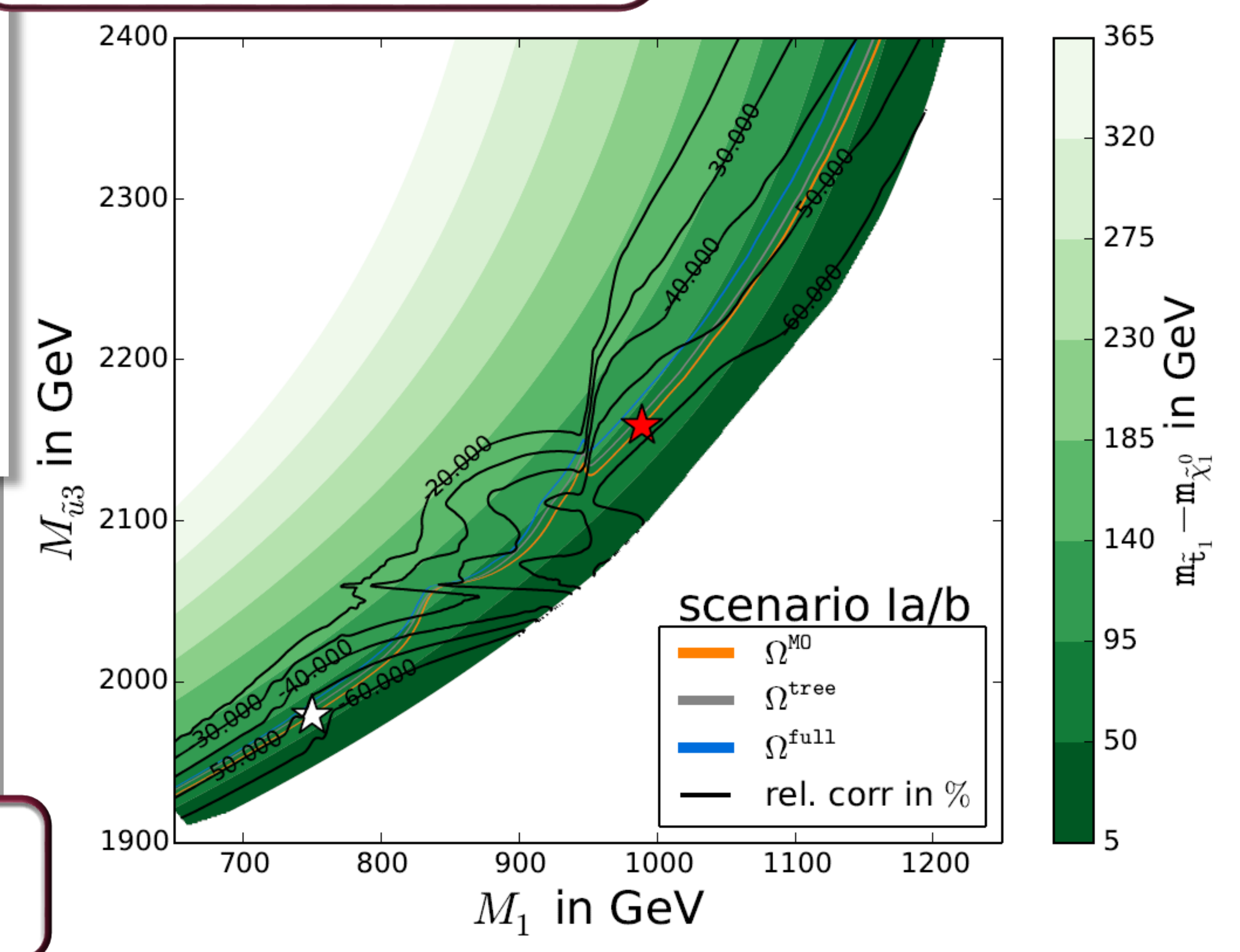
J. Harz, B. Herrmann, M. Klasen, K. Kovařík, and M. Meinecke, arXiv:1410.8063 [hep-ph]

Stop Annihilation



with 46.1 % $\tilde t_1 \tilde t_1^* \to hh$
dominant contribution





- small v: steep rise due to Coulomb corr.
- large corrections (~ 35% shift NLO/tree)

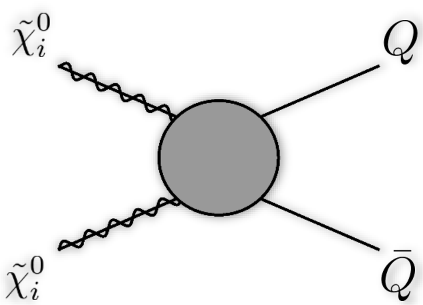
correction of ~ 50% on the relic density

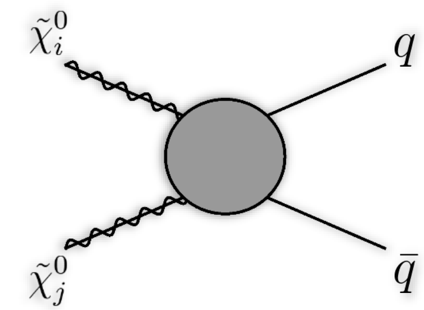
$m_{\tilde\chi^0_1}$	$m_{\tilde t_1}$	$m_{\tilde t_2}$	$m_{\tilde b_1}$	$m_{\tilde\chi^0_2}$	$m_{\tilde\chi^\pm_1}$	m_{h^0}	m_{H^0}	$m_{H^\pm}$	$\lvert Z_{\tilde\chi^0,1\tilde B}\rvert^2$	$\lvert Z_{\tilde t,1L}\rvert^2$	$\lvert Z_{\tilde t,1R}\rvert^2$	$\mathrm{BR}(b\to s\gamma)$	δa_μ	$\Omega_{\tilde\chi^0_1}h^2$
758.0	826.1	1435.1	1260.5	1986.7	1986.8	128.8	1917.4	1919.6	0.9996	0.27	0.74	$3.1\cdot 10^{-4}$	$284\cdot 10^{-11}$	0.1146

J. Harz, B. Herrmann, M. Klasen, K. Kovařík, M. Meinecke, arXiv:1410.8063 [hep-ph]

IV. Conclusions

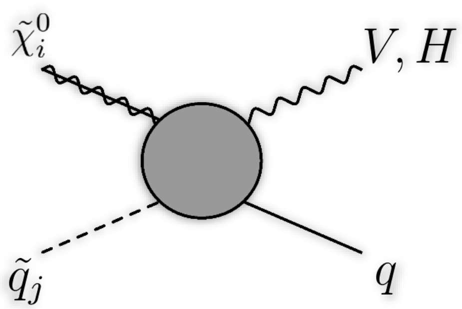
Conclusions & Outlook

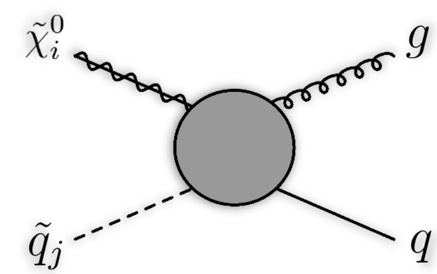




- current tools calculate relic density just on an (effective) tree level

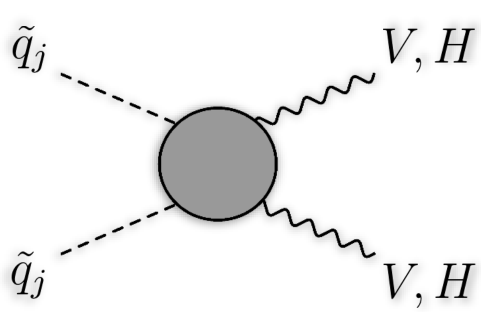
- we provide SUSY-QCD corrections to (almost) all processes

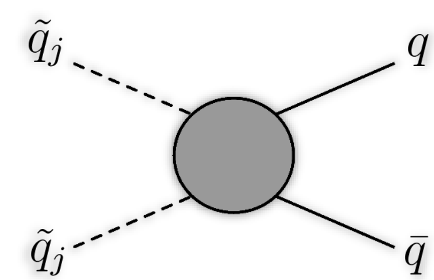




- significant corrections of 10% - 50% expected

- we provide tool linkable to MicrOMEGAs for precise parameter studies and global fits





DM@NLO

http://dmnlo.hepforge.org/

stay tuned :)

Merci beaucoup!

Vielen Dank!

Uncertainties Entering the Calculation

Arising from cosmology

- choice of cosmological model
  Hamann, Hannestad, et al. , Phys. Rev. D (2007)
- variation in hubble expansion rate
  Arbey, Mahmoudi, Phys. Lett. B (2008)
- effective degrees of freedom of the universe
  Hindmarsh, Philipsen, Phys. Rev. D (2005)

Arising from particle physics

- three-body processes
  Yaguna, Phys. Rev. D (2010)
- determination of mass parameters
  Allanach, Kraml, Porod, JHEP (2003)
  Allanch, Belanger, JHEP (2004)
  Belanger, Kraml, Porod, Phys. Rev. D (2005)
- precision of (co)annihilation cross
- section σ_{eff}

DM@NLO

Precision data from CMB measurements

PLANCK: ~ 2% uncertainty

Theoretical Prediction of Dark Matter Relic Density

- number density of DM in early universe can be described by Boltzmann equation

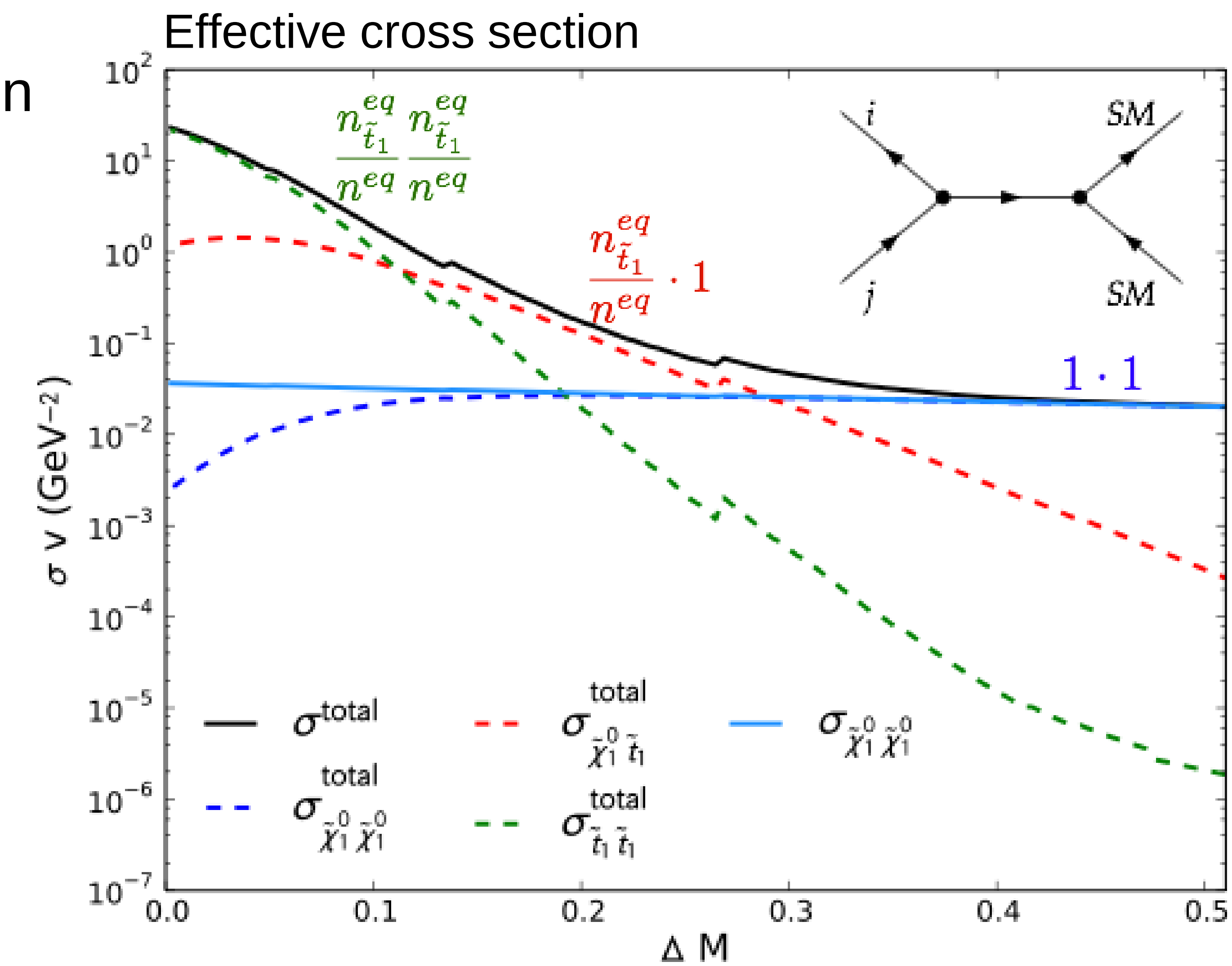
$$\dot{n} + 3Hn = -\langle\sigma_{\text{eff}}v\rangle(n^2 - n_{\text{eq}}^2)$$

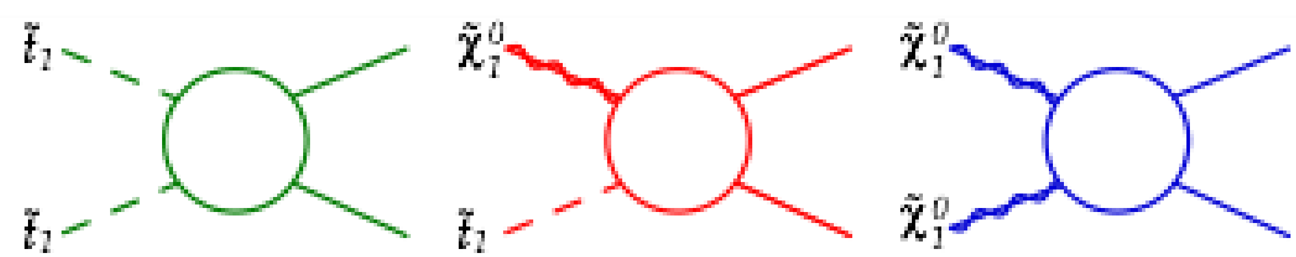
$$\langle\sigma_{\text{eff}}v\rangle = \sum_{ij}\langle\sigma_{ij}v_{ij}\rangle\frac{n_i^{eq}}{n^{eq}}\frac{n_j^{eq}}{n^{eq}}$$

$$\frac{n_i^{eq}}{n^{eq}} \propto \exp^{\frac{-(m_i-m_\chi)}{T}} = \exp^{\frac{-(m_i-m_\chi)}{x\ m_\chi}}$$

- assuming lightest stop being the NLSP

$$\Delta M = \frac{m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}}{m_{\tilde{\chi}_1^0}}$$





Interesting for the right Relic Density

- number density of DM in early universe can be described by Boltzmann equation

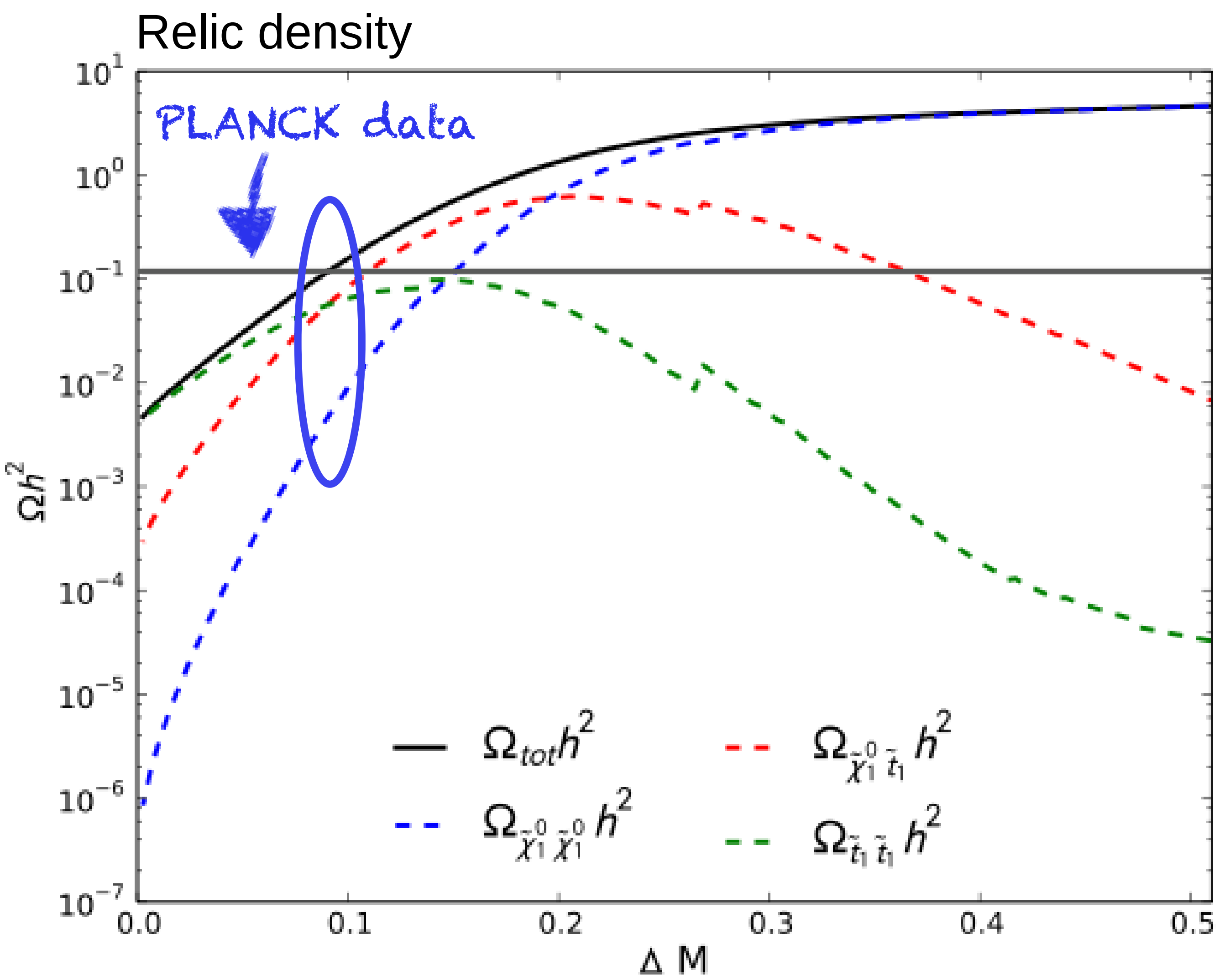
$$\dot{n} + 3Hn = -\langle\sigma_{\text{eff}\,v}\rangle(n^2 - n_{\text{eq}}^2)$$

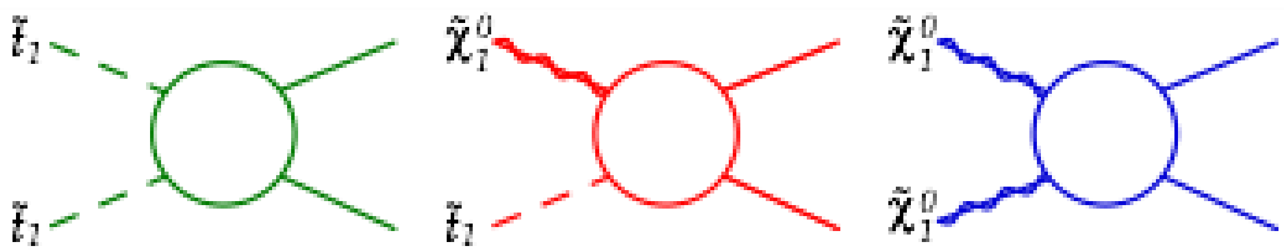
$$\langle\sigma_{\text{eff}}v\rangle = \sum_{ij}\langle\sigma_{ij}v_{ij}\rangle\frac{n_i^{eq}}{n^{eq}}\frac{n_j^{eq}}{n^{eq}}$$

$$\frac{n_i^{eq}}{n^{eq}} \propto \exp^{\frac{-(m_i-m_\chi)}{T}} = \exp^{\frac{-(m_i-m_\chi)}{x\ m_\chi}}$$

- assuming lightest stop being the NLSP

$$\Delta M = \frac{m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}}{m_{\tilde{\chi}_1^0}}$$

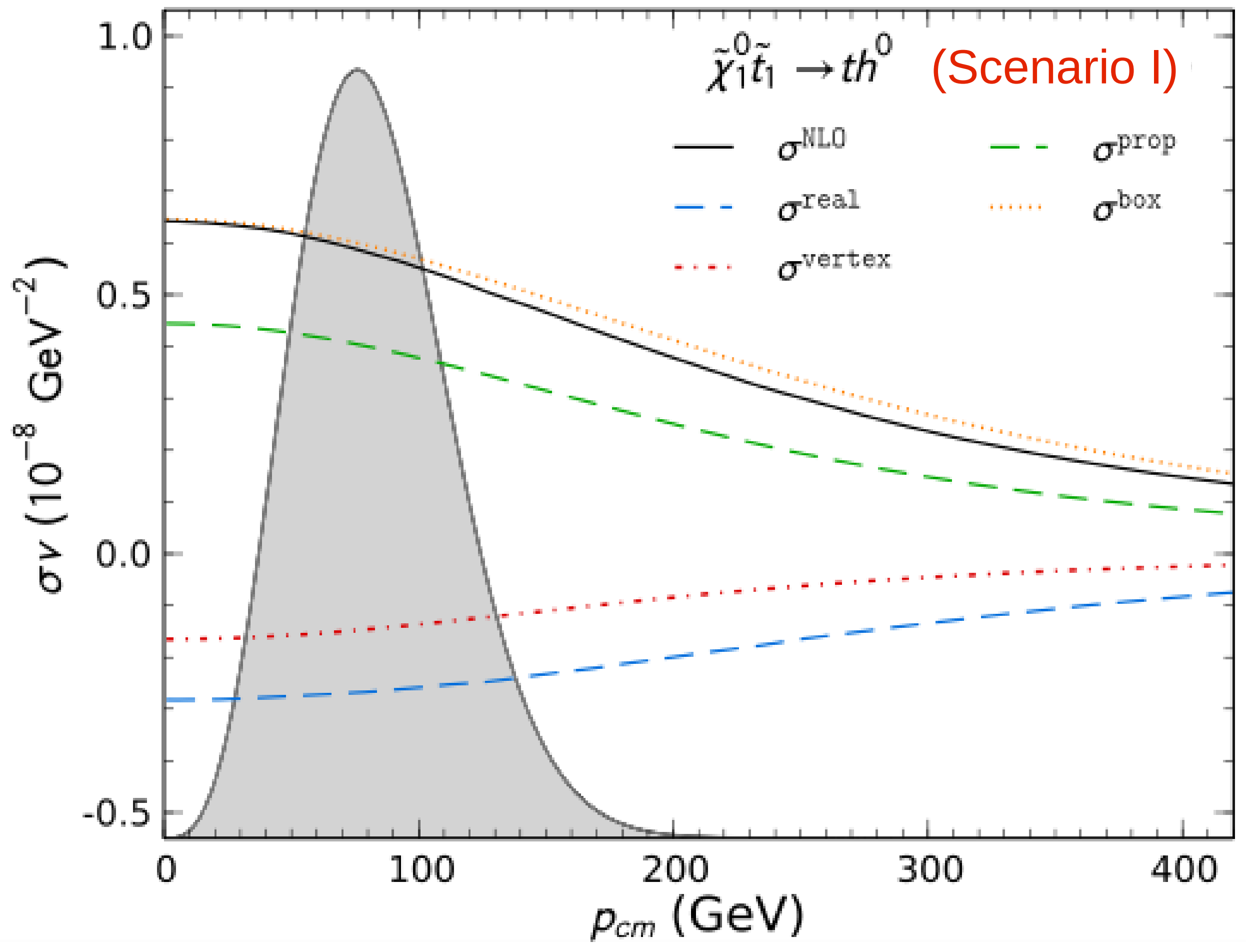


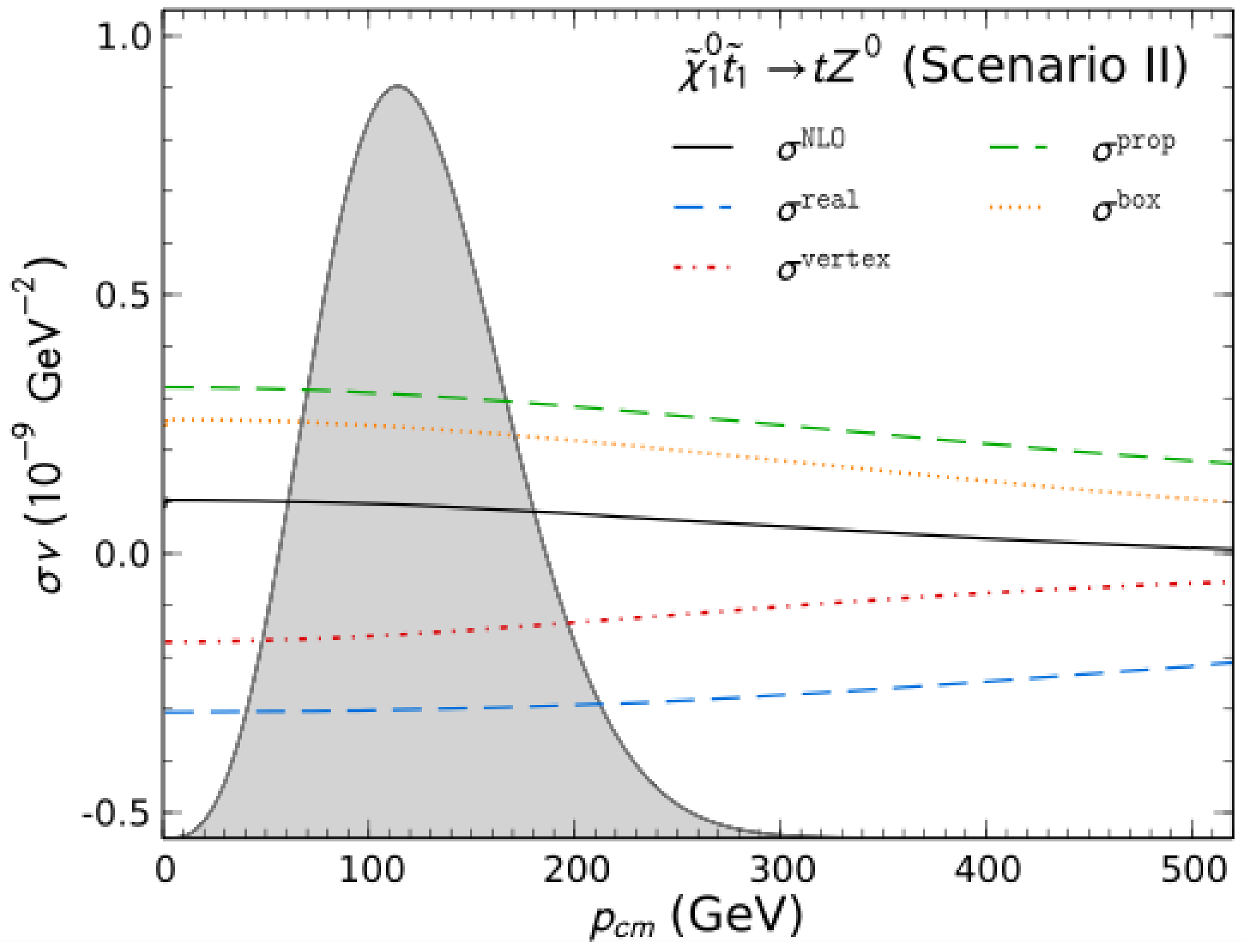


admixture of neutralino-stop coannihilation processes can be important to achieve the right relic abundance and not to overclose the universe

Interplay of Virtual and Real Corrections

- contribution of the different corrections to the total coannihilation cross section

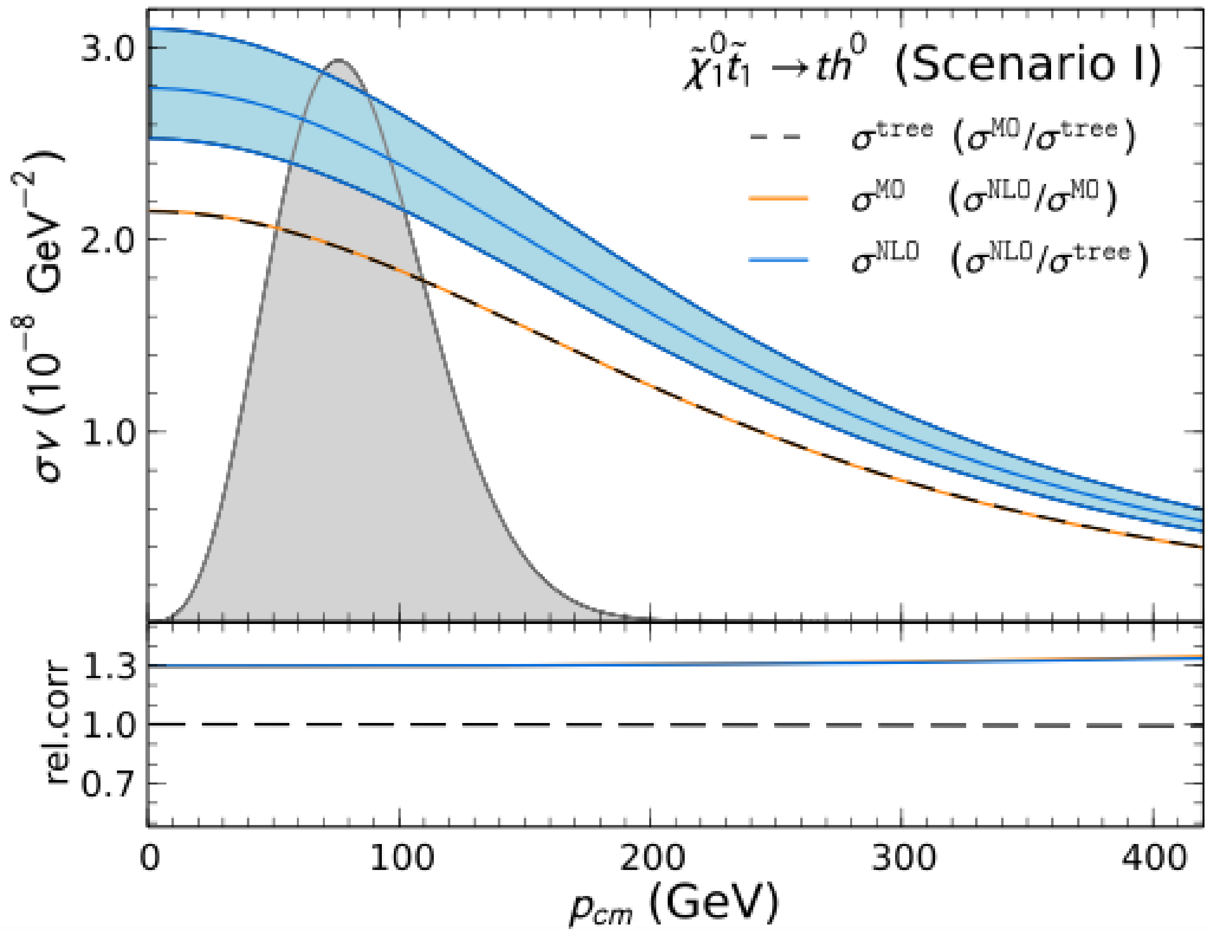


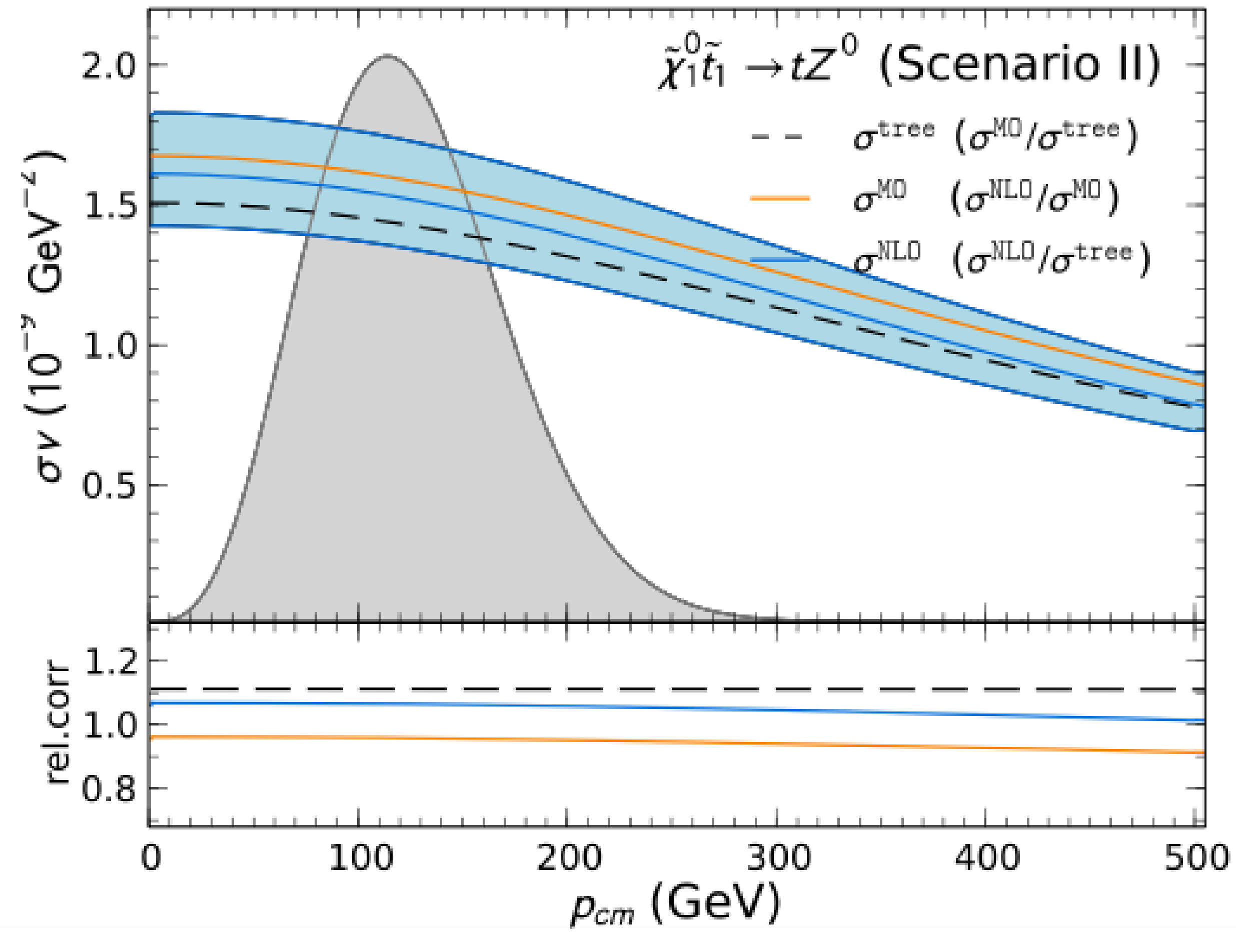


⇨ contributions still contain uncancelled logarithms

Scale Variation

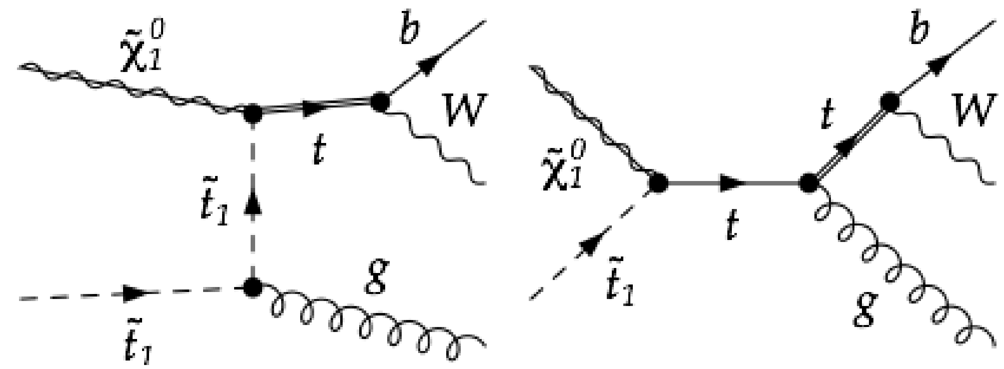
$$\frac{1}{2}\mu_R < \mu < 2\mu_R$$





Intermediate On-Shell States

- with $m_t > m_b + m_W$ an intermediate on-shell state can occur as soon as $\sqrt{s} > m_t$



- local on-shell subtraction (DS) / “Prospino“ scheme

W. Beenakker, R. Hoepker, M. Spira, P.M. Zerwas, Nuclear Physics B 492 (1997)

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{res}}|^2 - |\mathcal{M}_{\text{res}}^{\text{sub}}|^2 + 2Re(\mathcal{M}_{\text{res}}^* \mathcal{M}_{\text{rem}}) + |\mathcal{M}_{\text{rem}}|^2$$

- “counterterm” consists of Breit-Wigner weighted on-shell squared matrix element

$$|\mathcal{M}_{\text{res}}^{\text{sub}}|^2 = \frac{m_t^2 \Gamma_t^2}{(p_t^2 - m_t^2)^2 + m_t^2 \Gamma_t^2} |\mathcal{M}_{\text{res}}|^2_{p_t^2 = m_t^2}$$

- resonant propagators are regularized by Breit-Wigner propagator

⇒ consistent, width independent, gauge invariant treatment retaining interference terms