Phenomenology of Dark Matter — Precision Calculation and Minimal Models

Björn Herrmann

Laboratoire d'Annecy-le-Vieux de Physique Théorique (LAPTh)
Université Savoie Mont Blanc / CNRS

Graduiertenkolleg "Strong and Weak Interactions — from Hadrons to Dark Matter"
Graduate Days 2015 — 25 November 2015, Münster/Telgte

Curriculum Vitae

2000–2005	Studies of Physics Universität Karlsruhe and Université Joseph Fourier Grenoble Double diploma programme of Franco-German University
2005–2008	PhD thesis Université Joseph Fourier Grenoble, LPSC Grenoble Supervisor: Prof. Michael Klasen
2008–2010	Postdoctoral researcher Universität Würzburg, Institut für Theoretische Physik und Astrophysik Working group of Prof. Werner Porod
2010–2011	Young Investigator Group Leader Deutsches Elektronen Synchrotron (DESY) Hamburg Excellence Initiative "Connecting particles with the cosmos"
since 2011	Maître de Conférences (tenured assistant professor) Université Savoie Mont Blanc, LAPTh Annecy-le-Vieux
since 2015	Organizer of the "PhysTeV Les Houches" workshop series (with Fawzi Boudjema and Diego Guadagnoli)

Flavour violation in supersymmetric theories

— Constraints on the NMFV MSSM parameter space

K. De Causmaecker, B. Fuks, B. Herrmann, N. Mahmoudi, B. O'Leary, W. Porod, S, Sekmen, N. Strobbe — arXiv:1509.05414

— Signatures of non-minimal squark flavour violation at the LHC

A. Bartl, H. Eberl, B. Herrmann, K. Hidaka, W. Majerotto, W. Porod — PLB 698 (2011) — arXiv:1007.5483
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M. Bruhnke, B. Herrmann, W. Porod — JHEP 1009 (2010) — arXiv:1007.2100

— Reconstruction of the squark sector of the MSSM at the LHC

B. Herrmann, W. Porod — *in progress*

— Footprints of *SU(5)*-like unification in observables at the LHC

S. Fichet, B. Herrmann, Y. Stoll — PLB 742 (2015) — arXiv:1403.3397
S. Fichet, B. Herrmann, Y. Stoll — JHEP 1505 (2015) — arXiv:1501.05307
Y. Stoll, B. Herrmann, S. Fichet — *to be published*

Two Higgs Doublet Models (*e.g.* Inert Doublet Model)

— Constraints from dark matter, Higgs boson, vacuum stability

A. Goudelis, B. Herrmann, O. Stal — JHEP 1309 (2013) — arXiv:1303.3010

— Constraints from LHC searches

G. Bélanger, B. Dumont, A. Goudelis, B. Herrmann, S. Kraml, D. Sengupta — PRD 91(2015) — arXiv:1503.07367

Precision calculations for dark matter annihilation…

Minimal models for dark matter (and more)…

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Minimal models for dark matter (and more)…

→ next 20-25 minutes...

DM@NLO

Predicting the dark matter relic density more precisely

http://dmnlo.hepforge.org

DM@NLO — Collaboration

Universität Münster

Sonja Esch, Oleh Fedkevych,
Michael Klasen, Karol Kovařík,
Saskia Schmiemann, Patrick Steppeler

Westfälische Wilhelms-Universität Münster

Graduiertenkolleg 2149
Research Training Group

LAPTh Annecy-le-Vieux

Björn Herrmann

LAPTh — Université Savoie Mont Blanc — cnrs

LPTHE Paris

Julia Harz

ILP — UPMC Sorbonne Universités — cnrs

http://dmnlo.hepforge.org

The Minimal Supersymmetric Standard Model (MSSM)

SM Particles		Spin		Spin		Superpartners
Quarks	$(u_L \;\; d_L)$	$1/2$	Q	0	$(\tilde{u}_L \;\; \tilde{d}_L)$	Squarks
	$u_R^\dagger$	$1/2$	$\bar{u}$	0	$\tilde{u}_R^*$	
	$d_R^\dagger$	$1/2$	$\bar{d}$	0	$\tilde{d}_R^*$	
Leptons	$(\nu \;\; e_L)$	$1/2$	L	0	$(\tilde{\nu} \;\; \tilde{e}_L)$	Sleptons
	$e_R^\dagger$	$1/2$	$\bar{e}$	0	$\tilde{e}_R^*$	
Higgs	$(H_u^+ \;\; H_u^0)$	0	H_u	$1/2$	$(\tilde{H}_u^+ \;\; \tilde{H}_u^0)$	Higgsinos
	$(H_d^0 \;\; H_d^-)$	0	H_d	$1/2$	$(\tilde{H}_d^0 \;\; \tilde{H}_d^-)$	
W bosons	$W^0, W^\pm$	1		$1/2$	$\tilde{W}^0, \tilde{W}^\pm$	Winos
B boson	B^0	1		$1/2$	$\tilde{B}^0$	Bino
Gluon	g	1		$1/2$	$\tilde{g}$	Gluino
Graviton	G	2		$3/2$	$\tilde{G}$	Gravitino

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Higgs	$(H_u^+ \;\; H_u^0)$	0	H_u	$1/2$	$\tilde{\chi}^0_{1,2,3,4}$	Neutralinos
	$(H_d^0 \;\; H_d^-)$	0	H_d			
W bosons	$W^0, W^\pm$	1		$1/2$	$\tilde{\chi}^\pm_{1,2}$	Charginos
B boson	B^0	1				
Gluon	g	1		$1/2$	$\tilde{g}$	Gluino
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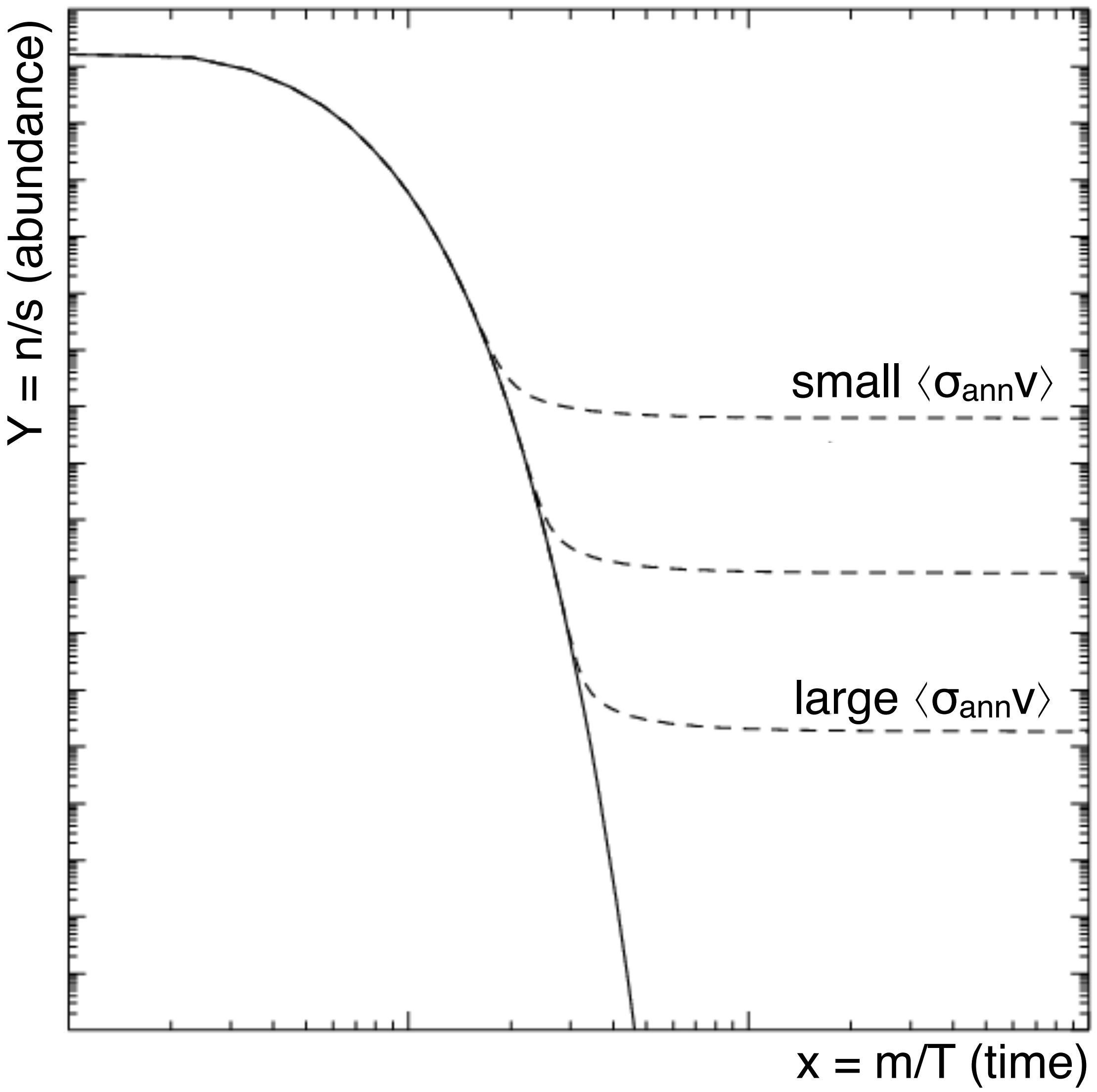
Lightest neutralino is dark matter (WIMP) candidate “par excellence”

$$\tilde{\chi}^0_1 \;=\; Z_{1\tilde{B}}\tilde{B} + Z_{1\tilde{W}}\tilde{W} + Z_{1\tilde{H}_1}\tilde{H}_1 + Z_{1\tilde{H}_2}\tilde{H}_2$$

Dark matter relic abundance — freeze-out picture



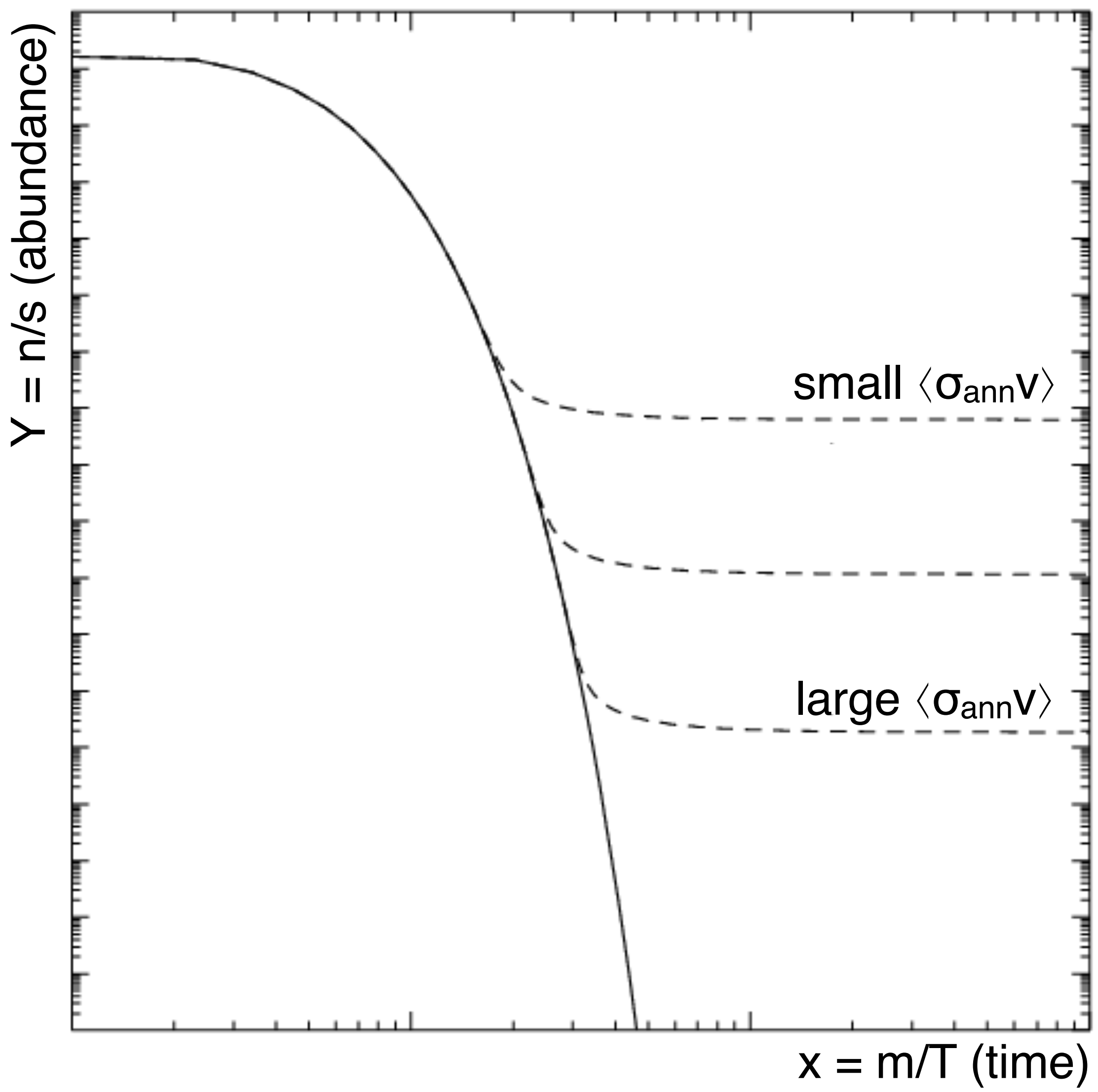
Time evolution of number density of the relic particle described by Boltzmann equation

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

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

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

Dark matter relic abundance — freeze-out picture



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(dis)favoured parameter regions…?

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

Dark matter relic abundance very precisely known

Planck collaboration 2015

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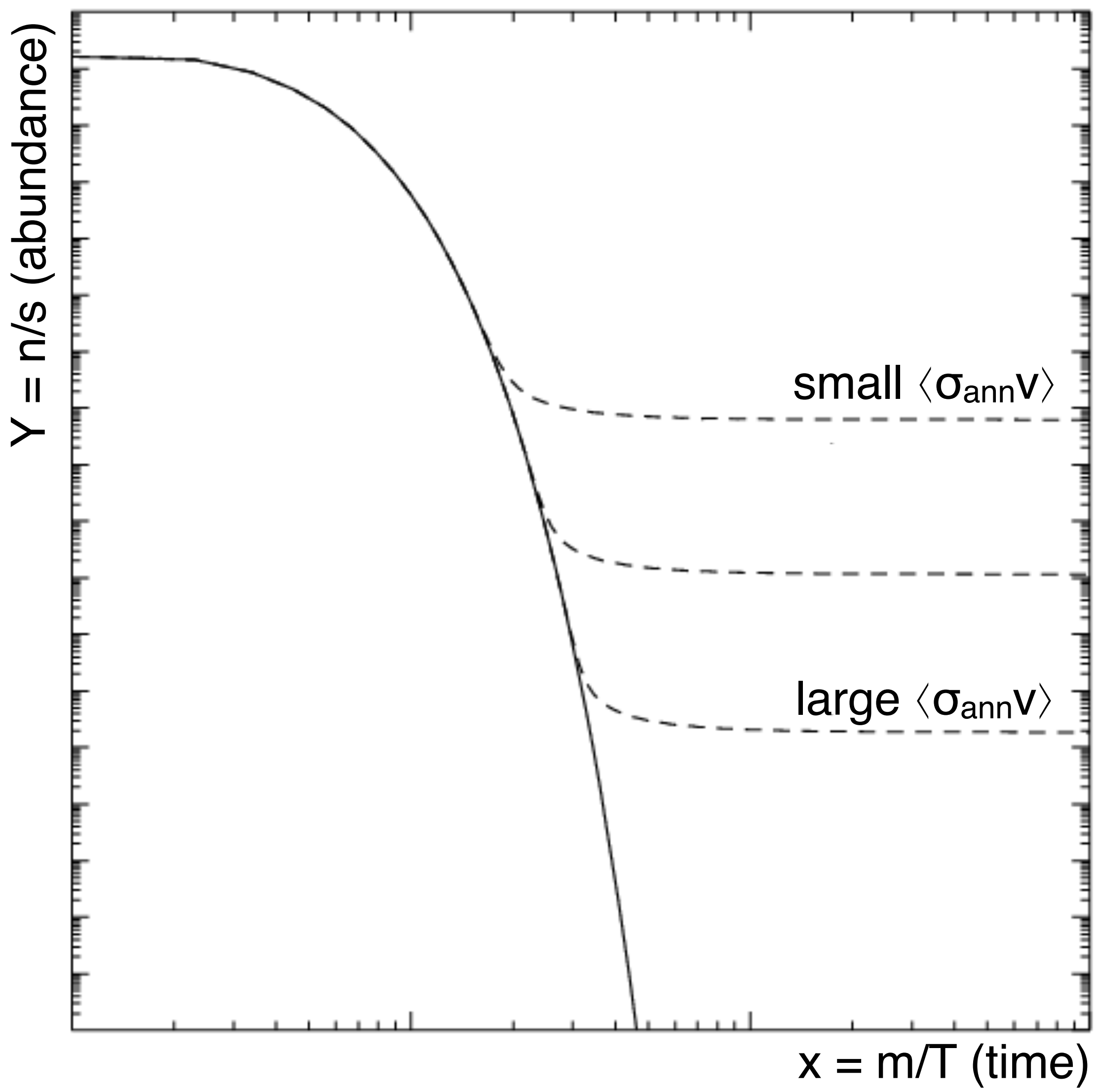

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Dark matter relic abundance very precisely known

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.* 2004-2015, **micrOMEGAs** Bélanger, Boudjema, Pukhov *et al.* 2003-2015, …

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

Cross-section in Boltzmann equation includes the sum over all relevant processes

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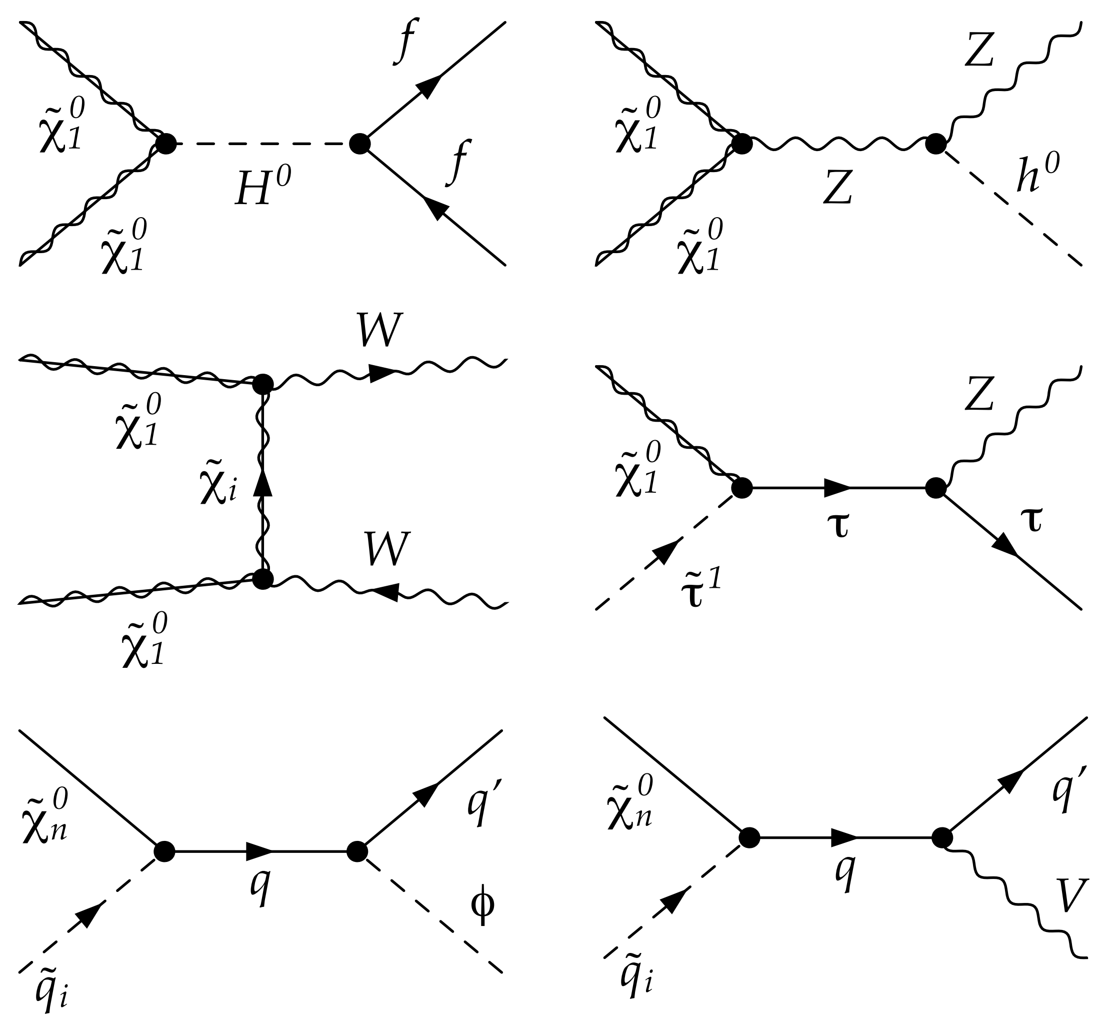
$$\langle \sigma_{\mathrm{ann}} v \rangle = \sum_{i,j} \sigma_{ij} v_{ij} \frac{n_i^{\mathrm{eq}}}{n_\chi^{\mathrm{eq}}} \frac{n_j^{\mathrm{eq}}}{n_\chi^{\mathrm{eq}}}$$



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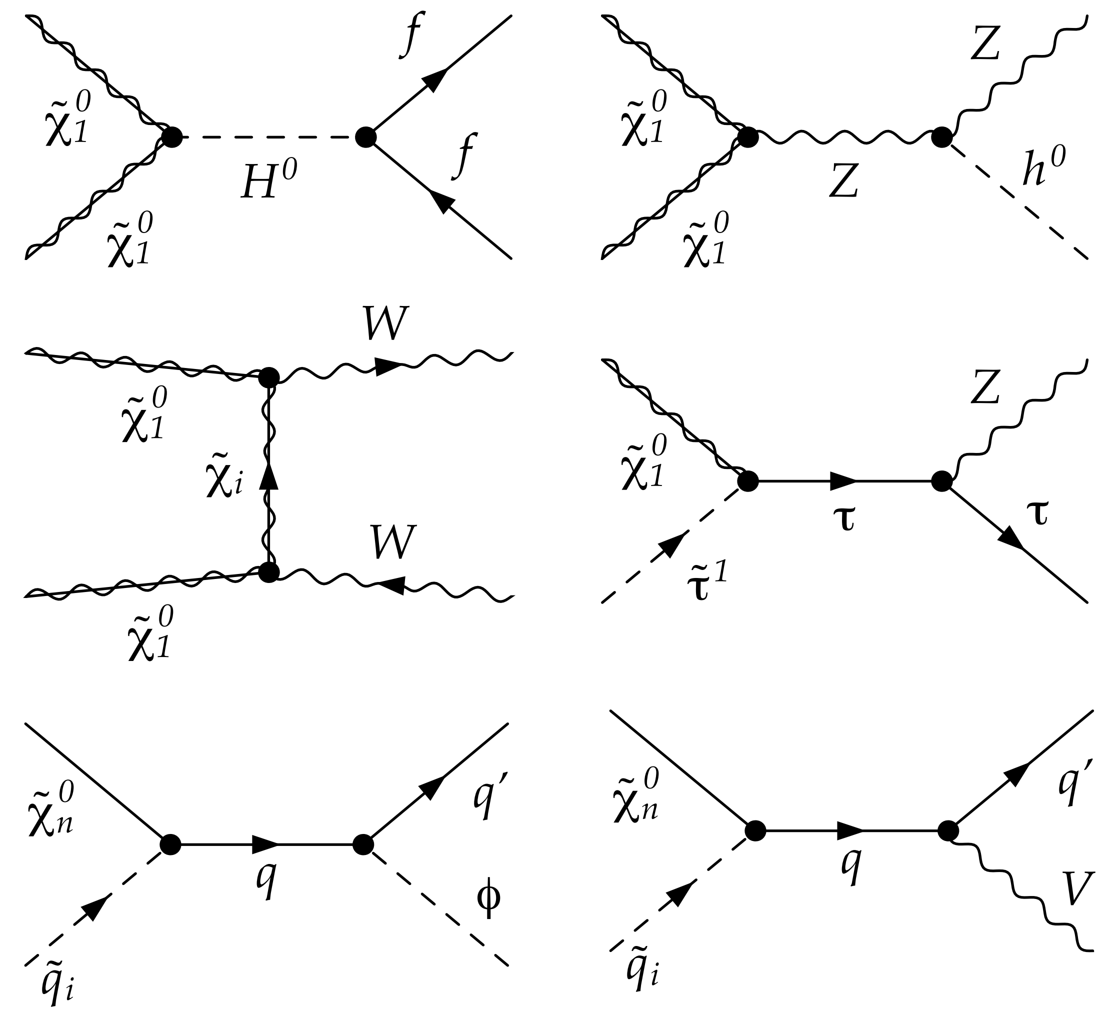
$$\frac{n_i^{\mathrm{eq}}}{n_\chi^{\mathrm{eq}}} \sim \exp\left\{-\frac{m_i - m_\chi}{T}\right\}$$

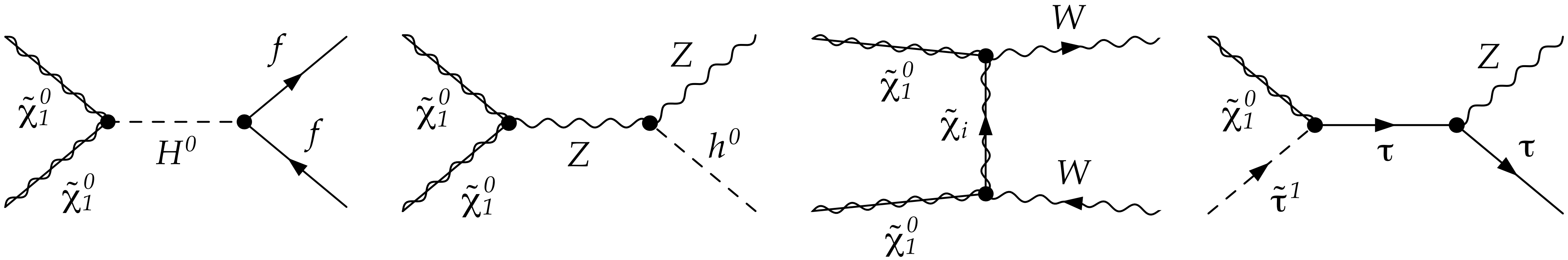


Only co-annihilations with almost mass-degenerate particles are numerical relevant

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**



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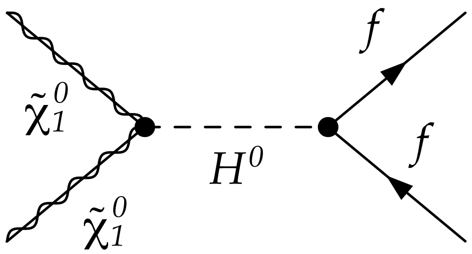
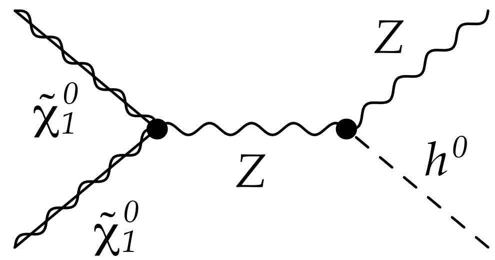
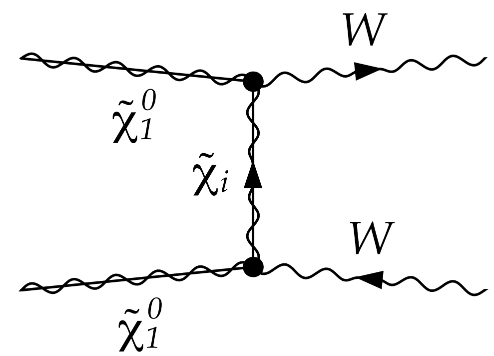
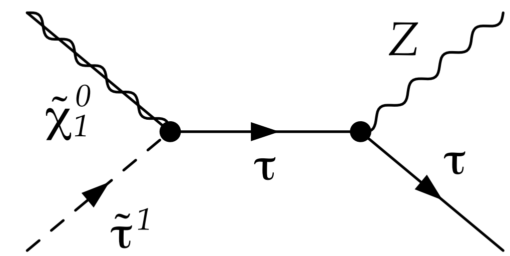




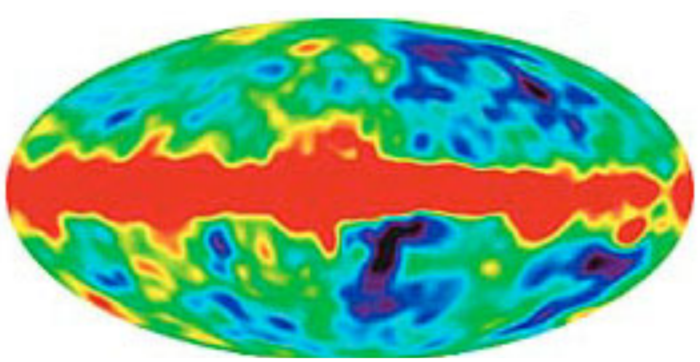




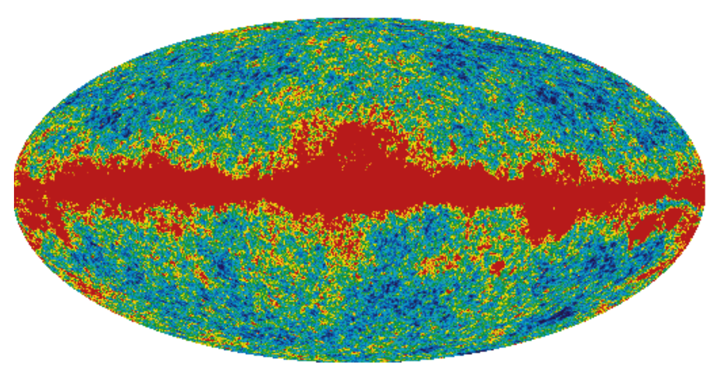
Higher-order loop corrections can give important contributions to cross-sections

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

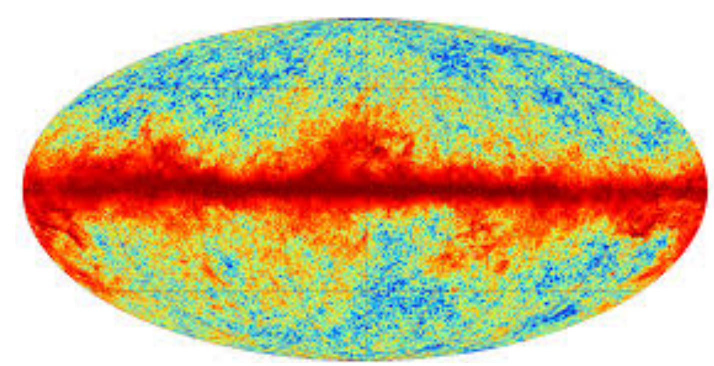
More precise theoretical predictions needed to keep up with experimental improvements



COBE 1989



WMAP 2002



Planck 2013

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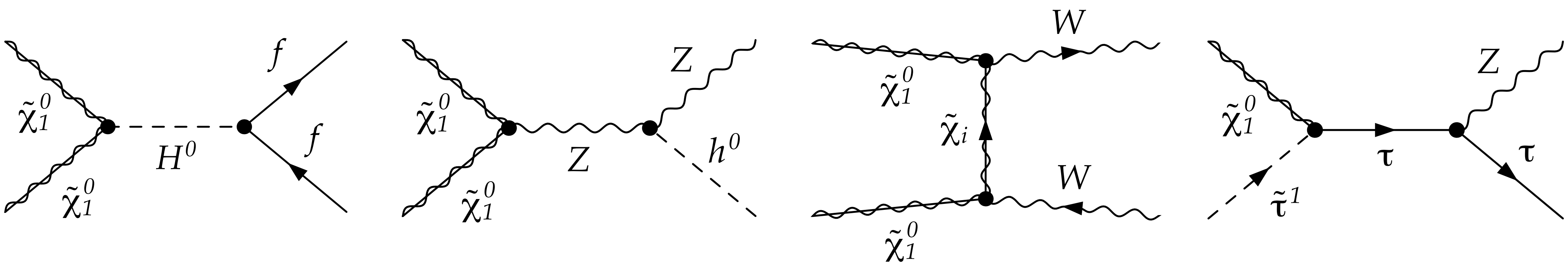

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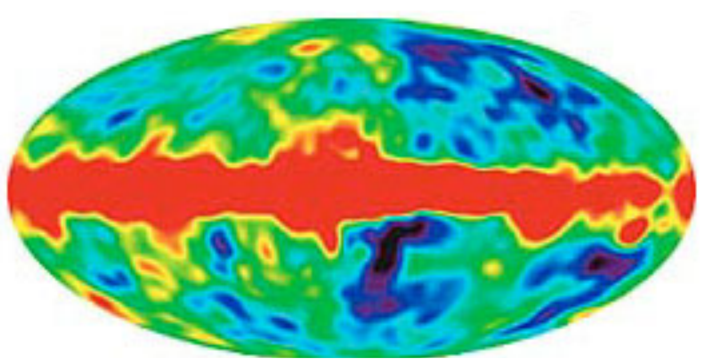

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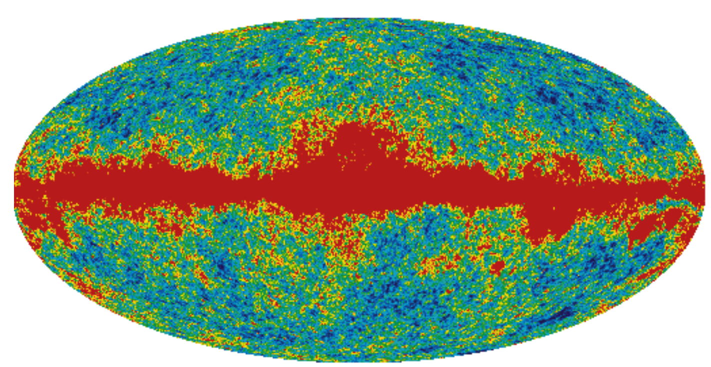

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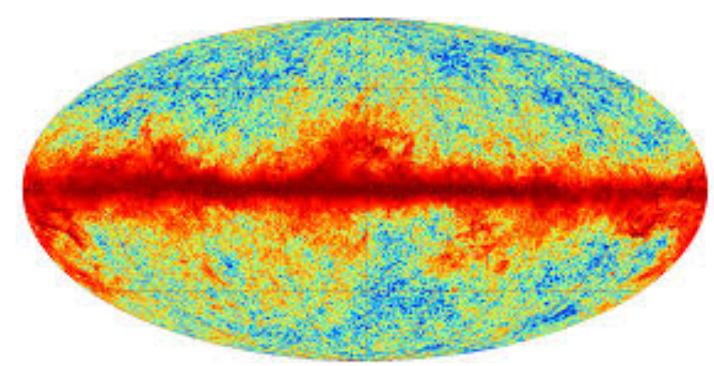
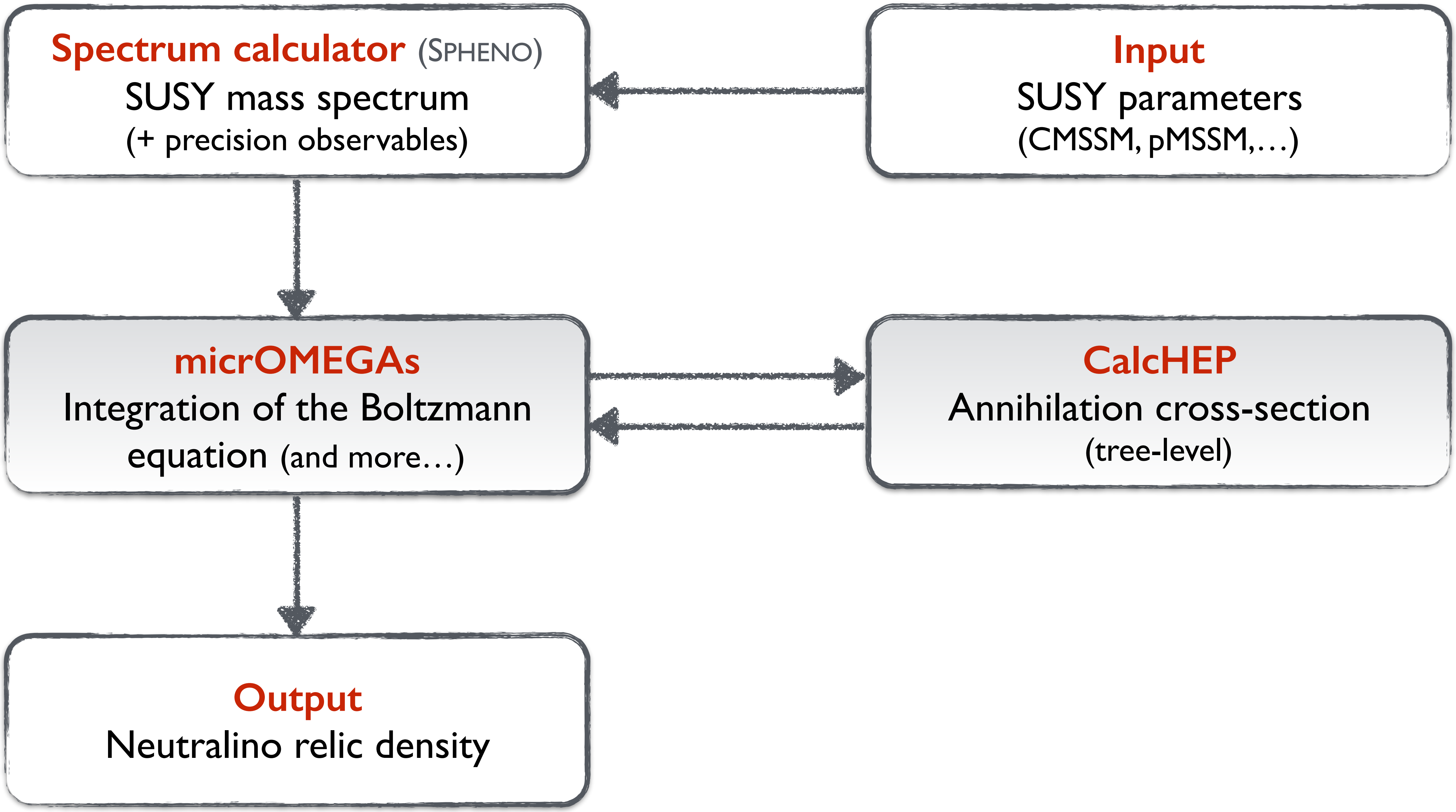


Planck 2013

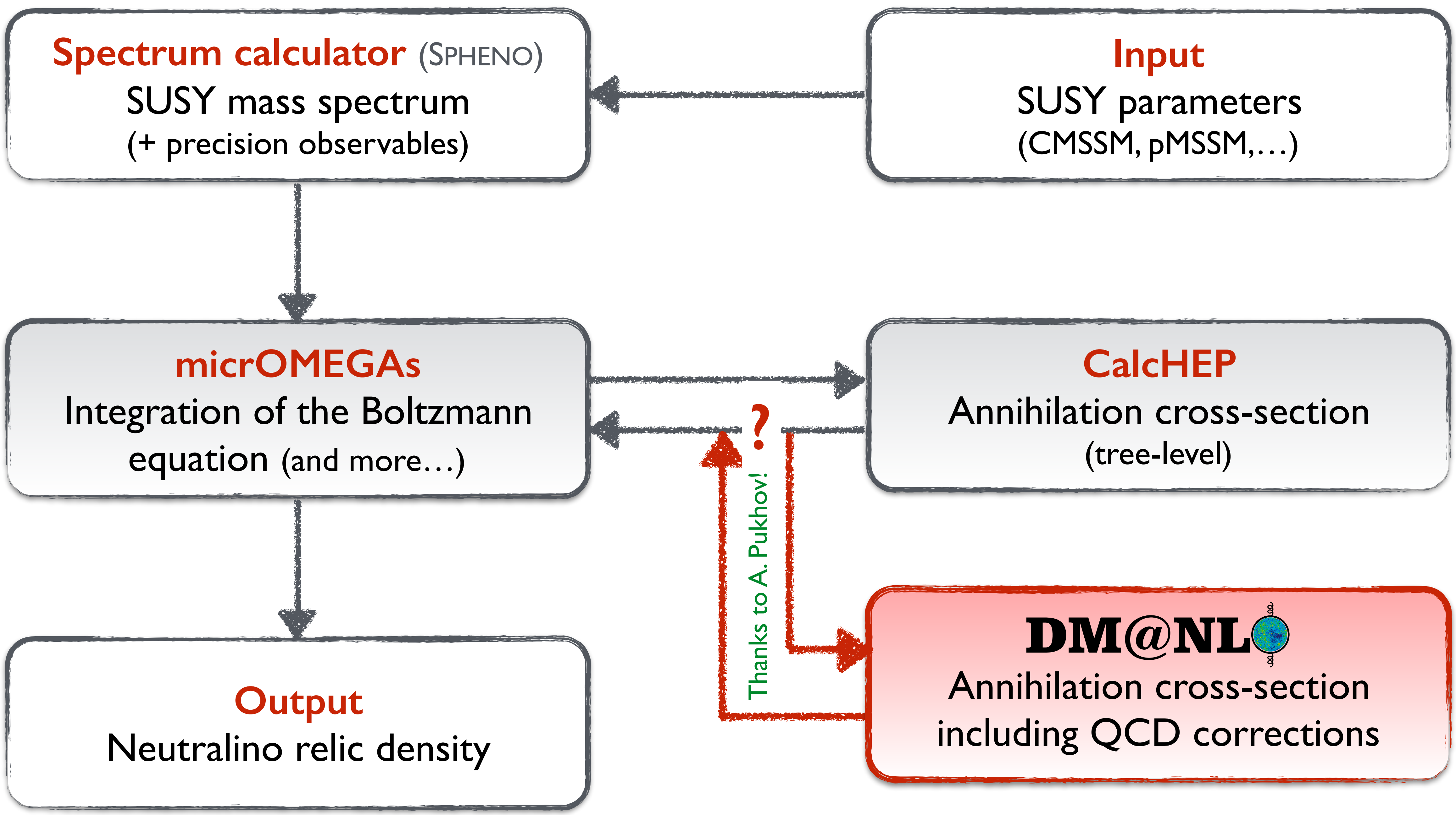
DM@NLO project — **Provide calculation of σ_{ann} including QCD corrections**

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

DM@NLO — Setup


Spectrum calculator (SPHENO)
SUSY mass spectrum
(+ precision observables)
Input
SUSY parameters
(CMSSM, pMSSM,…)
micrOMEGAs
Integration of the Boltzmann
equation (and more…)
CalcHEP
Annihilation cross-section
(tree-level)
Output
Neutralino relic density

DM@NLO — Setup



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?
Thanks to A. Pukhov!
DM@NLO
Annihilation cross-section including QCD corrections
Output
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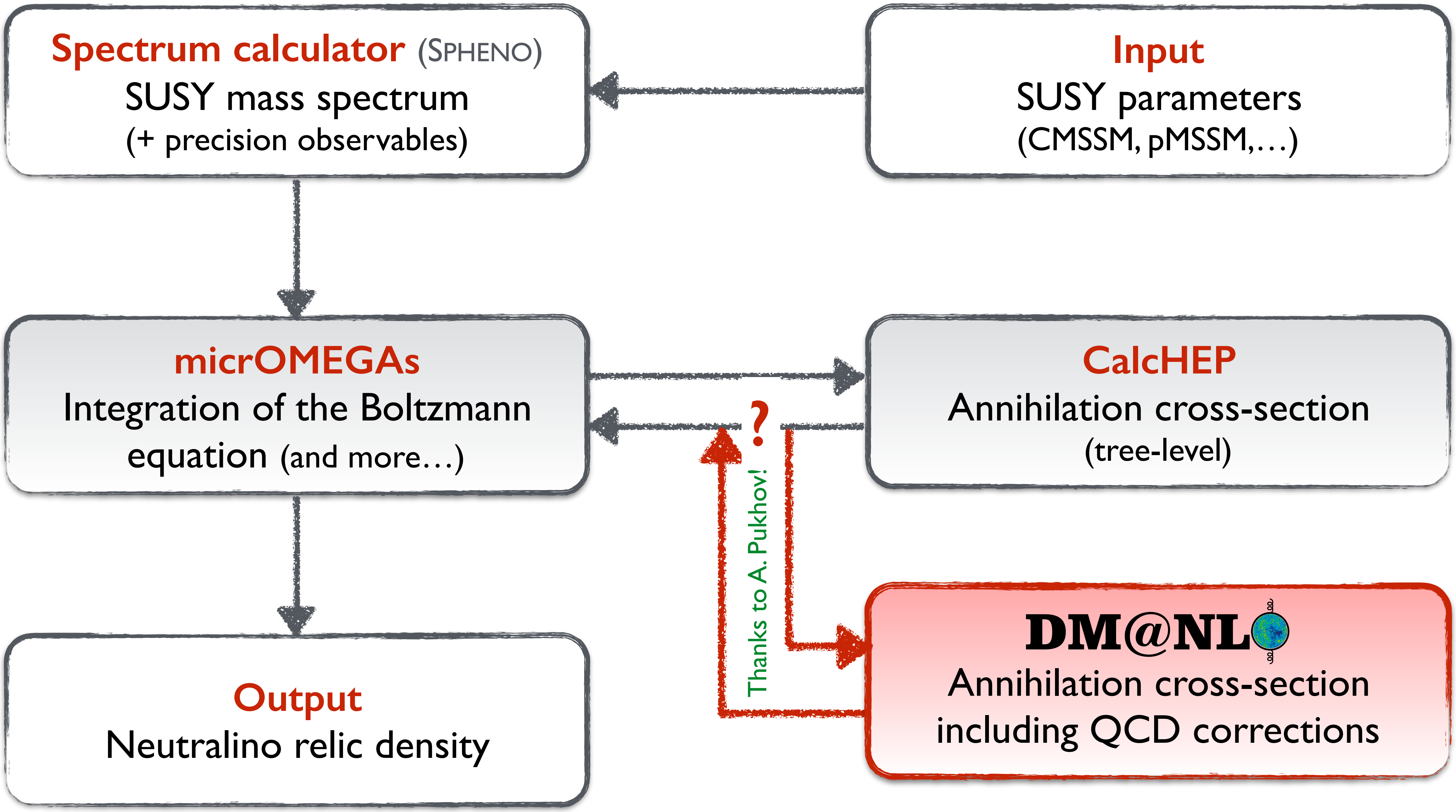
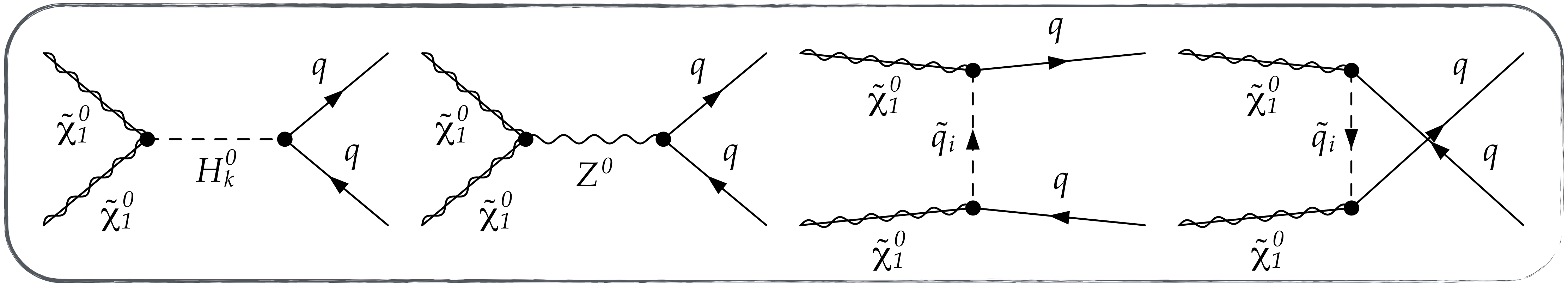


Similar setup for use with DarkSUSY in development.

J. Edsjö, B. Herrmann, C. Niblaeus — *in progress…*

Gaugino pair annihilation into quarks



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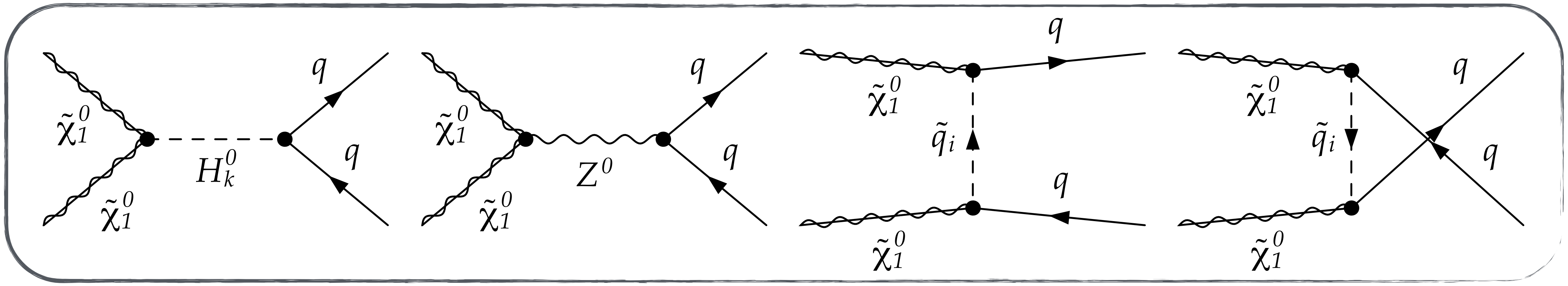
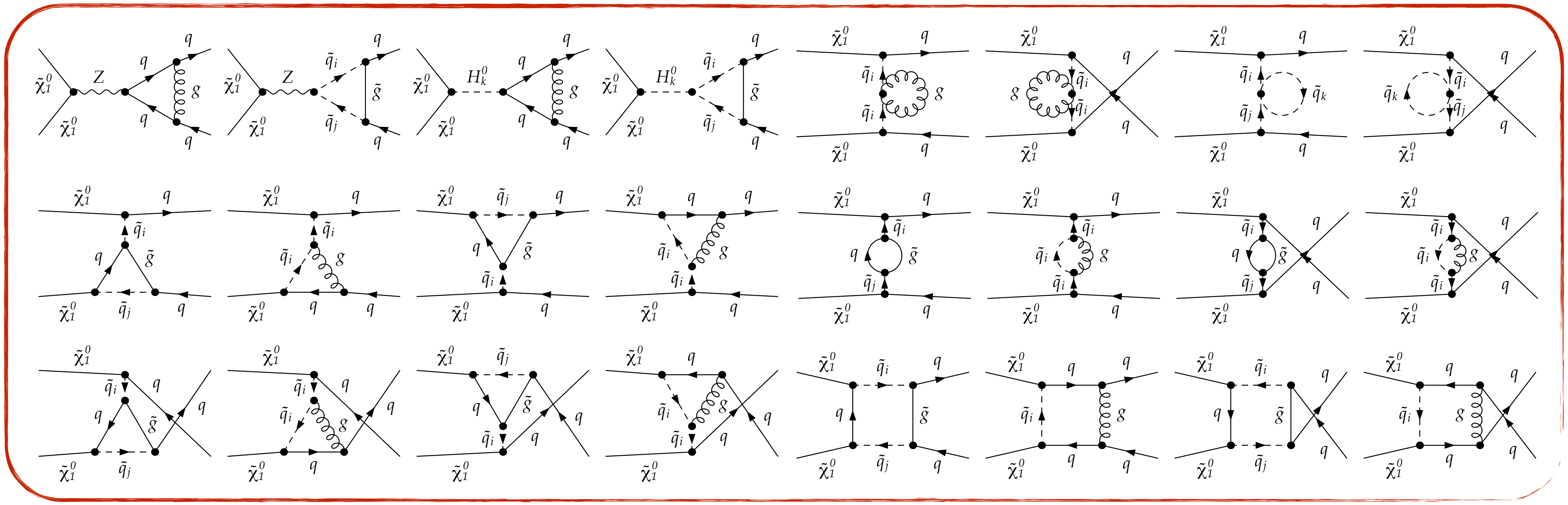


Loop corrections



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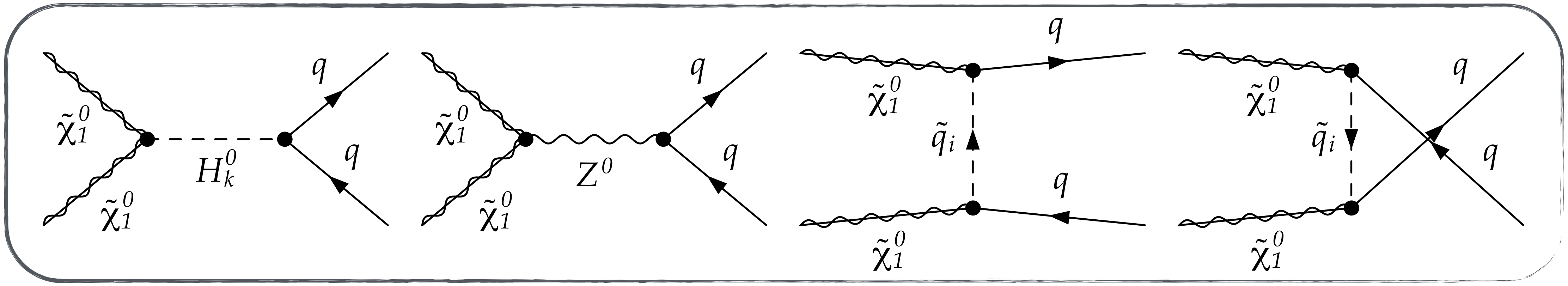

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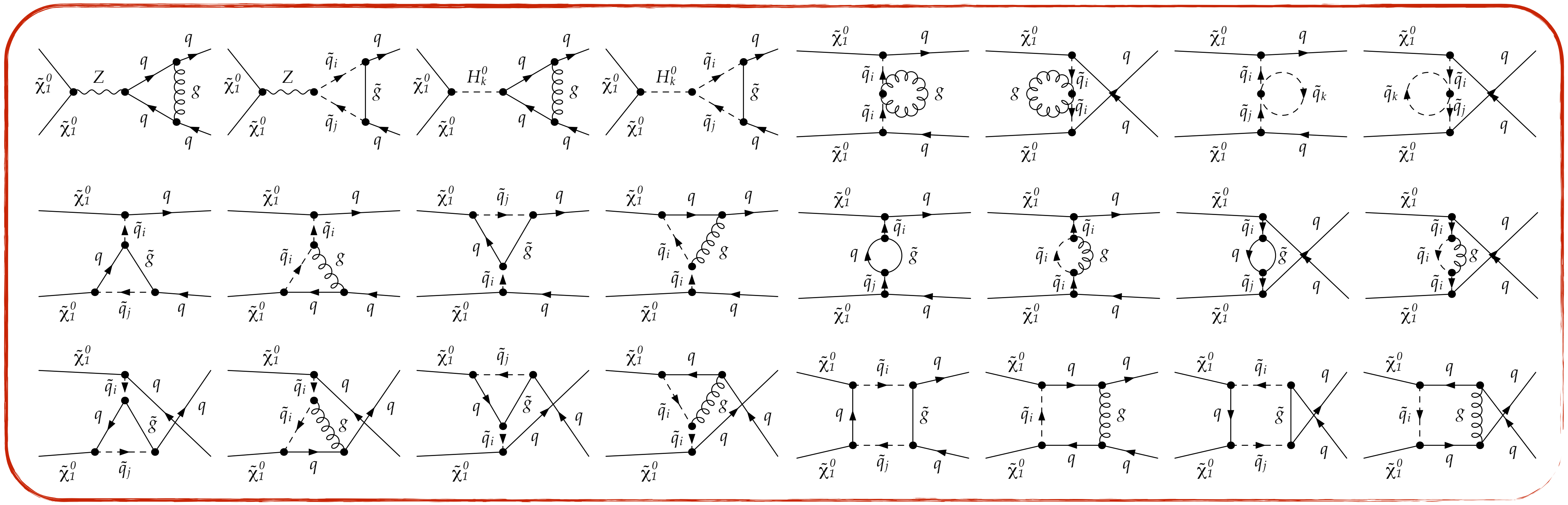
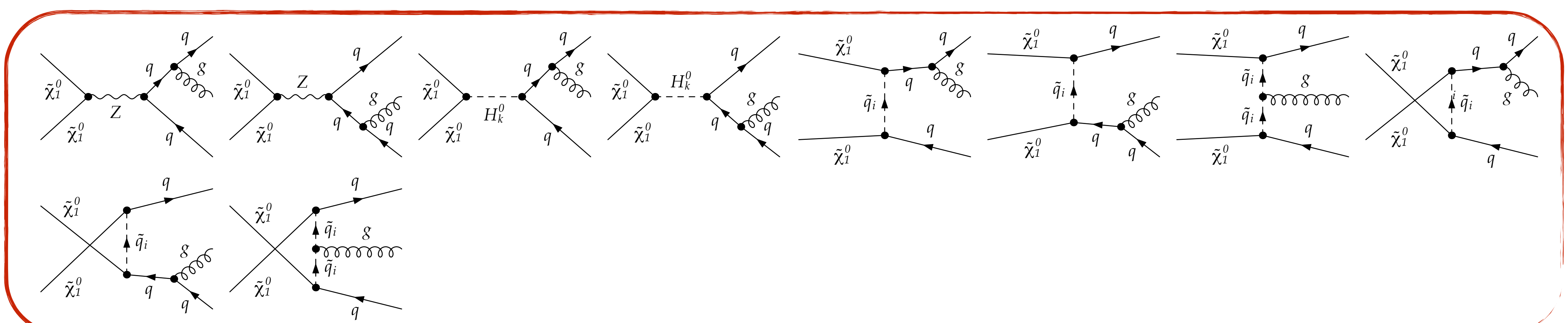


Real emission



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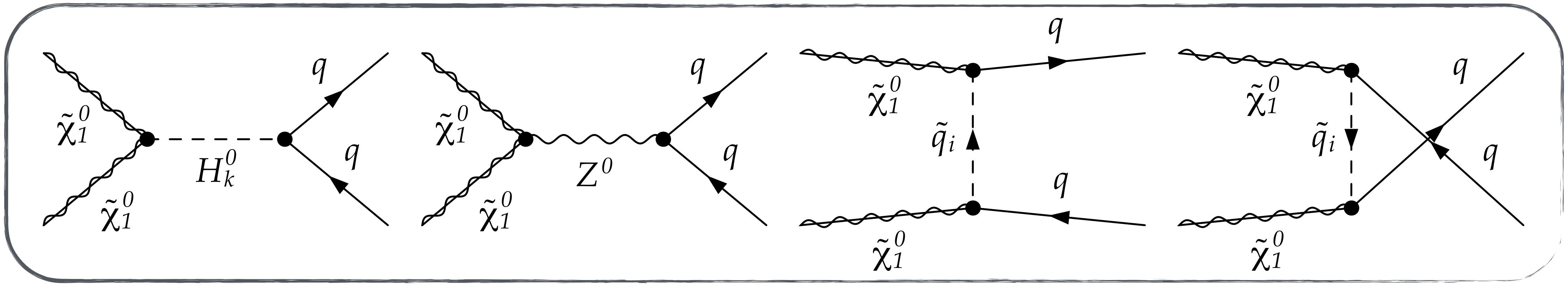

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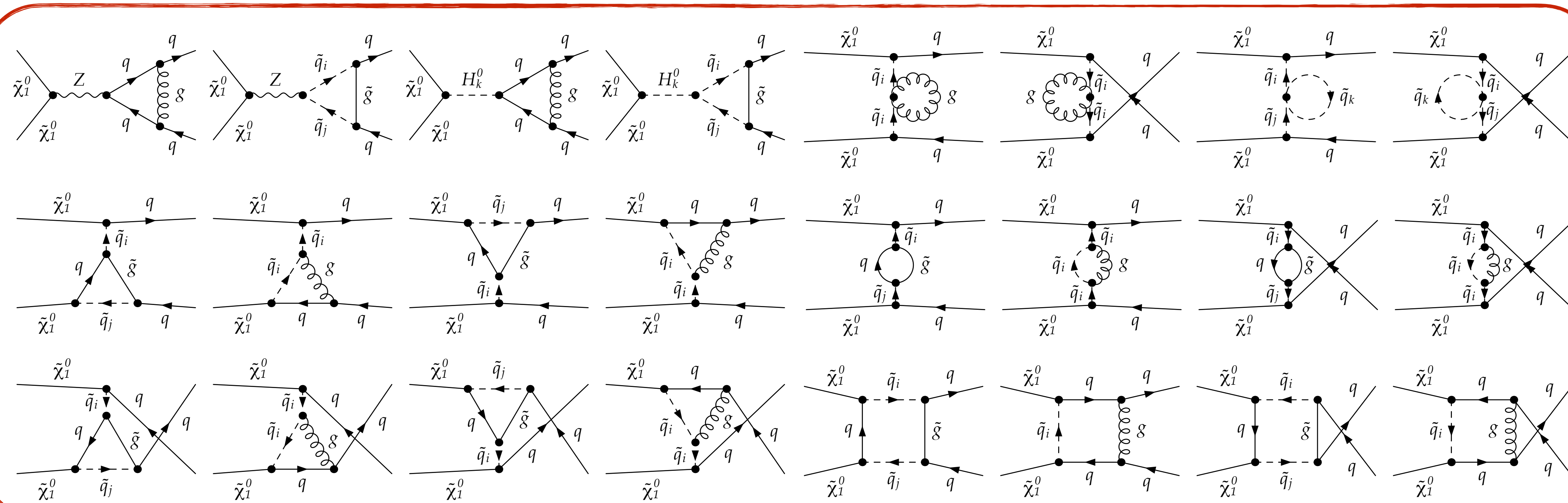

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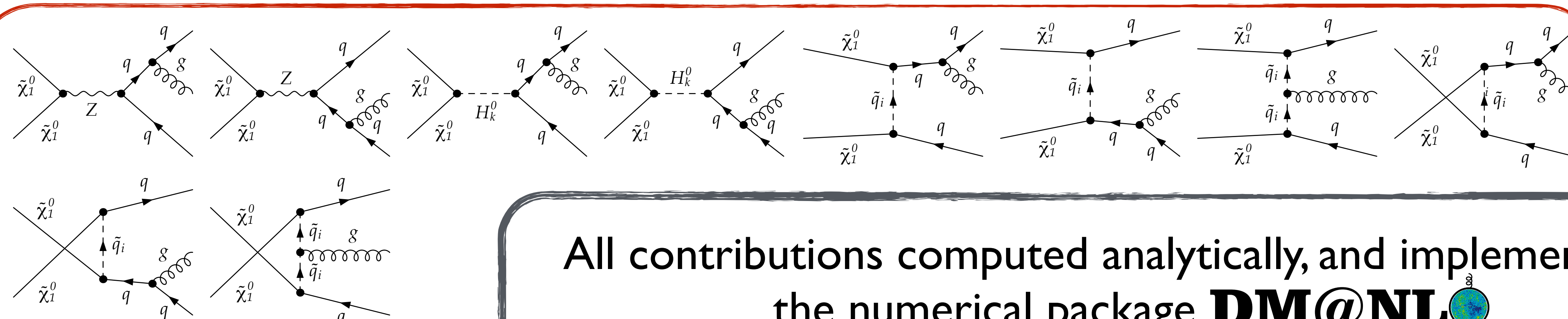

Herrmann, Klasen (2007); Herrmann, Klasen, Kovarik (2009),
Herrmann, Klasen, Kovarik, Meinecke, Steppeler (2013)

All contributions computed analytically, and implemented in the numerical package **DM@NLO**
(goal: extension to existing dark matter codes)

Interlude — a few technical details

Loop diagrams include UV-divergent integrals → **Renormalization!**

Hybrid on-shell/$\overline{\text{DR}}$ renormalization scheme for the squark sector (3rd generation), which is applicable to all (co)annihilation processes

A_t, A_b

$m_{\tilde{t}_1}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$

Independent "input" parameters

→

$M^2_{\tilde{Q}}, M^2_{\tilde{U}}, M^2_{\tilde{D}}$

$m_{\tilde{t}_2}, \theta_{\tilde{t}}, \theta_{\tilde{b}}$

Dependent parameters

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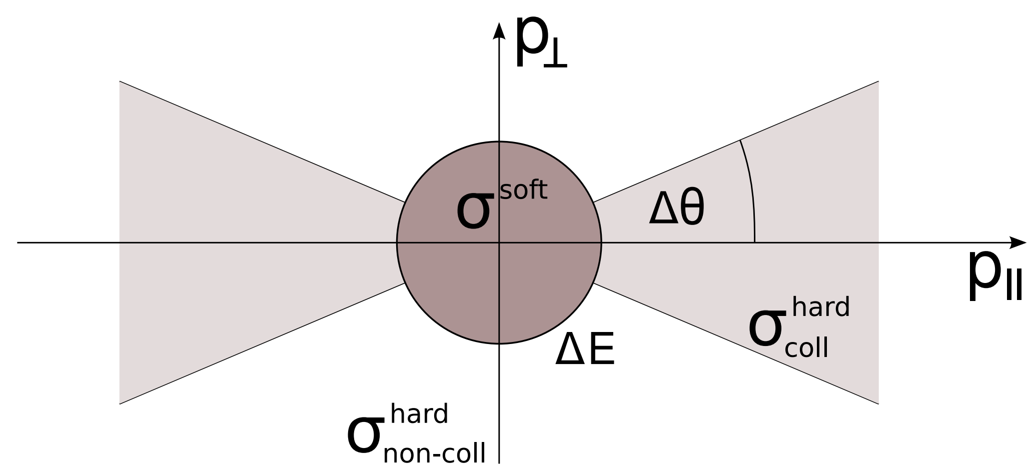
Dependent parameters

Loop diagrams contain **IR-divergencies** (soft and/or collinear), which vanish when taking into account the real emission of a gluon (2→3 processes)

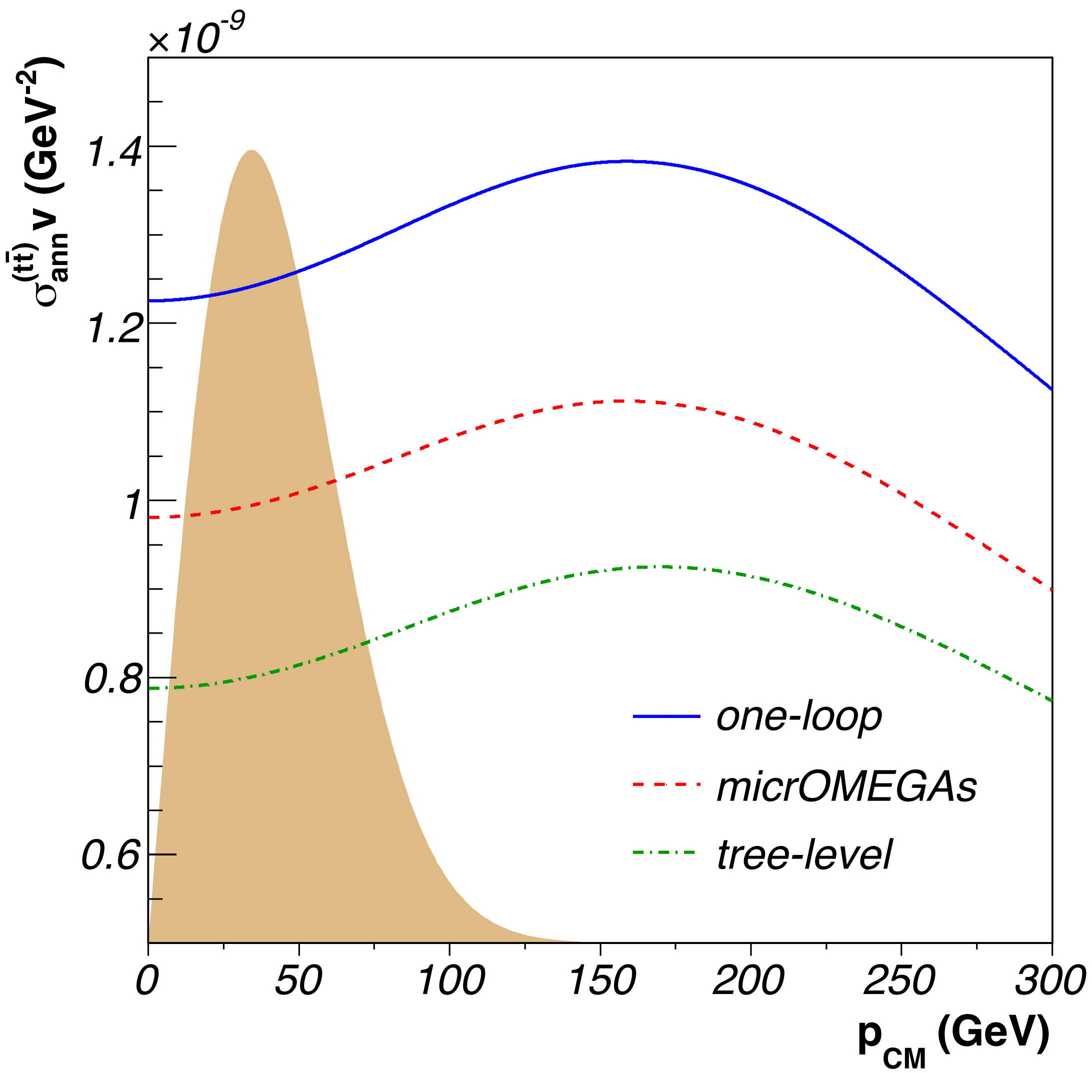
Dipole Subtraction Method and **Phase Space Slicing**

Catani, Seymour (2001)

$$\sigma_{\rm NLO} = \int_3 \left[{\rm d}\sigma^{\rm R}\Big|_{\epsilon=0} - {\rm d}\sigma^{\rm A}\Big|_{\epsilon=0} \right] + \int_2 \left[{\rm d}\sigma^{\rm V} + \int_1 {\rm d}\sigma^{\rm A} \right]_{\epsilon=0}$$

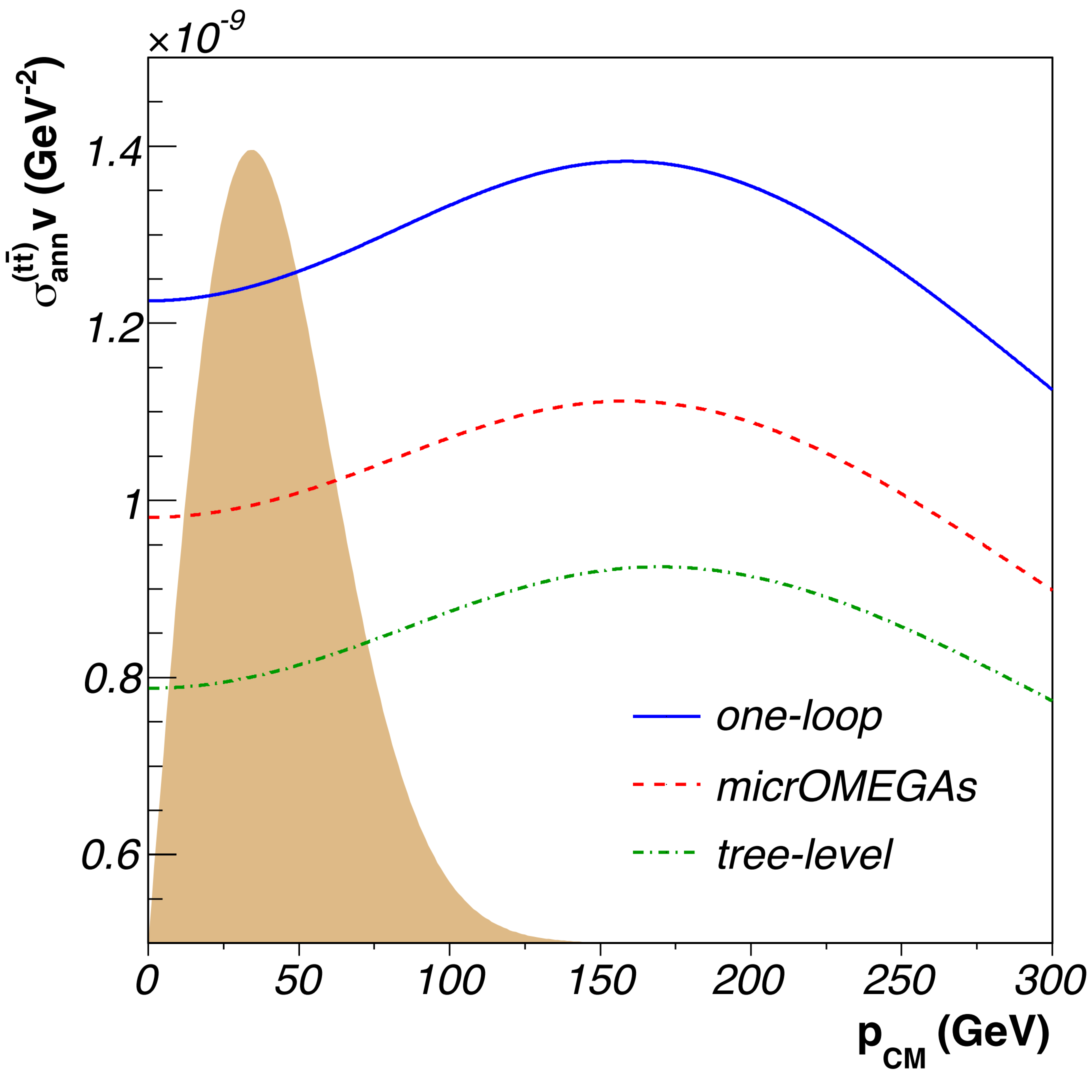


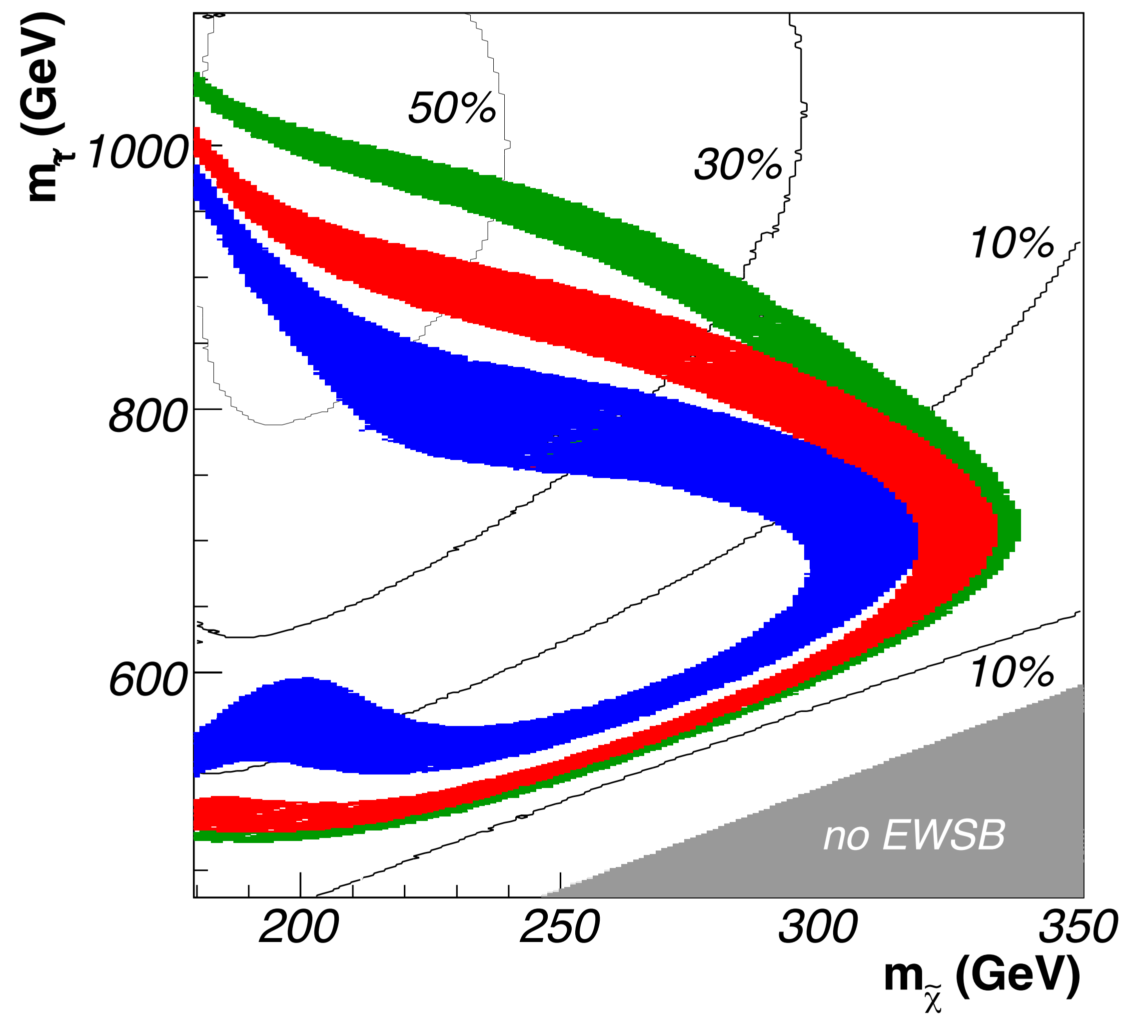
Neutralino pair annihilation into top quarks



Herrmann, Klasen, Kovařík — Phys. Rev. D 79: 061709 (2009) — arXiv:0901.0481 [hep-ph]
Harz, Herrmann, Klasen, Kovařík, Steppeler — Phys. Rev. D 91: 034028 (2015) — arXiv:1409.2898 [hep-ph]

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})

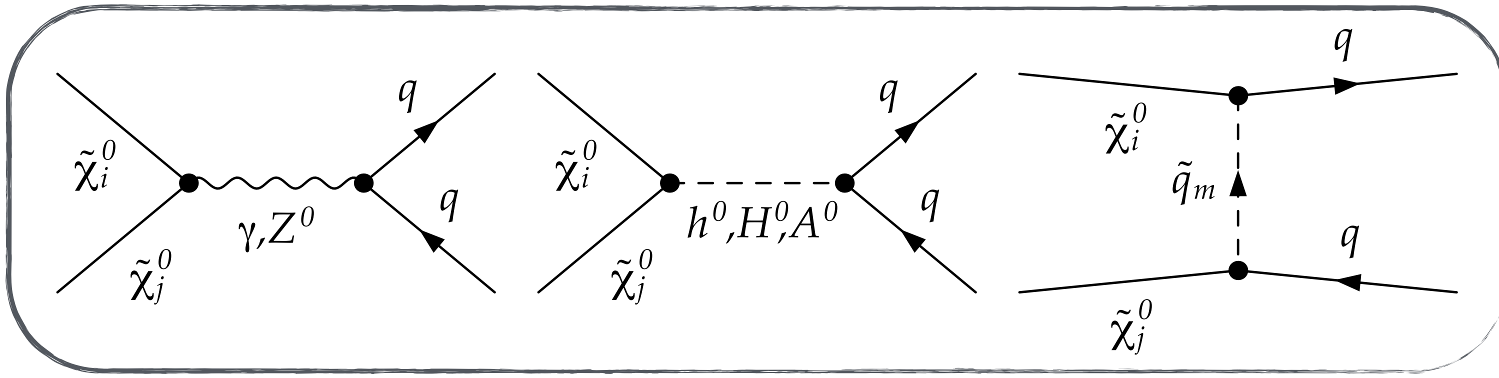
Effective Yukawa couplings (as e.g. in micrOMEGAs) very good approximation around Higgs-resonances, **but other sub-channels can be dominant** (here: Z/squark-exchange)

Herrmann, Klasen, Kovařík — Phys. Rev. D 79: 061709 (2009) — arXiv:0901.0481 [hep-ph]

Harz, Herrmann, Klasen, Kovařík, Steppeler — Phys. Rev. D 91: 034028 (2015) — arXiv:1409.2898 [hep-ph]

Gaugino pair annihilation into quarks

Generalization of previous results to annihilation of any gauginos into any quarks



Impact of corrections comparable to case of $\tilde{\chi}_1\tilde{\chi}_1$ annihilation…

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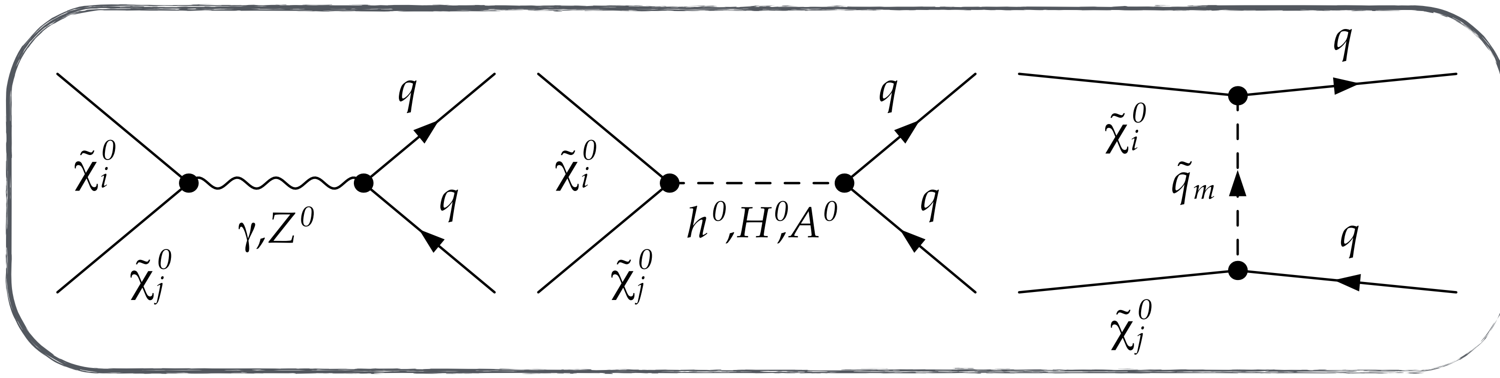

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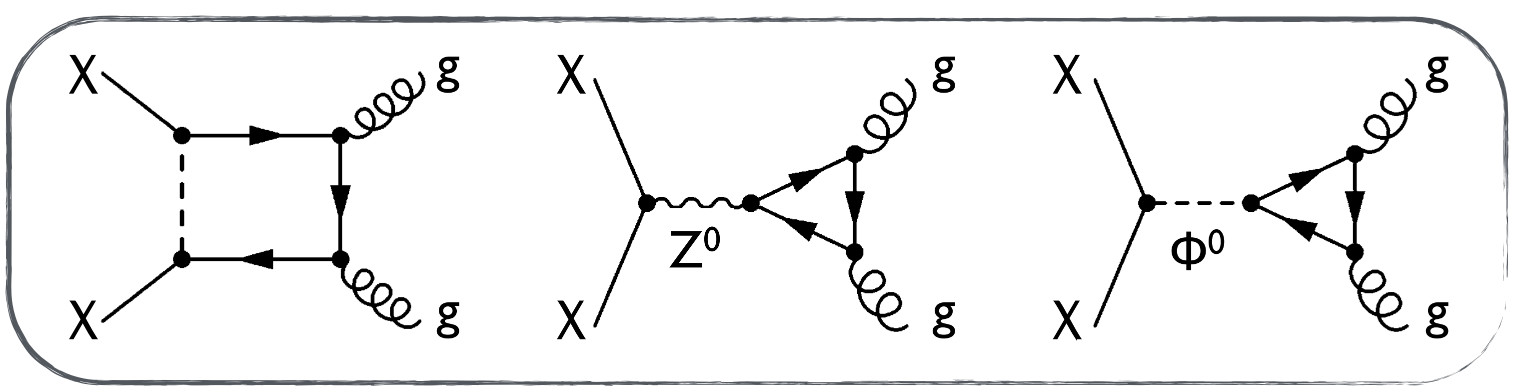
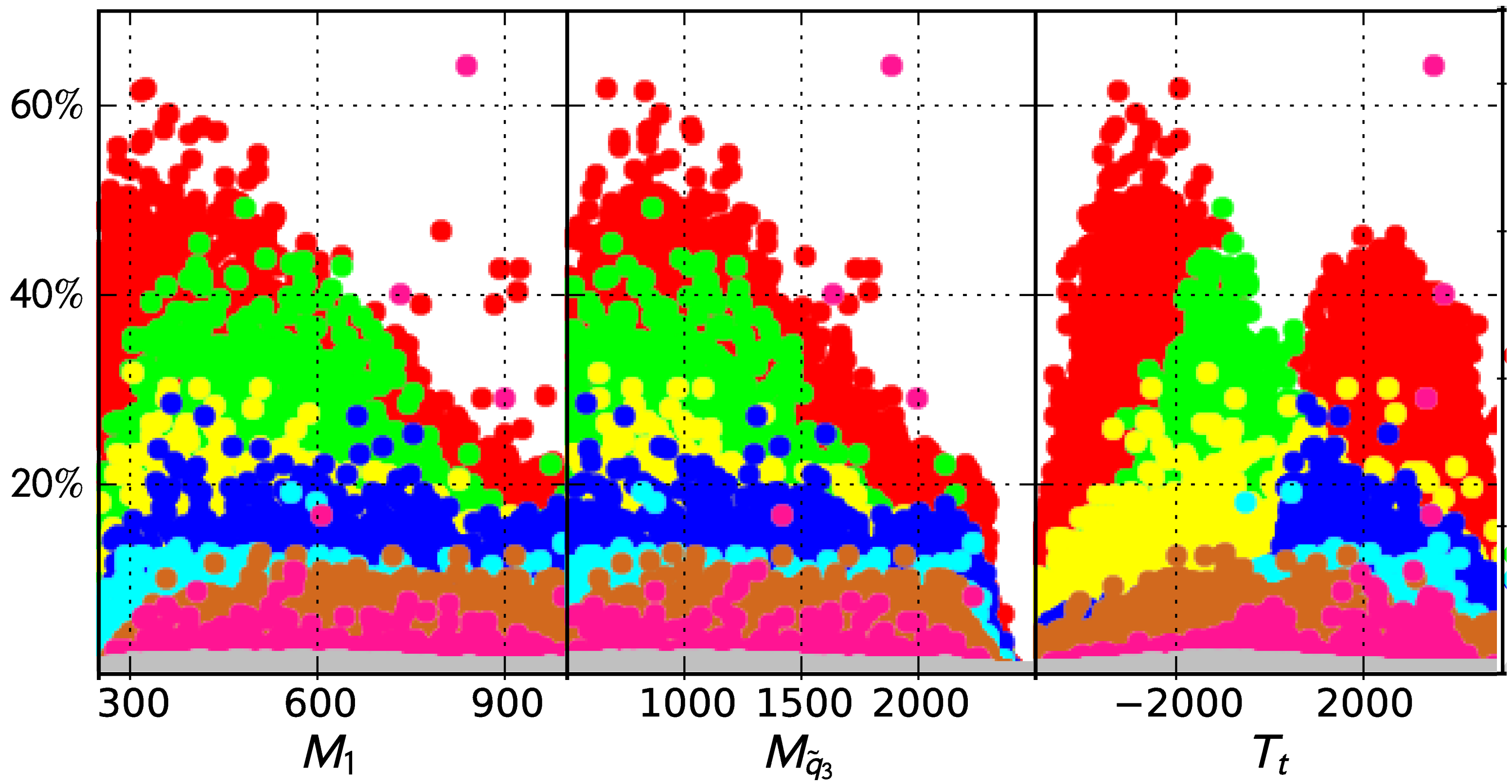
Neutralino pair annihilation into gluons

Process occurring only at one-loop level (no renormalization needed)



Fedkevych, Klasen, Kovařík — *in progress…*

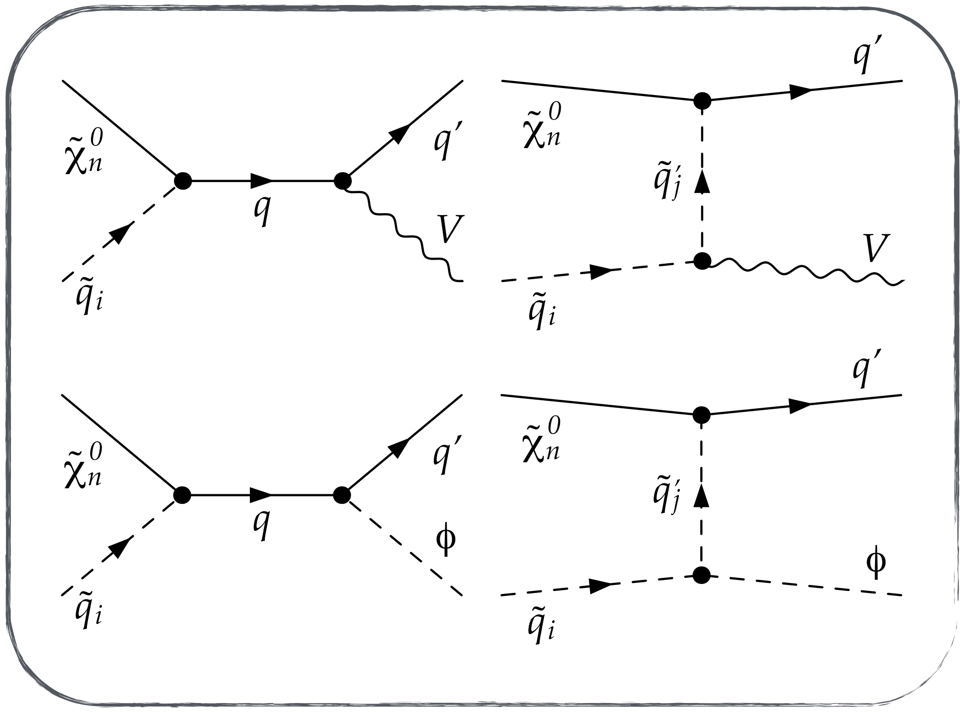
Neutralino-stop co-annihilation



$\tilde{\chi}\tilde{t} \to th^0$

$\tilde{\chi}\tilde{t} \to tg$

$\tilde{\chi}\tilde{t} \to tZ^0$



Harz, Herrmann, Klasen, Kovařík, Le Boulc'h — Phys. Rev. D 87: 054031 (2013) — arXiv:1212.5241 [hep-ph]

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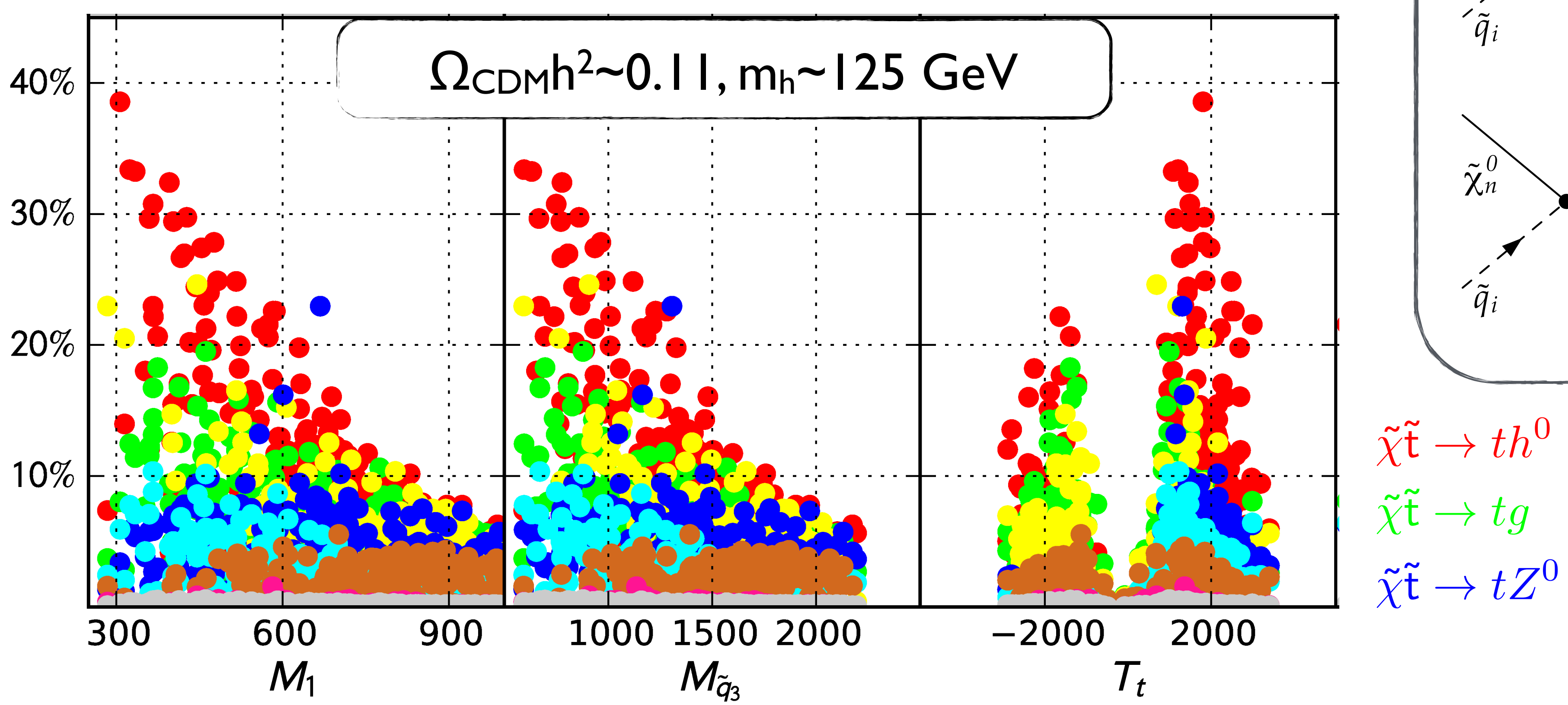

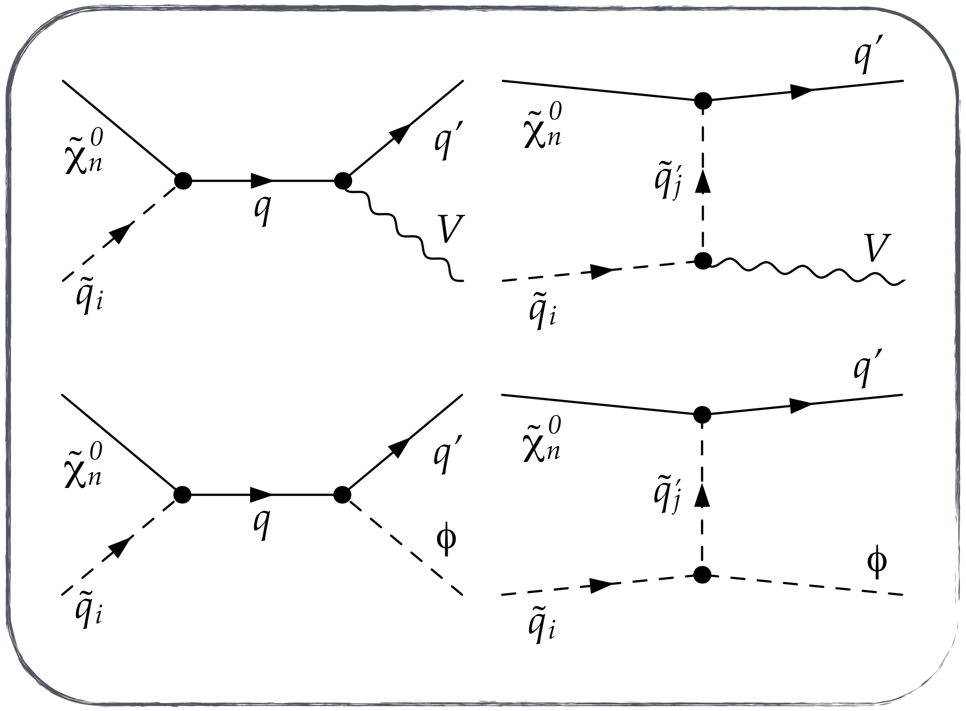

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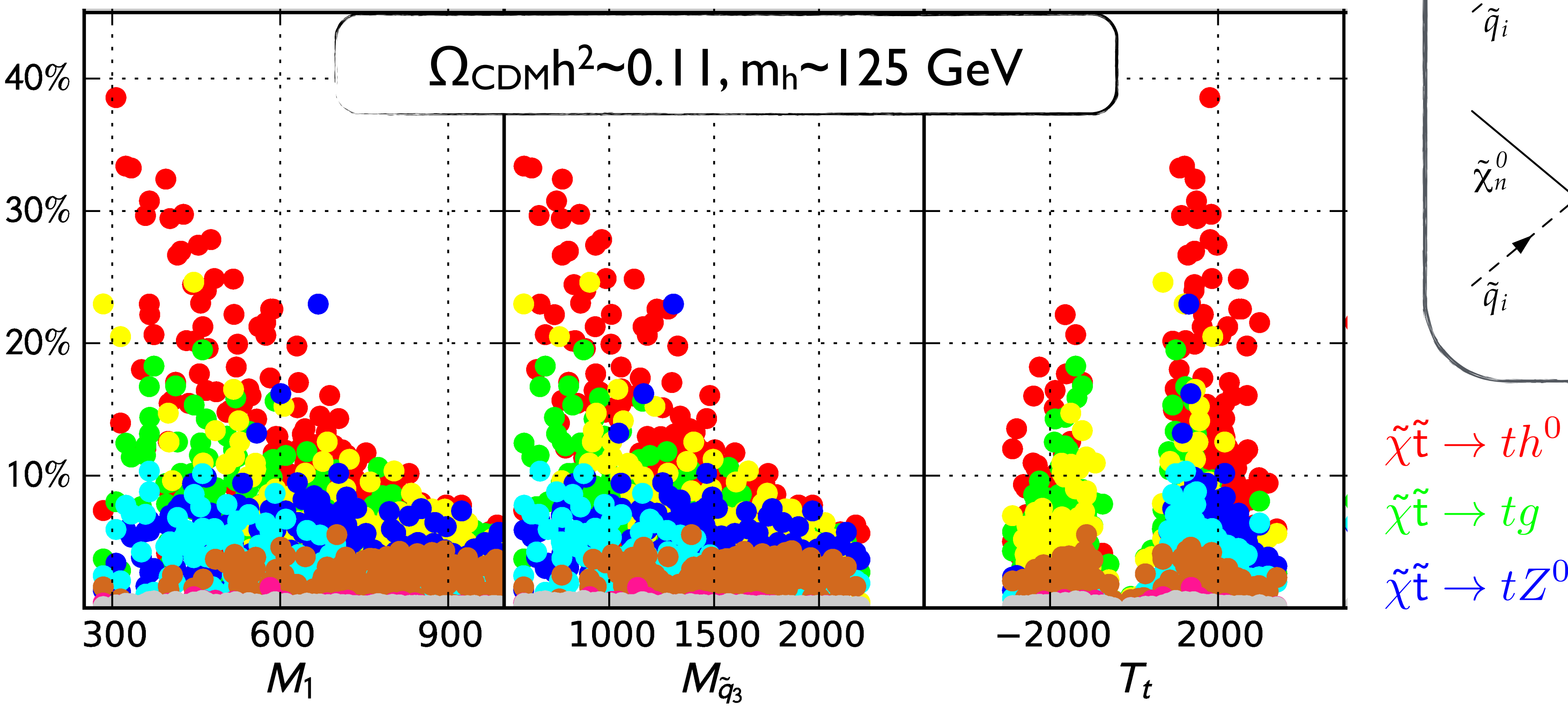

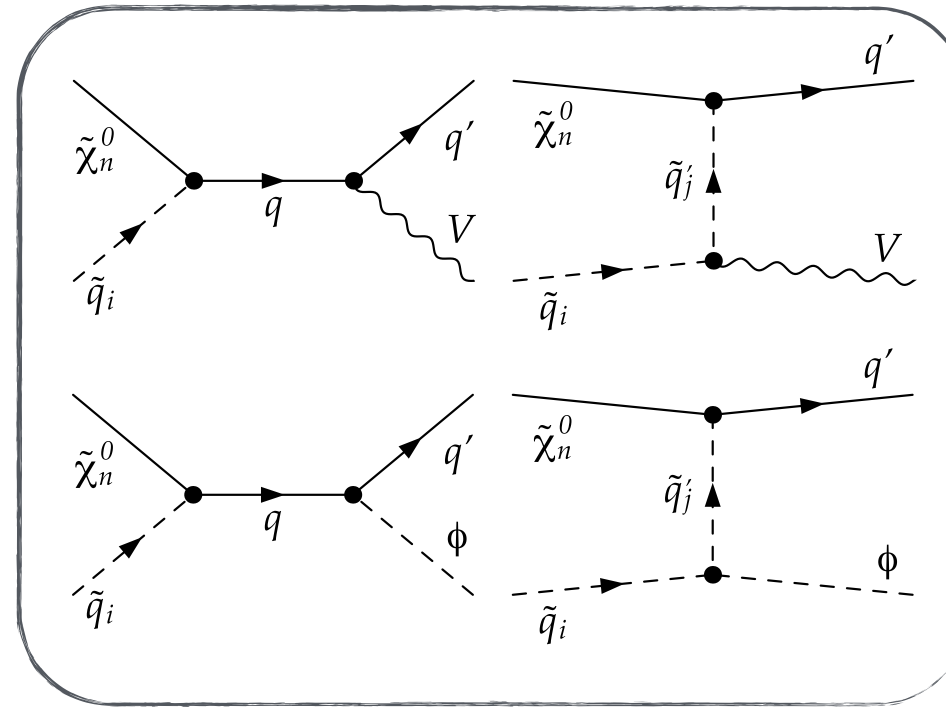

The observed Higgs mass favours large mass splitting of the stops, typically achieved through large trilinear coupling A_t

$$m_{h^0} = m_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\log\frac{M^2}{m_t^2} + \frac{X_t^2}{M^2}\left(1 - \frac{X_t^2}{12M^2}\right)\right]$$

$$X_t = A_t - \mu \tan\beta \approx \sqrt{6}M = \sqrt{6}\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

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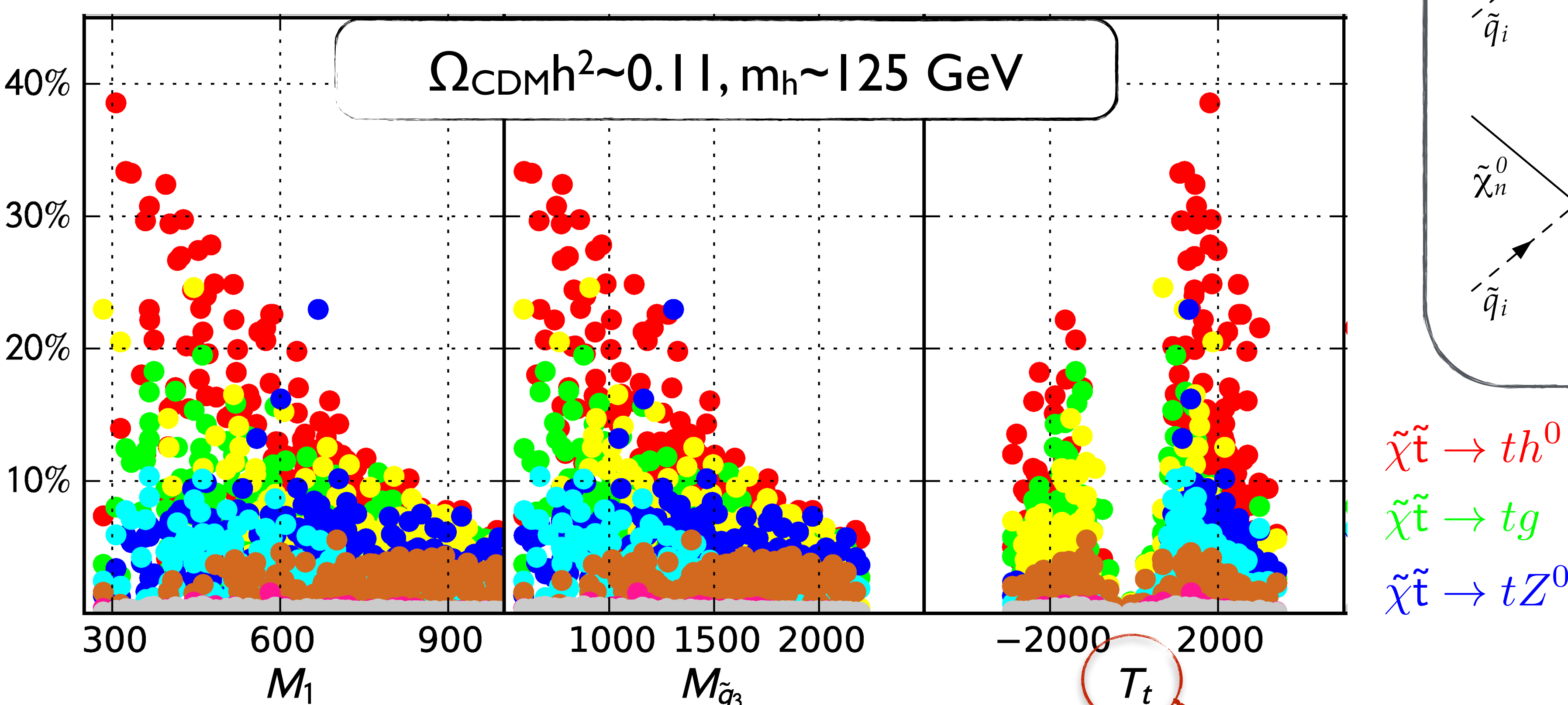

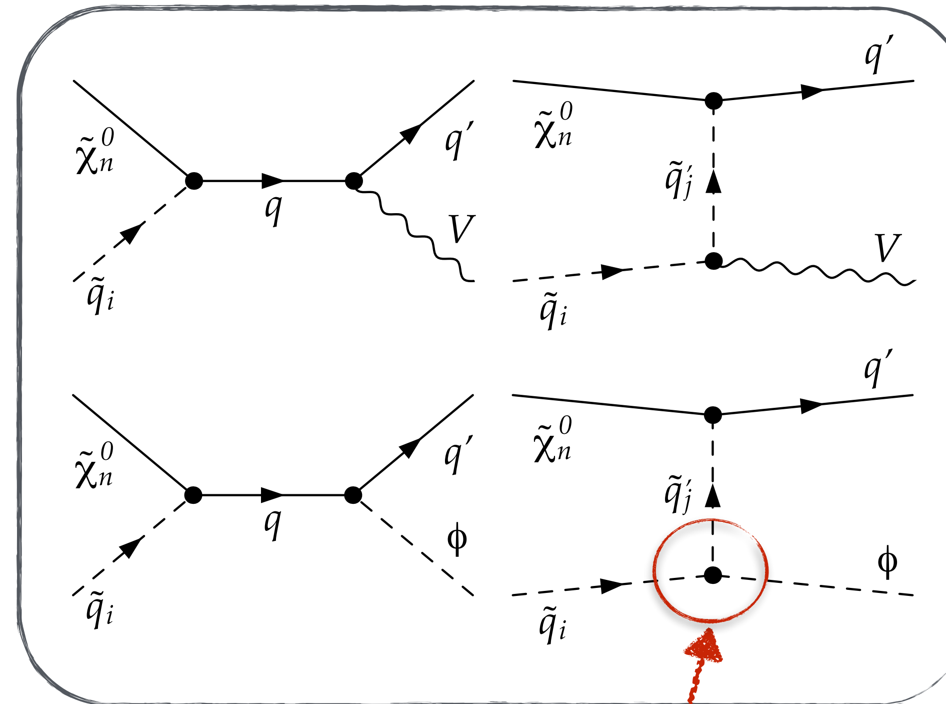

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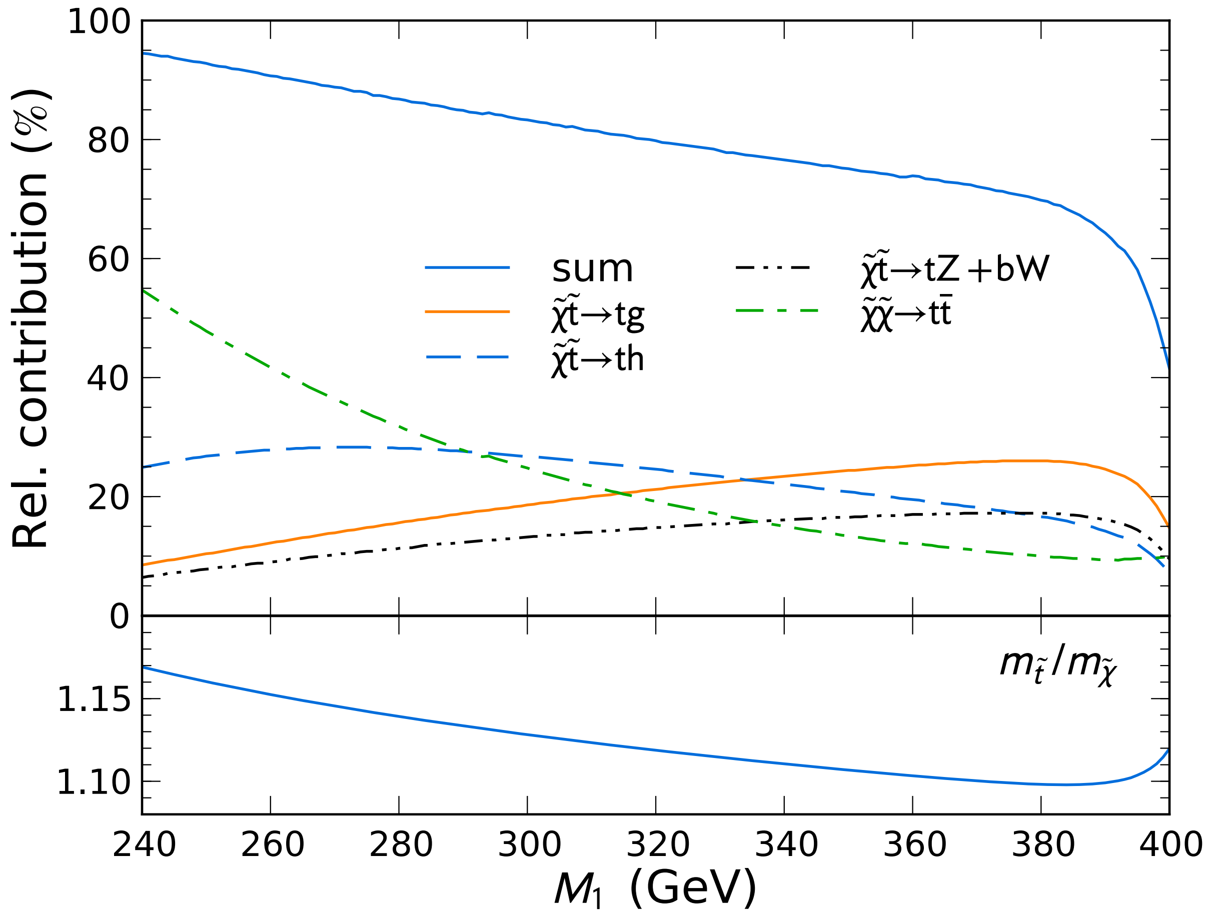
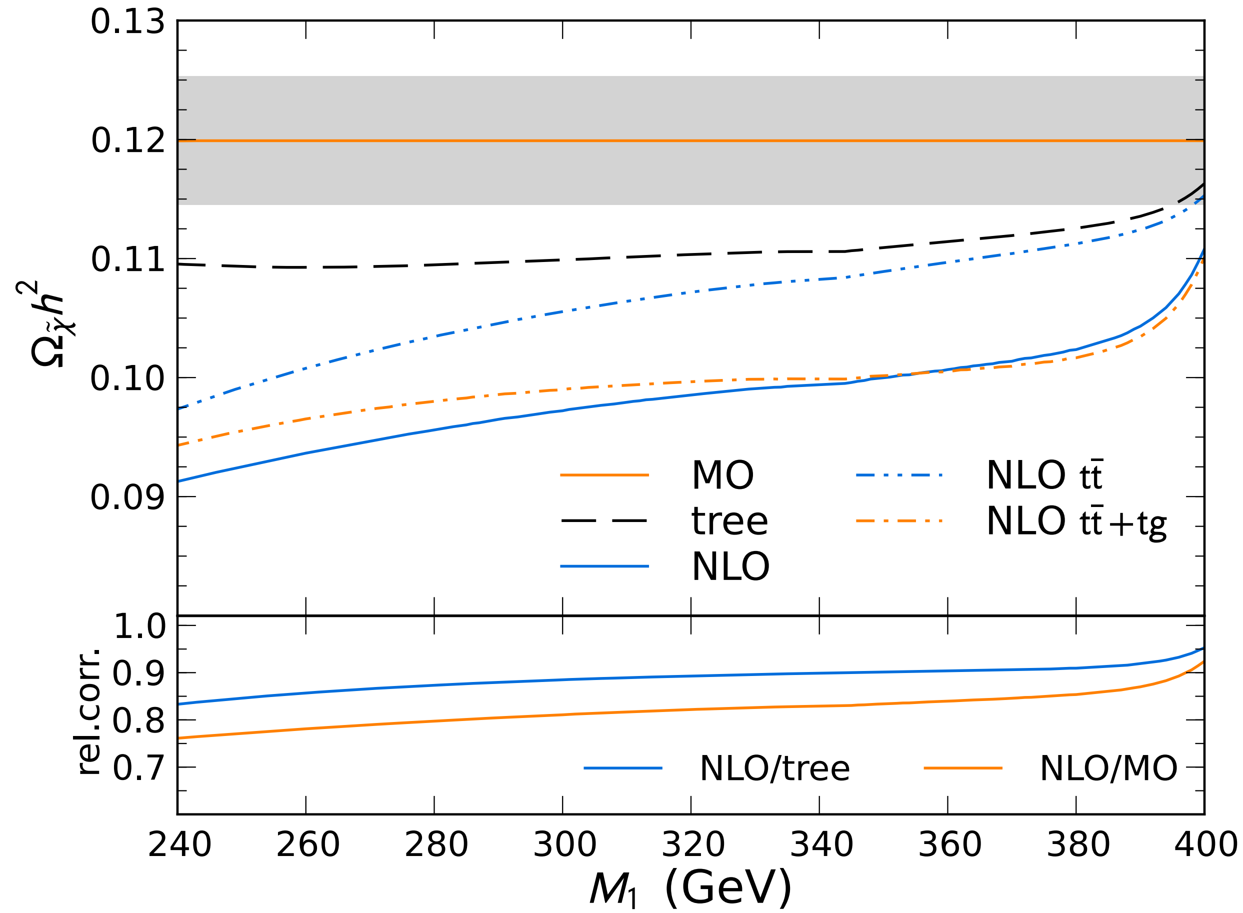
Contribution from $\tilde{\chi}_1\tilde{t}_1 \to th^0$ via t-channel stop-exchange increased

Harz, Herrmann, Klasen, Kovařík, Le Boulc'h — Phys. Rev. D 87: 054031 (2013) — arXiv:1212.5241 [hep-ph]

Neutralino-stop co-annihilation





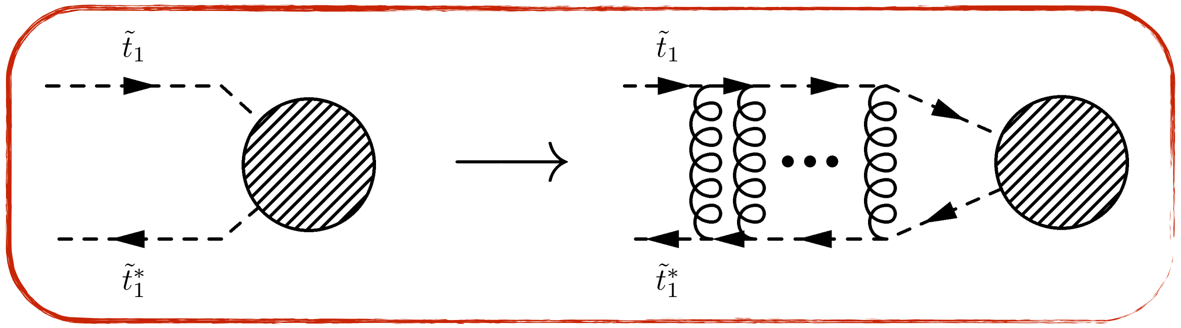
Relative corrections of 40-50% observed for the coannihilation cross-section, leading to an **important shift** (up to almost 25% — more than Planck uncertainty!) for the predicted **neutralino relic density**

Coannihilation 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]
Harz, Herrmann, Klasen, Kovařík — Phys. Rev. D 91: 034028 (2015) — arXiv:1409.2898 [hep-ph]

Stop pair annihilation (including Coulomb corrections)

Exchange of multiple gluons in the initial state (in addition to one-loop diagrams)
— **resummation to all orders using non-relativistic QCD**



$$\sigma^{\mathsf{Coul}} = \frac{4\pi}{\mathsf{v} m_{\tilde{\mathsf{t}}}^2} \Im\left\{ \mathsf{G}^{[1]}\left(\mathbf{r}=0; \sqrt{\mathsf{s}} + \mathsf{i}\Gamma_{\tilde{\mathsf{t}}}\right)\right\} \sigma^{\mathsf{LO}}$$

$$\left[\mathsf{H}^{[1]} - \left(\sqrt{\mathsf{s}} + \mathsf{i}\Gamma_{\tilde{\mathsf{t}}}\right)\right]\mathsf{G}^{[1]} = \delta^{(3)}(\mathbf{r})$$

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

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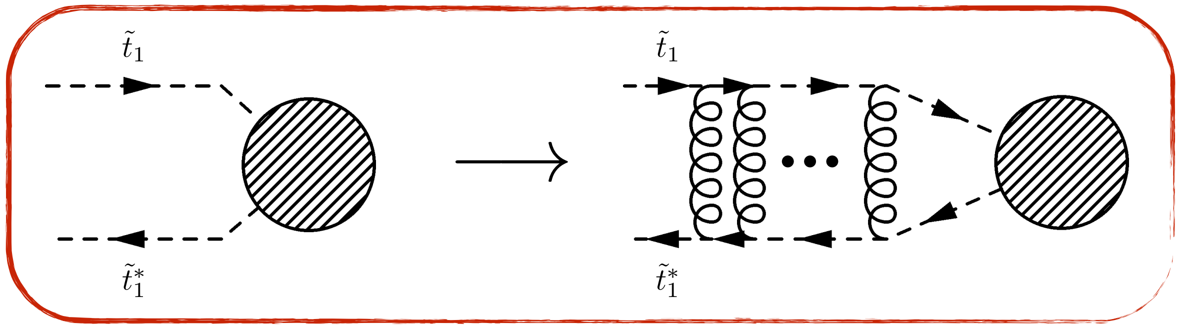

$$\sigma^{\mathrm{Coul}} = \frac{4\pi}{v m_{\tilde{t}}^2} \Im\left\{ G^{[1]}\left(\mathbf{r}=0; \sqrt{s}+i\Gamma_{\tilde{t}}\right)\right\} \sigma^{\mathrm{LO}}$$

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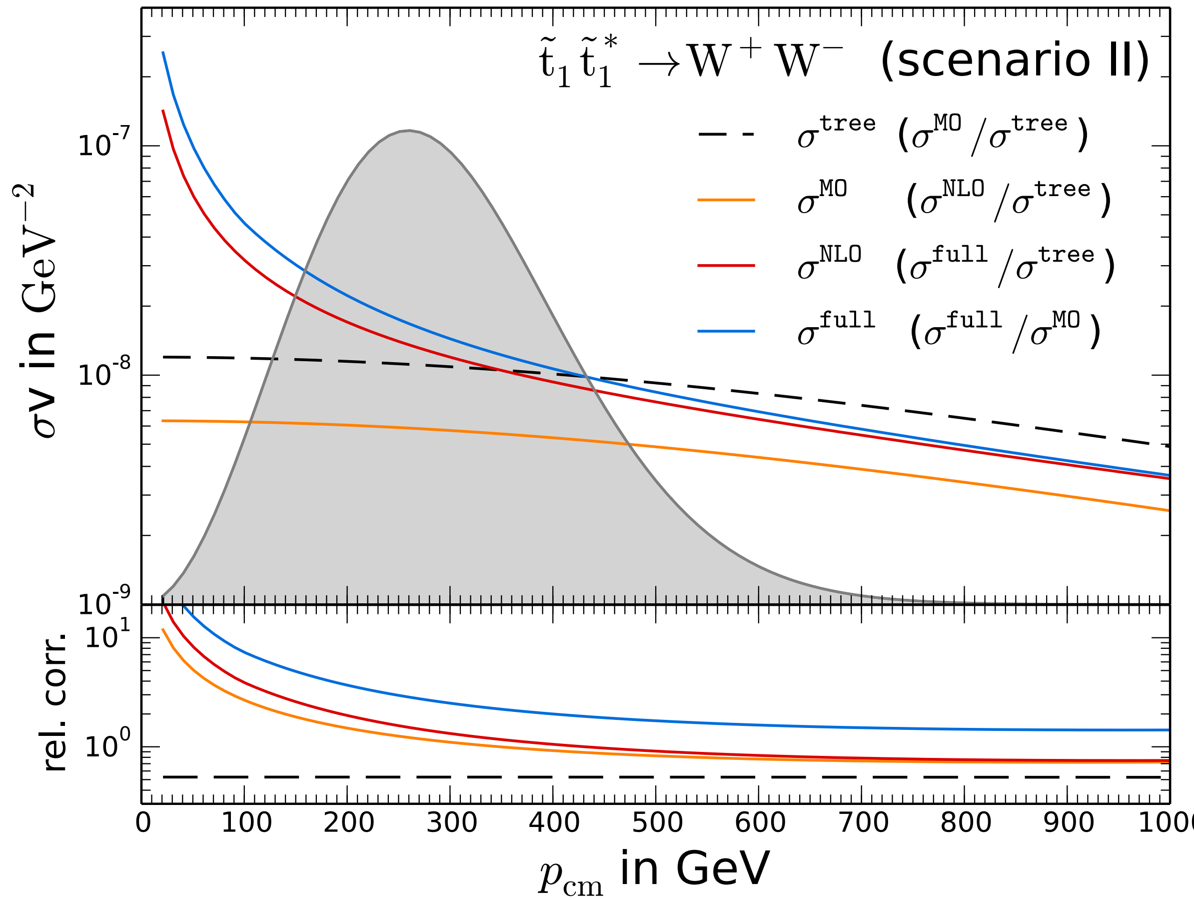

Coulomb corrections **dominant for small values of p_{cm}** (Coulomb singularity),
while fixed-order corrections dominant for high-momentum region

Stop pair annihilation into **electroweak final states** included — **coloured final states** to be implemented…

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

Scale dependence of neutralino (co)annihilation

Loop calculation introduces a dependence on an unphysical parameter: **renormalization scale**
— **Evaluation of theory uncertainty by varying renormalization scale**

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

scale-dependent parameters

Harz, Herrmann, Klasen, Kovařík, Steppeler — *to be published…*

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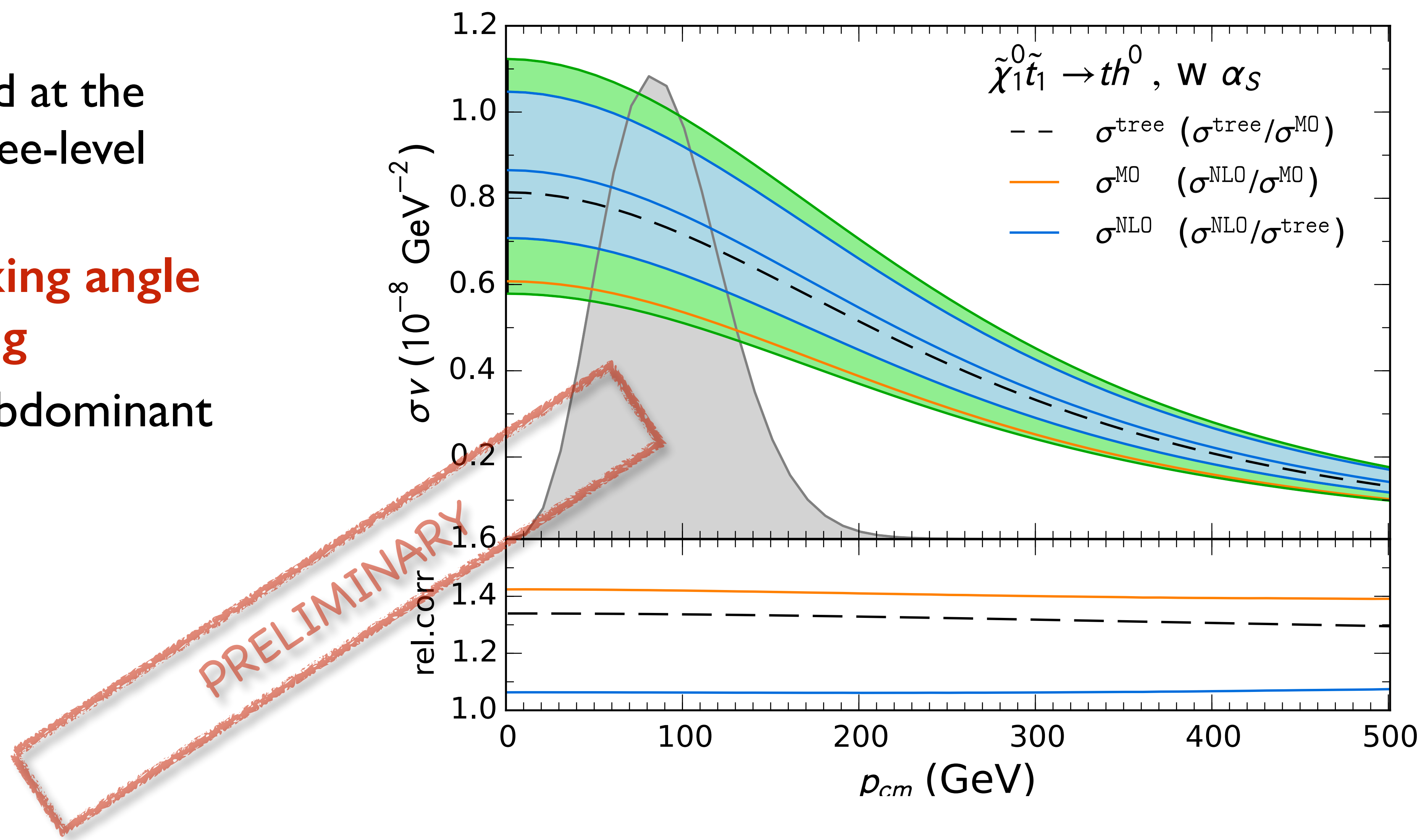
scale-dependent parameters

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**

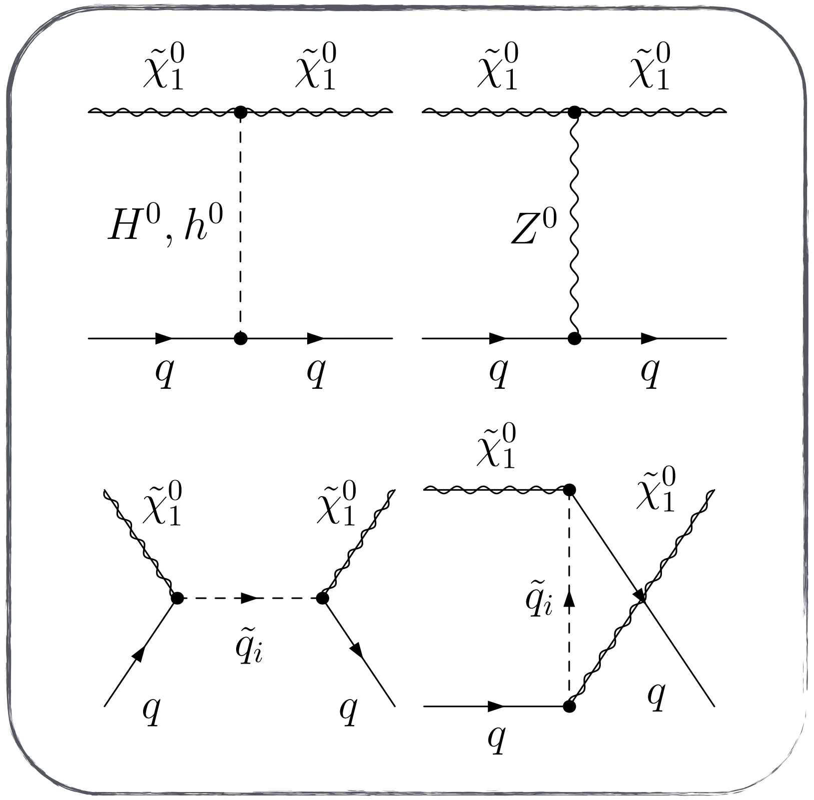
— dependence of α_s subdominant



Harz, Herrmann, Klasen, Kovařík, Steppeler — *to be published…*

Direct dark matter detection

Same topologies as neutralino pair annihilation into quarks



Klasen, Kovařík, Steppeler — *in progress…*

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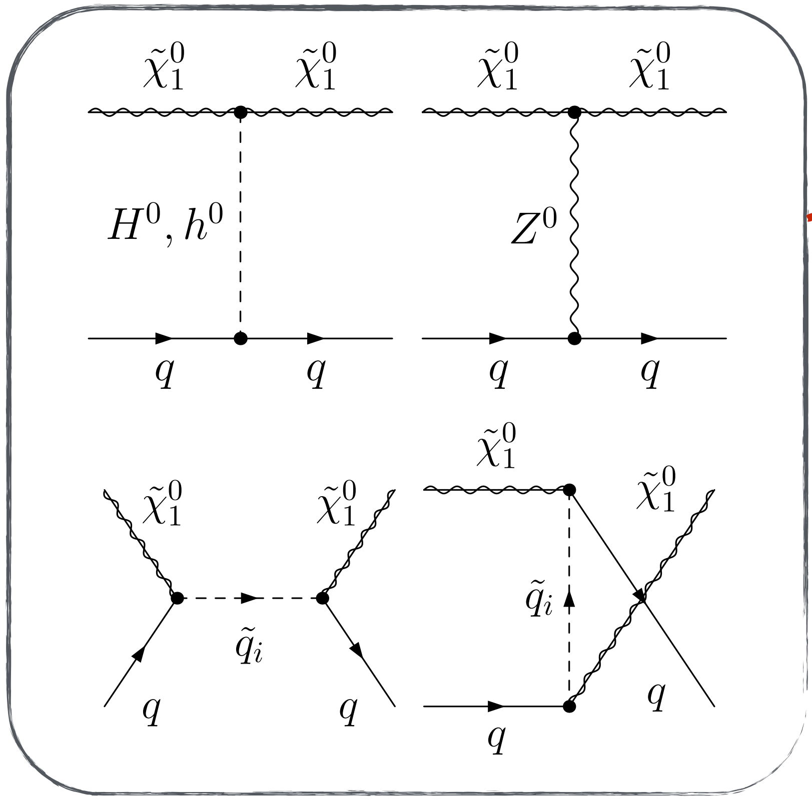
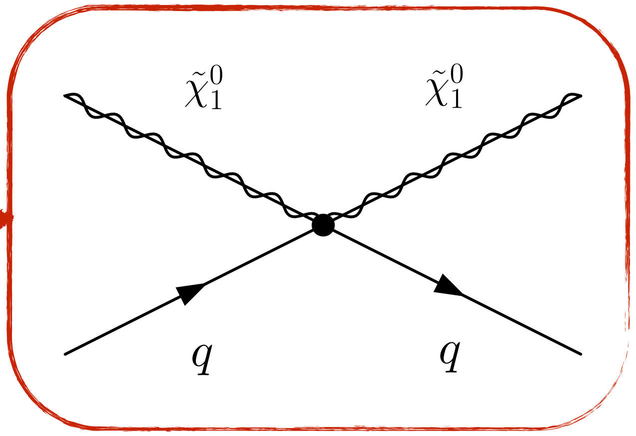


Matching procedure
Q ~ 1 TeV



Low-energy effective theory
Q ~ 2-5 GeV
(intermediate particles integrated out)

Klasen, Kovařík, Steppeler — *in progress…*

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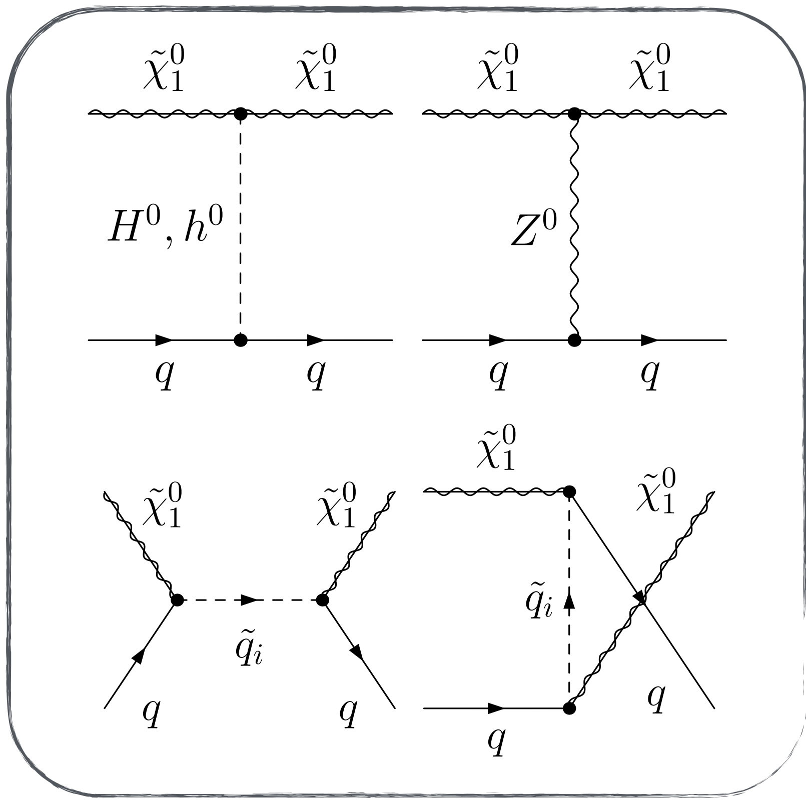

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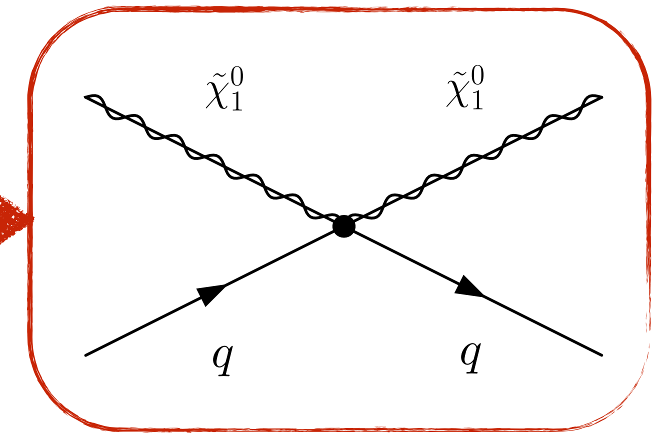

Low-energy effective theory
Q ~ 2-5 GeV
(intermediate particles integrated out)

Calculation carried out at very low energy: p_{cm}~0

— standard **reduction of loop tensor integrals** not applicable

— need to implement specific reduction procedure for threshold…

Finiteness (UV and IR) of **loop calculation within effective theory** verified

Klasen, Kovařík, Steppeler — *in progress…*

DM@NLO — Summary

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

Package providing a 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

$$\tilde{\chi}\tilde{\chi}' \to gg/\gamma\gamma$$
$$\tilde{q}\tilde{q}^* \to q\bar{q}'$$
$$\tilde{q}\tilde{q} \to qq$$
$$\tilde{\tau}\tilde{\tau}^* \to qq'$$

work in progress…

Impact of corrections on the relic density more important than current exp. uncertainty

http://dmnlo.hepforge.org

Minimal models —
Dark matter and Neutrino masses

Example: T1-2A

Standard Model + fermionic singlet + fermionic doublet + scalar singlet + scalar doublet

X_1, X_2, X_3 (fermionic singlet + fermionic doublet)

Φ_1, Φ_2, Φ_3 (scalar singlet + scalar doublet)

Example: T1-2A

Standard Model + fermionic singlet + fermionic doublet + scalar singlet + scalar doublet

χ_1, χ_2, χ_3 Φ_1, Φ_2, Φ_3

↓ Z_2 -parity

Lightest odd particle is stable — “WIMP”

χ_1 or Φ_1

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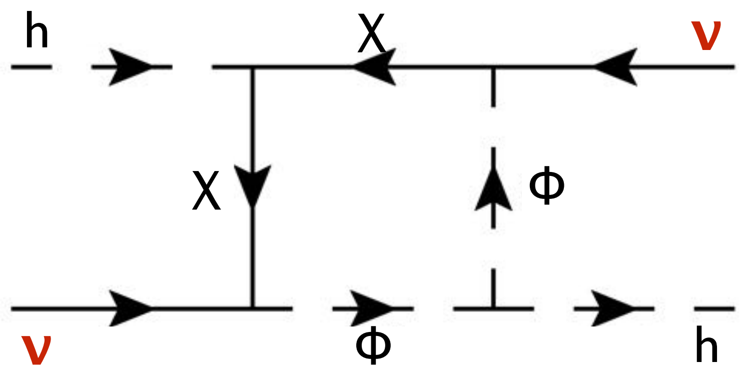
Neutrino mass generated radiatively



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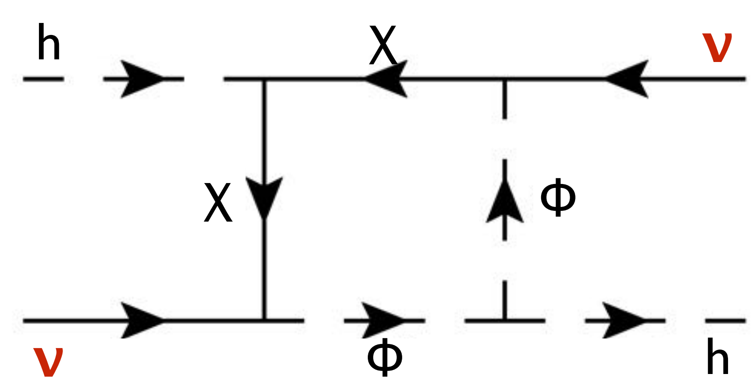

Parameters of the model:

$M_{\Phi 1}, M_{\Phi 2}, M_{\Phi 3}, \lambda_1, \lambda_2, \lambda_3, \lambda_4, A_\Phi$ — additional scalars

$M_{X1}, M_{X2}, M_{X3}, Y_X$ — additional fermions

$\lambda_{\ell 1}, \lambda_{\ell 2}$ — fermion-scalar-lepton coupling

Project: T1-2A

Analysis of the relevant parameter space with respect to dark matter and flavour constraints
— **Markov Chain Monte Carlo** technique for efficient scanning
— study also dark matter annihilation channels, neutrino and collider aspects

Esch, Herrmann — *in preparation…*

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Loop corrections to DM annihilation…?
— link to **DM@NLO**

Esch, Herrmann — *in preparation…*

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— Large Hadron Collider / linear collider

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— mass patterns, astroparticle physics

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Sonja Esch — visit Annecy — march 2016

Graduiertenkolleg 2149
Research Training Group

Enigmass

Esch, Herrmann — *in preparation…*


thank you
danke
謝謝
ngiyabonga
teşekkür ederim
gracias
спасибо
dank je
tapadh leat
bedankt
hvala
maururu
mochchakkeram
dziękuję
go raibh maith agat
obrigado
sagolun
sukriya
kop khun krap
arigato
takk
dakujem
мерси
ありがとう
grazie
terima kasih
감사합니다
merci