Phenomenology of Neutralino-Stop Coannihilation including SUSY-QCD Corrections

Julia Harz

University College London

in collaboration with B. Herrmann, M. Klasen and K. Kovarik

J. Harz, B. Herrmann, M. Klasen, K. Kovařík and Q. Le Boulc'h,
Phys. Rev. D 87: 054031 (2013)
J. Harz, B. Herrmann, M. Klasen, K. Kovařík,
in preparation

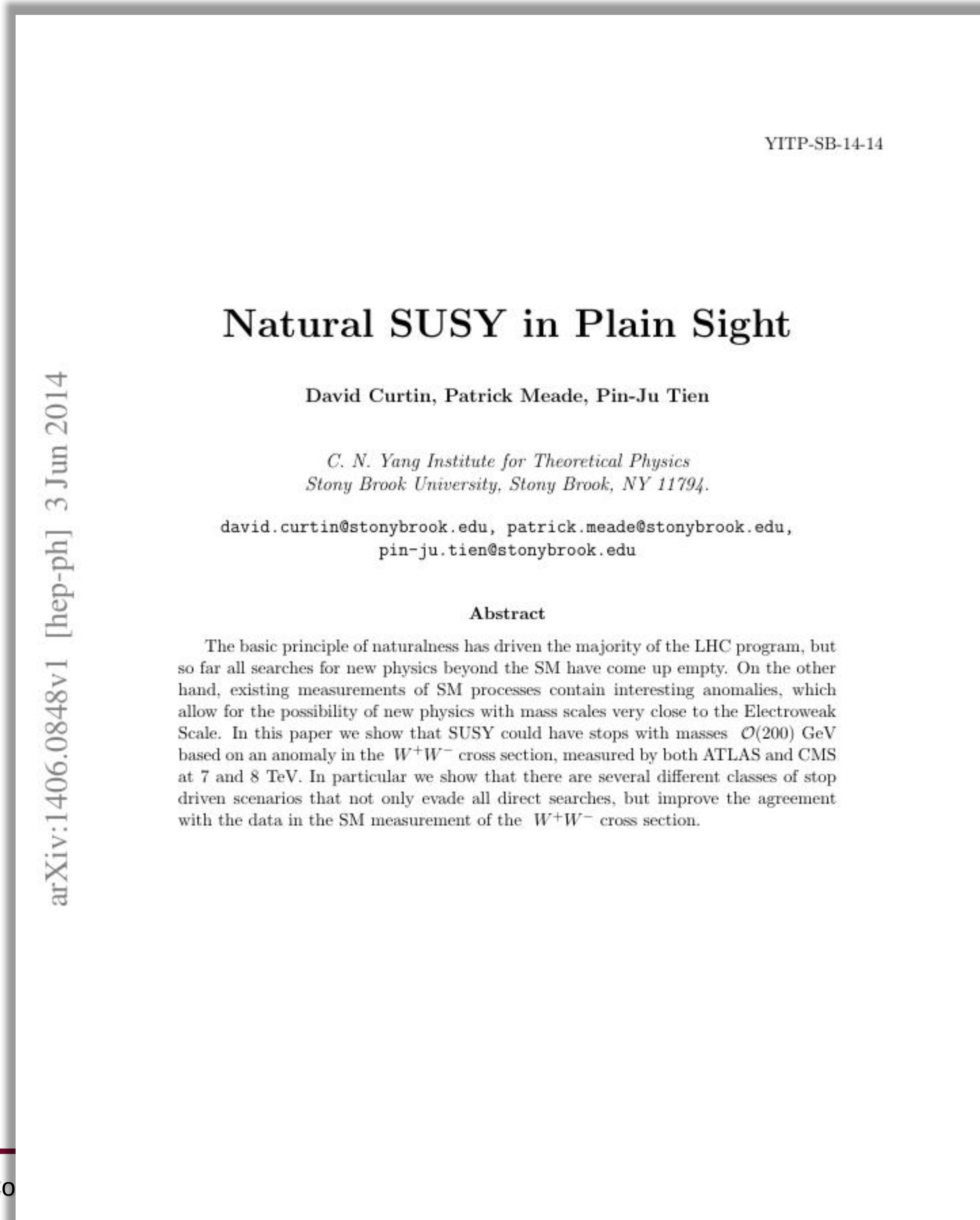
SUSY 2014, Manchester

Where is Supersymmetry hiding?

Where is Supersymmetry hiding?

… maybe in the light stop region?

Quite some Activities on this Topic…



YITP-SB-14-14

arXiv:1406.0848v1 [hep-ph] 3 Jun 2014

Natural SUSY in Plain Sight

David Curtin, Patrick Meade, Pin-Ju Tien

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`pin-ju.tien@stonybrook.edu`

Abstract

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CERN-PH-TH-2014-114, DESY 14-107, Cavendish-HEP-14/04, TTK-14-12

Closing the stop gap

Michal Czakon,[1] Alexander Mitov,[2] Michele Papucci,[3, 4] Joshua T. Ruderman,[3, 4, 5] and Andreas Weiler[6, 7]
[1] *Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, D-52056 Aachen, Germany*
[2] *Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK*
[3] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley CA 94720*
[4] *Department of Physics, University of California, Berkeley CA 94720*
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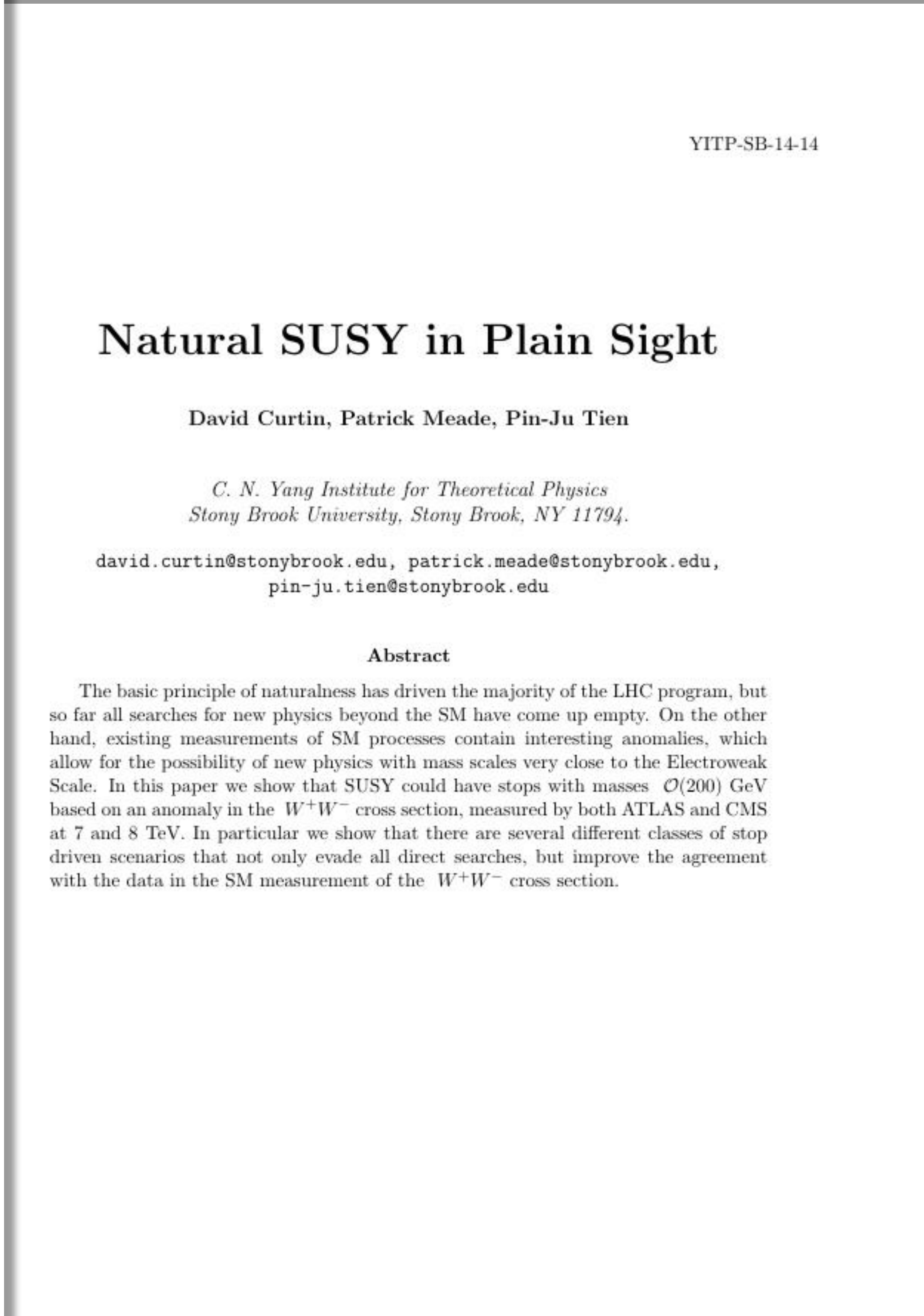
Light stops are a hallmark of the most natural realizations of weak-scale supersymmetry. While stops have been extensively searched for, there remain open gaps around and below the top mass, due to similarities of stop and top signals with current statistics. We propose a new fast-track avenue to improve light stop searches for R-parity conserving supersymmetry, by comparing top cross section measurements to the theoretical prediction. Stop masses below ∼ 180 GeV can now be ruled out for a light neutralino. The possibility of a stop signal contaminating the top mass measurement is also briefly addressed.

arXiv:1407.1043v1 [hep-ph] 3 Jul 2014

Introduction: One of the open questions in particle physics is why the weak and gravitational forces have such different strengths. If this *hierarchy problem* has a solution dictated by microscopic dynamics, one expects new particles not far from the weak scale, $\mathcal{O}(100\,\mathrm{GeV})$, in the form of partners of the Standard Model (SM) particles, responsible for insulating the Higgs mass from large ultraviolet quantum corrections. Weak-scale supersymmetry (SUSY) is a leading candidate for such a microscopic solution of the hierarchy problem and the mechanism is most natural if the partners of the SM particles having the largest coupling to the Higgs field are light [1, 2], the top squark being the most prominent one. This region of the SUSY parameter space has been called Natural SUSY in recent years [3]. Many theoretical studies [4–13, 15–18] and experimental searches [19–36] aimed at probing Natural SUSY models have therefore focused on searches for the top (and bottom) squarks $\tilde{t}$ ($\tilde{b}$).

In R-parity conserving scenarios, current LHC limits reach up to about 700 GeV, depending on the value of the lightest SUSY particle (LSP) mass, usually taken to be a neutralino (χ_1^0) or a gravitino ($\tilde{G}$). However, unconstrained regions for lighter values of stop masses still remain, the most important being the one where $m_{\tilde{t}} \sim m_t \gg m_{\chi_1^0,\tilde{G}}$ and $\tilde{t}$ decays into (off-shell) top and the LSP, i.e. where $\tilde{t}$ decays are kinematically very similar to top decays. Given that the production cross section for top squarks is much smaller than the one for top quarks ($\sigma_{\tilde{t}} \sim 0.15\,\sigma_{t\bar{t}}$ for $m_{\tilde{t}} \sim m_t$ at the LHC), constraining these *stealth stop* models [37–39] is particularly challenging. All of the strategies studied in the literature focused on exploiting the subtle kinematical differences between the top and stop production and/or decays [9, 10, 17]. Furthermore, the best known discriminating kinematical variables, such as the lepton rapidity distribution or the dilepton angular correlations, are either plagued by large theoretical and pdf uncertainties or require very large statistics, only accessible in future LHC runs [40]. To date, the strongest constraints come from dedicated searches using multivariate analyses and provide only a partial exclusion of the stealth stop window [21, 25]. Open gaps remain. For instance, for massless neutralino, $80\,\mathrm{GeV} \lesssim m_{\tilde{t}} \lesssim 100\,\mathrm{GeV}$ or $m_{\tilde{t}}$ around m_t are still allowed. While model-dependent limits in these gaps arise from indirect Higgs couplings constraints (see *e.g.* [41–45]) and from $\tilde{t} \to c\,\chi_0^1$ searches [29, 34], we stress that no robust exclusion is currently available.

In this letter we propose a different, *complementary* approach for constraining light top squarks. Instead of focusing on discriminating *differences* between SUSY signal and SM background, our method is based on exploiting the kinematical *similarities* between top and stops in this region. Namely, if stop production and decays are kinematically very similar to the SM top ones, then SUSY contributions may bias SM measurements. Similar methods have been proposed for constraining new physics with W^+W^- measurements [47–53]. Therefore, we propose to use top SM measurements and SM theoretical predictions to set limits on the stop contamination in $t\bar{t}$ event samples. We will illustrate our method by focusing on one of the most inclusive top properties, the top production cross section, $\sigma_{t\bar{t}}$. The inclusiveness has the advantage of reducing theoretical uncertainties. Furthermore the theoretical prediction for $\sigma_{t\bar{t}}$ in the SM [54, 55] has been recently improved to NNLO+NNLL by a multi-year effort of two of the authors [56–60], providing [59, 61] $\sigma_{t\bar{t}}^{LHC7} = 172^{+4.4}_{-5.8}(\mathrm{scale})^{+4.7}_{-4.8}(\mathrm{pdf})$ pb for $m_t = 173.3$ GeV. Interestingly, the theoretical uncertainties are now comparable to the experimental ones, providing a unique opportunity for performing this analysis: further experimental improvements alone will only marginally change the constraining power of this method.



YITP-SB-14-14

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arXiv:1407.1043v1 [hep-ph] 3 Jul 2014

arXiv:1212.6847v1 [hep-ph] 31 Dec 2012

The light stop window

Antonio Delgado[a], **Gian F. Giudice**[b], **Gino Isidori**[b,c],
Maurizio Pierini[b], **Alessandro Strumia**[d,e]

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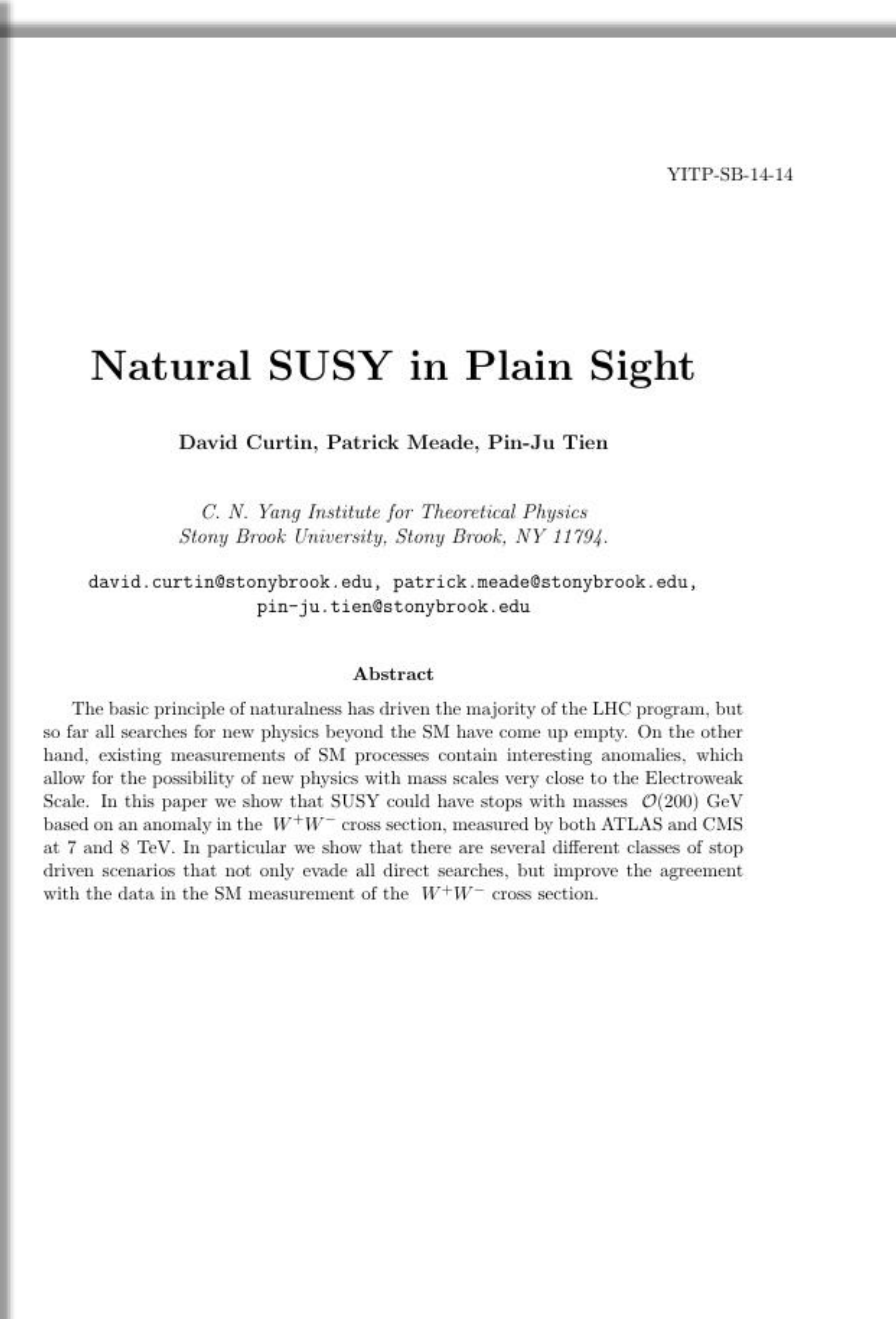
(*d*) *Dipartimento di Fisica, Università di Pisa and INFN Sez. Pisa, Pisa, Italy*
(*e*) *National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

Abstract

We show that a right-handed stop in the 200–400 GeV mass range, together with a nearly degenerate neutralino and, possibly, a gluino below 1.5 TeV, follows from reasonable assumptions, is consistent with present data, and offers interesting discovery prospects at the LHC. Triggering on an extra jet produced in association with stops allows the experimental search for stops even when their mass difference with neutralinos is very small and the decay products are too soft for direct observation. Using a razor analysis, we are able to set stop bounds that are stronger than those published by ATLAS and CMS.



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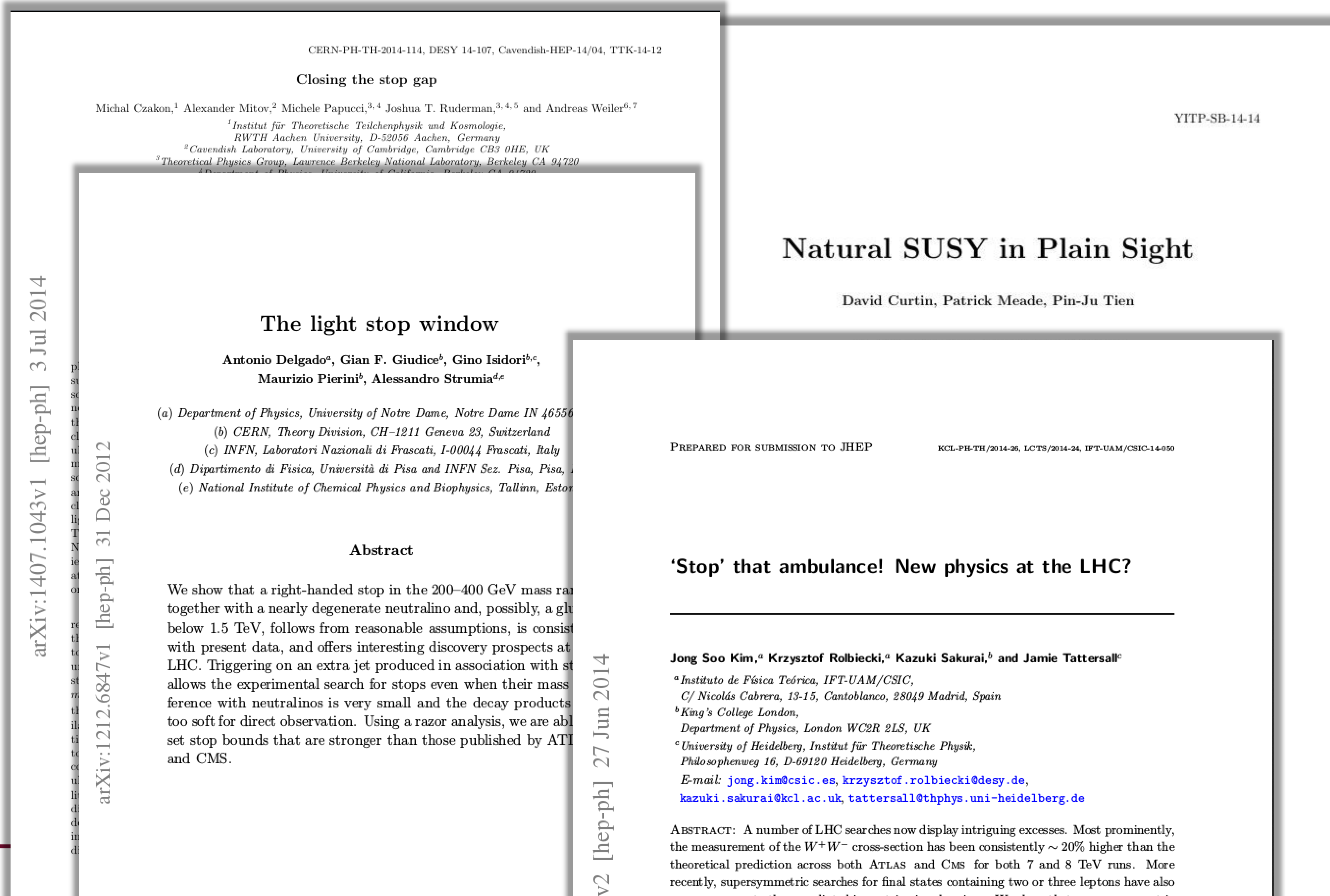

CERN-PH-TH-2014-114, DESY 14-107, Cavendish-HEP-14/04, TTK-14-12

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PREPARED FOR SUBMISSION TO JHEP

KCL-PH-TH/2014-26, LCTS/2014-24, IFT-UAM/CSIC-14-050

'Stop' that ambulance! New physics at the LHC?

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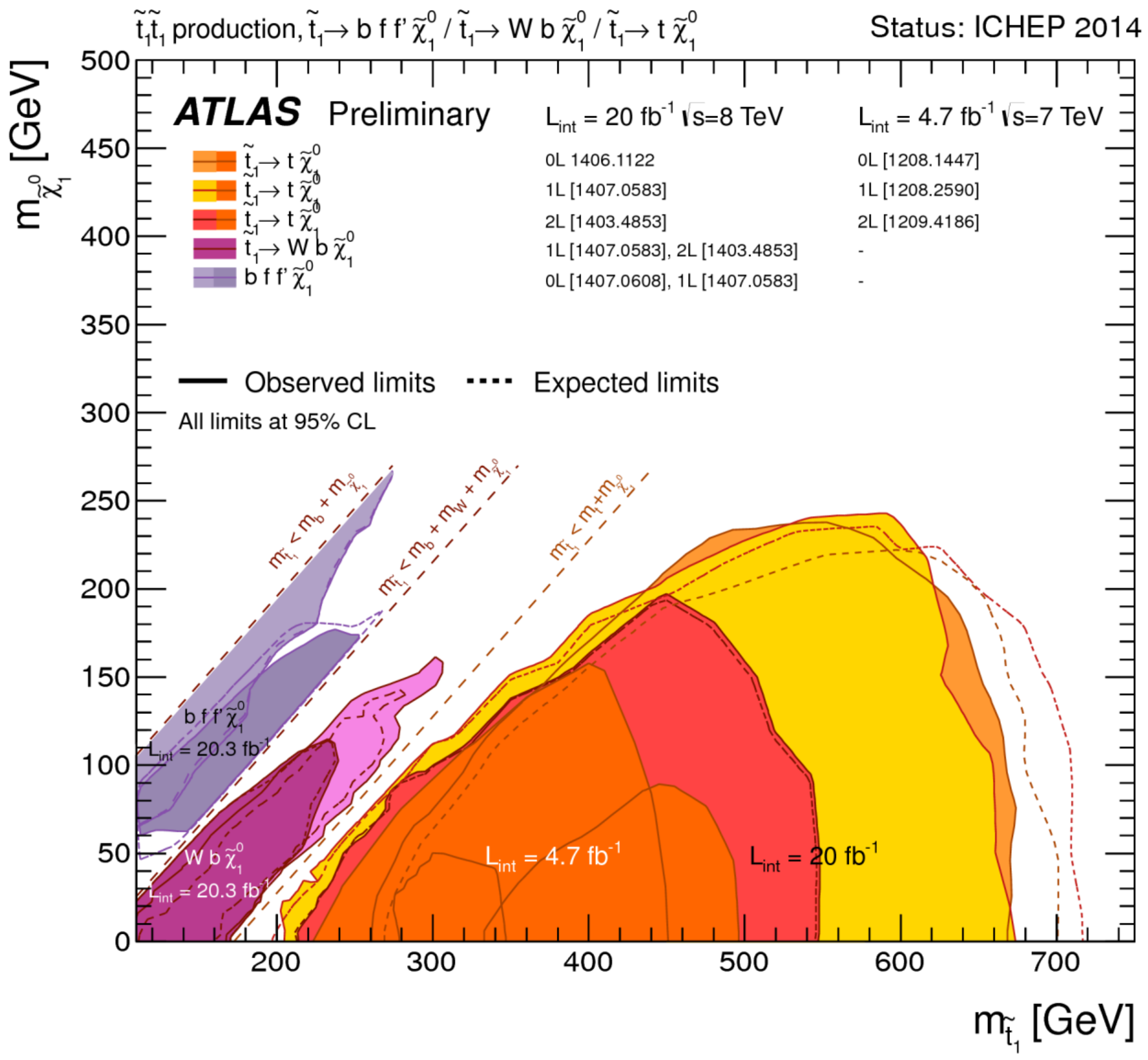
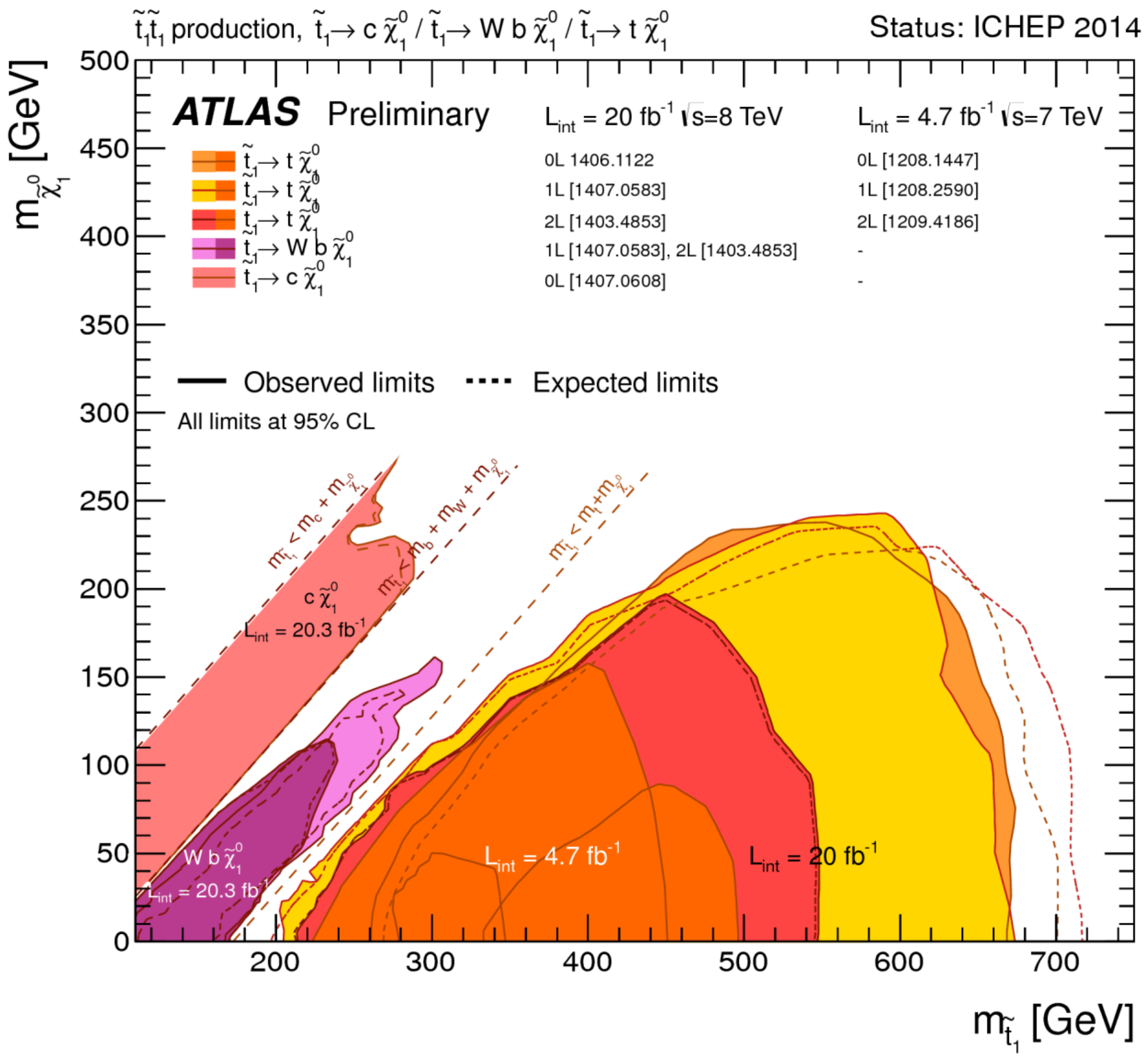
[b] *King's College London, Department of Physics, London WC2R 2LS, UK*
[c] *University of Heidelberg, Institut für Theoretische Physik, Philosophenweg 16, D-69120 Heidelberg, Germany*
E-mail: jong.kim@csic.es, krzysztof.rolbiecki@desy.de, kazuki.sakurai@kcl.ac.uk, tattersall@thphys.uni-heidelberg.de

ABSTRACT: A number of LHC searches now display intriguing excesses. Most prominently, the measurement of the W^+W^- cross-section has been consistently $\sim 20\%$ higher than the theoretical prediction across both ATLAS and CMS for both 7 and 8 TeV runs. More recently, supersymmetric searches for final states containing two or three leptons have also

v2 [hep-ph] 27 Jun 2014

What about Light Stop Scenarios?





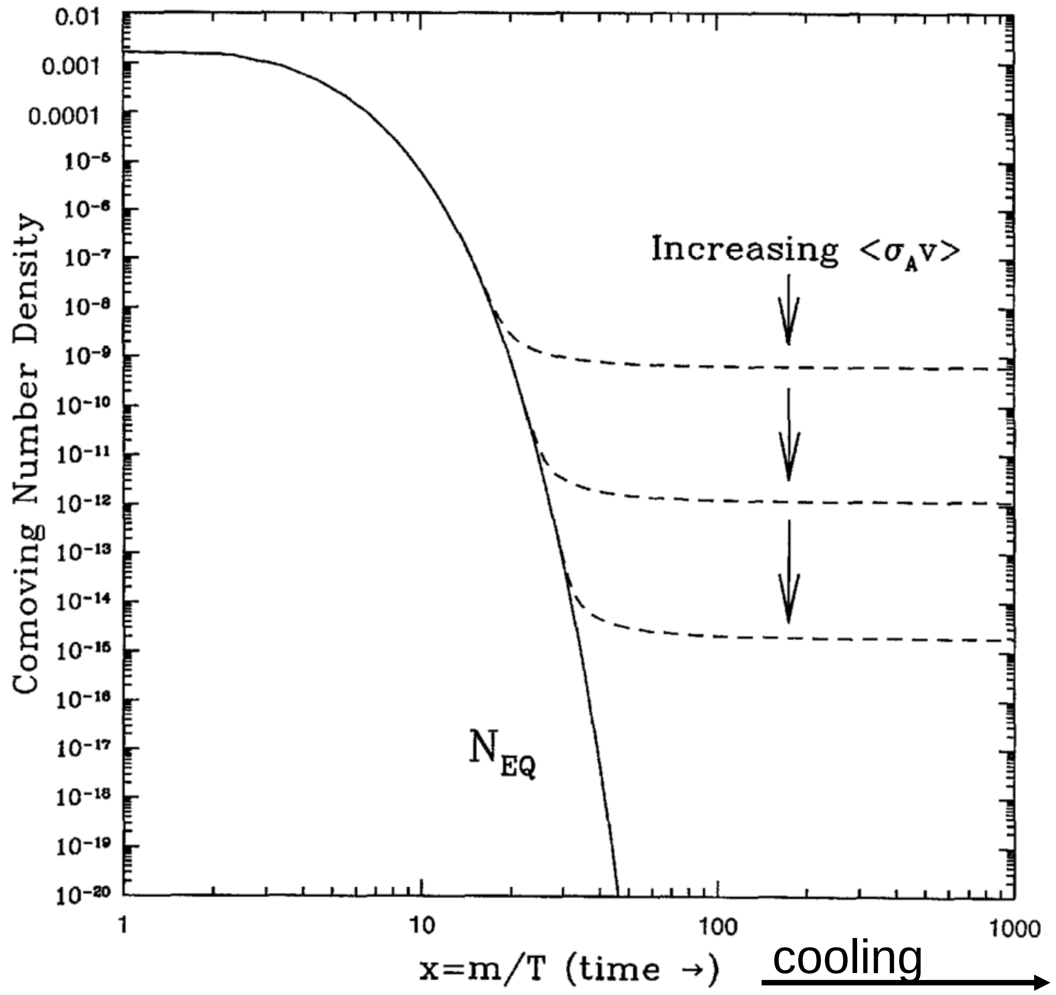
strip of degenerate masses of neutralino / stop very hard to probe

Interesting for the right Relic Density

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

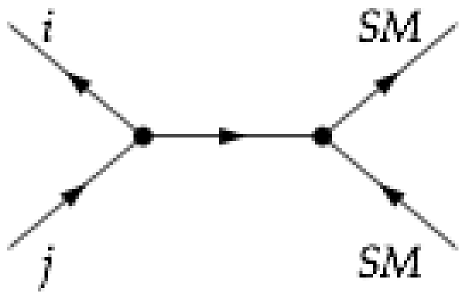
$$\dot{n} + 3Hn = -\langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2)$$

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



cooling down →

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



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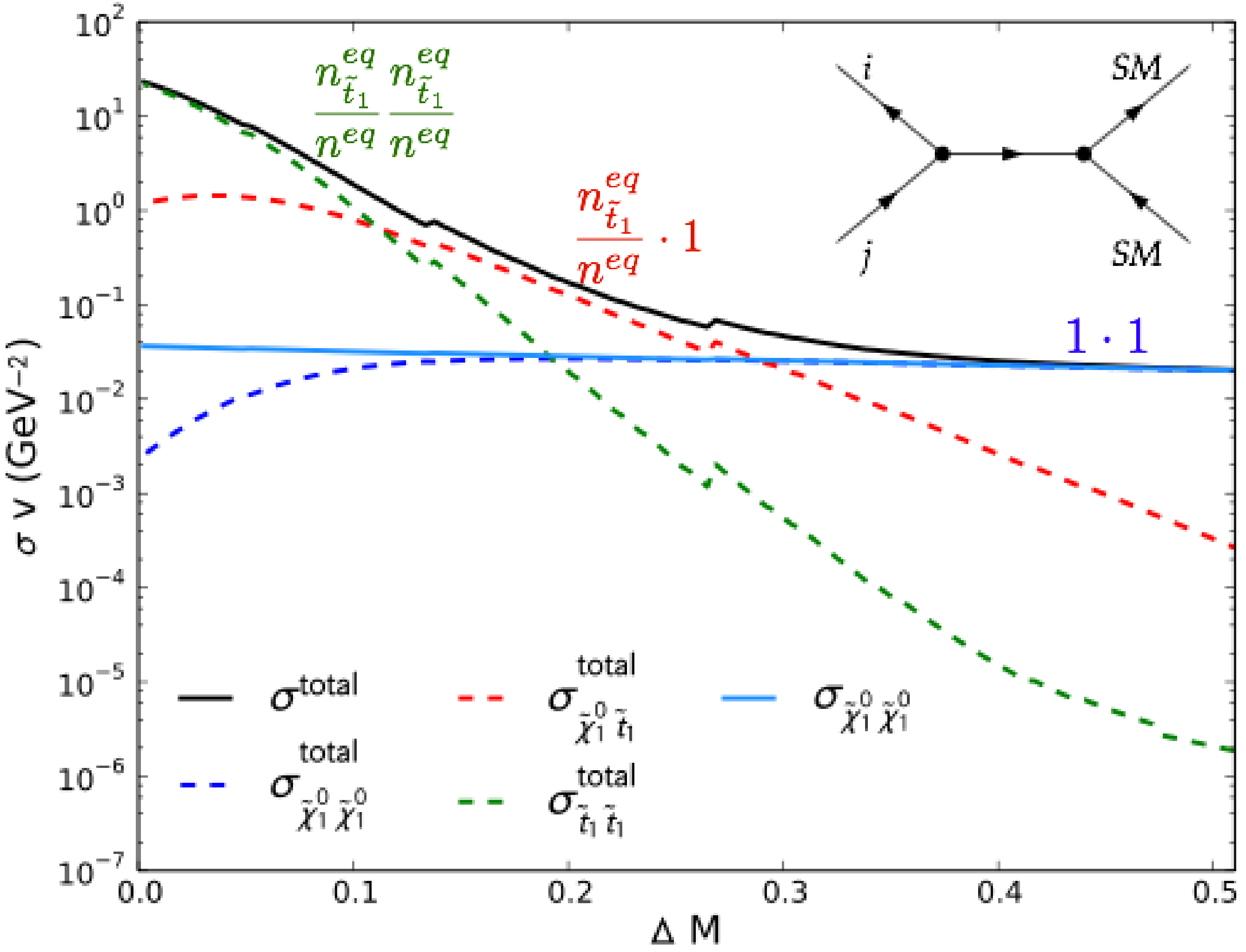
$$\langle\sigma_{\text{eff}} v\rangle = \sum_{ij}\langle\sigma_{ij}v_{ij}\rangle \frac{n_i^{eq}}{n^{eq}}\frac{n_j^{eq}}{n^{eq}}$$

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

- assuming lightest stop being the NLSP

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

Effective cross section



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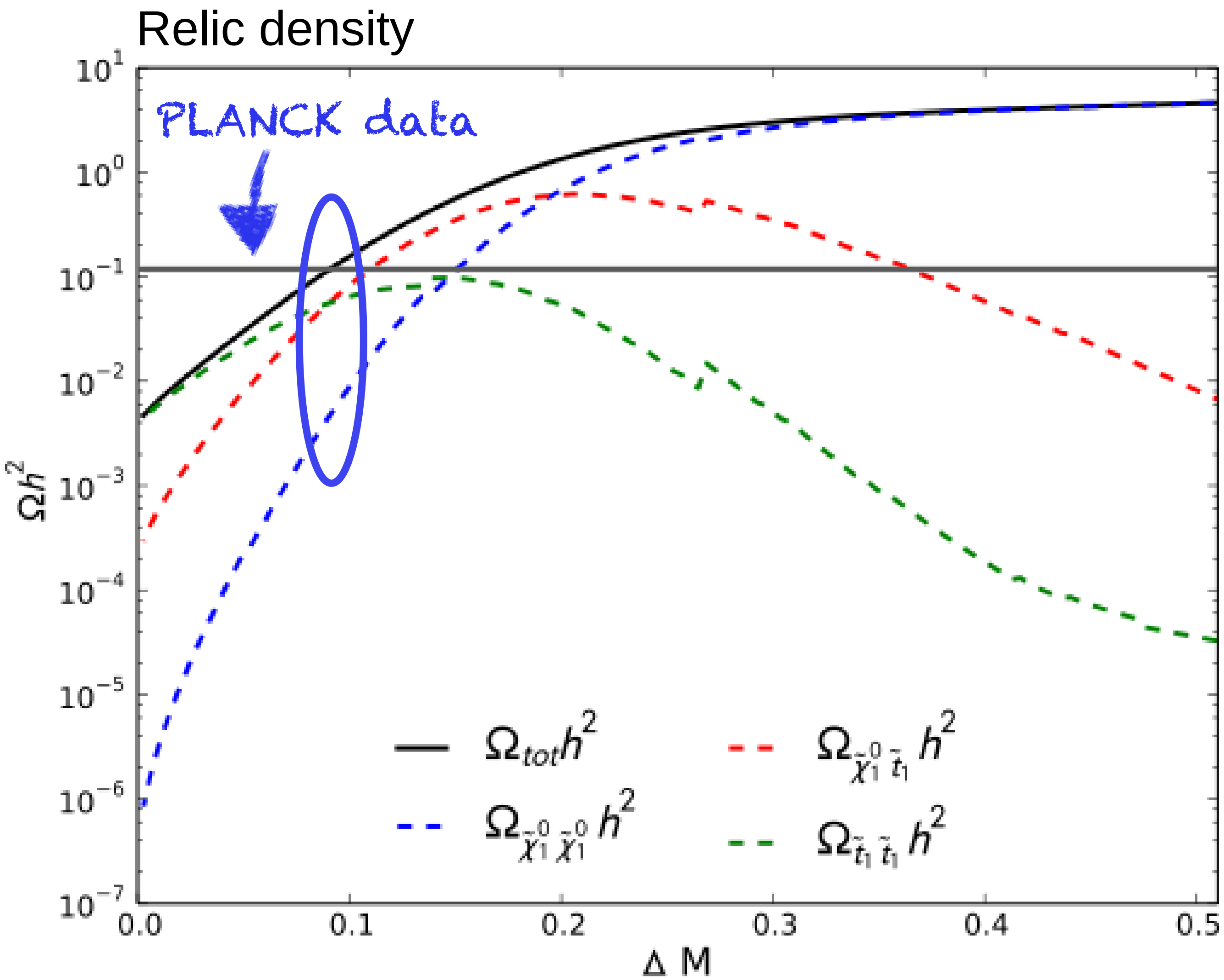
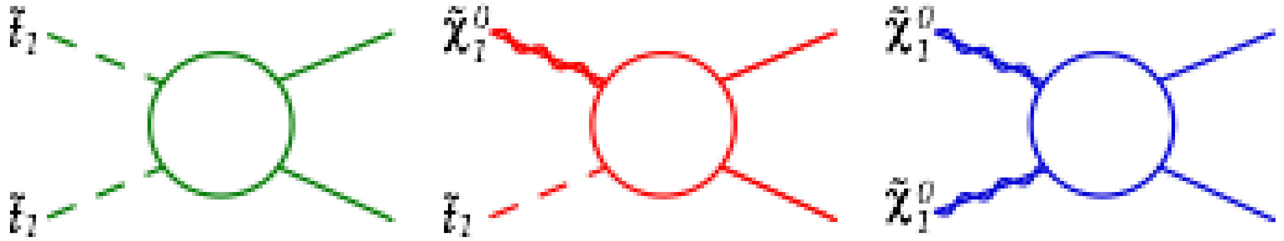




admixture of neutralino-stop coannihilation processes can be important to achieve the right relic abundance and not to overclose the universe

Current Status of Theoretical Calculation

- precise relic density determination by PLANCK

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

Planck Collaboration, arXiv:1303.5076

- 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)

- Theoretical prediction allows for constraining particle physics models

$$\dot{n} + 3Hn = -\langle \sigma_{\text{eff}\,v} \rangle (n^2 - n_{\text{eq}}^2) \quad \Rightarrow \quad \Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\text{eff}} v \rangle}$$

particle physics

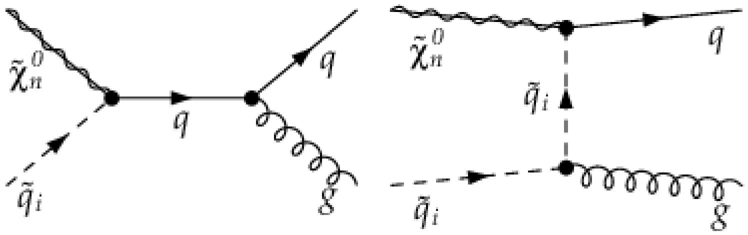
$\Rightarrow$ Calculation so far just on (effective) tree level

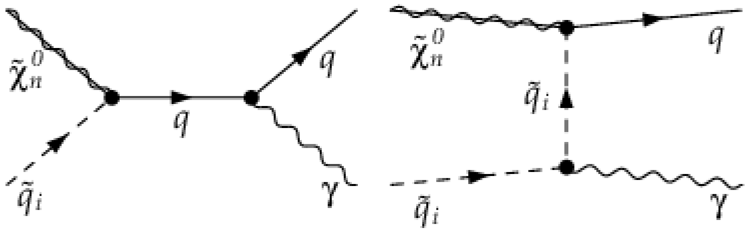
Neutralino-Stop Coannihilation at Tree Level

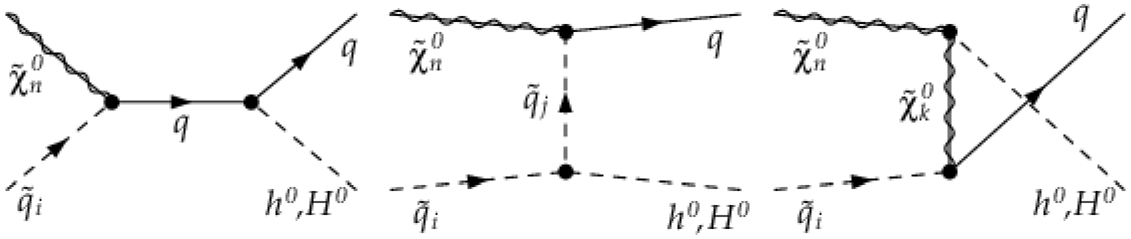
- 8 different final states have to be considered
- gluon, Higgs and electroweak vector bosons in the final state

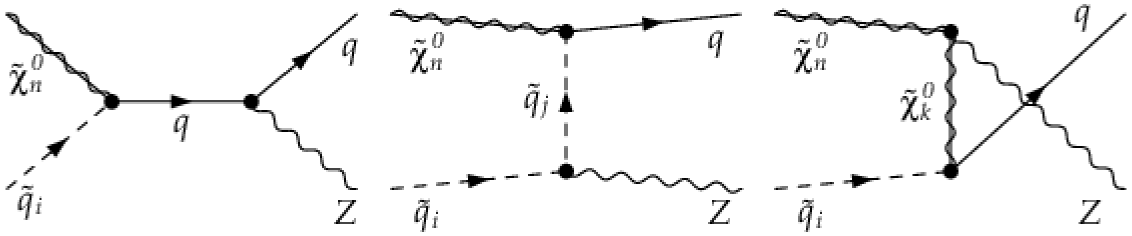
$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\text{eff}} v \rangle}$$

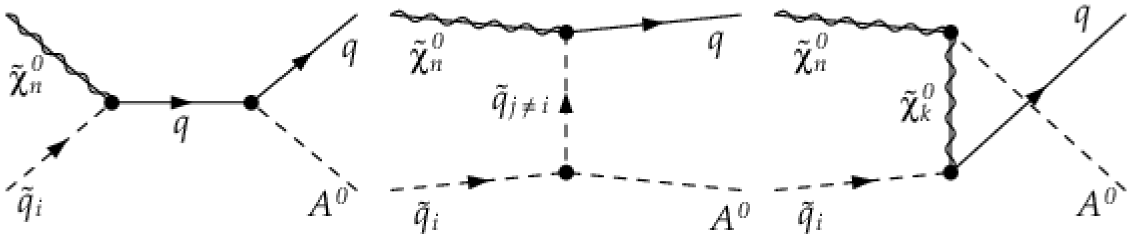
particle physics

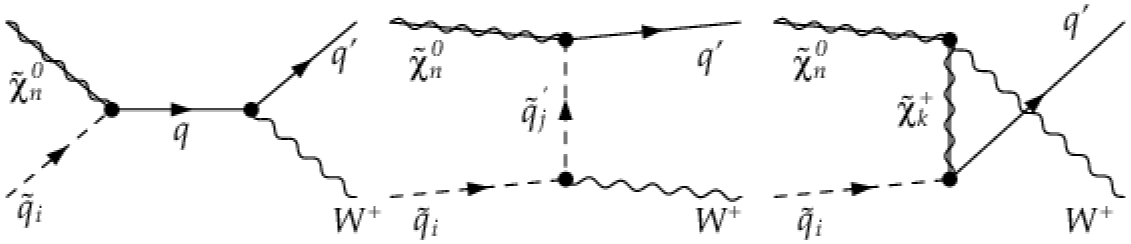


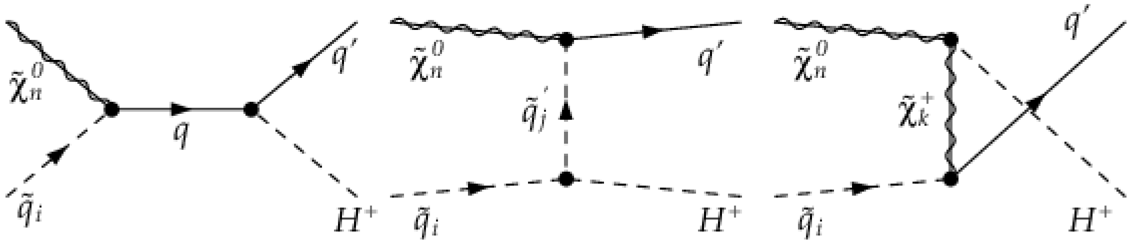








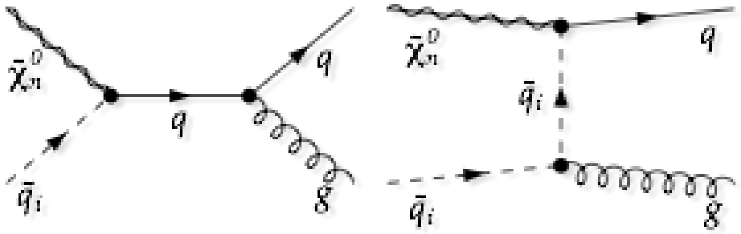




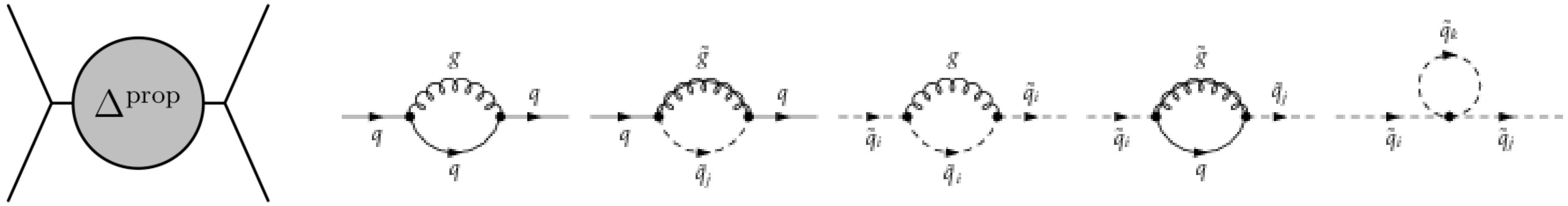
calculating loop corrections to match experimental precision

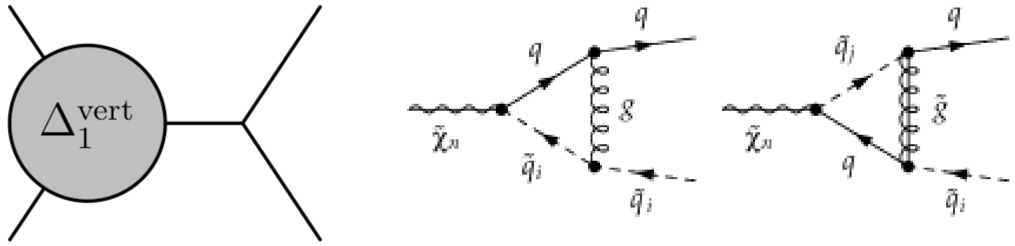
… and at one-loop level including SUSY-QCD

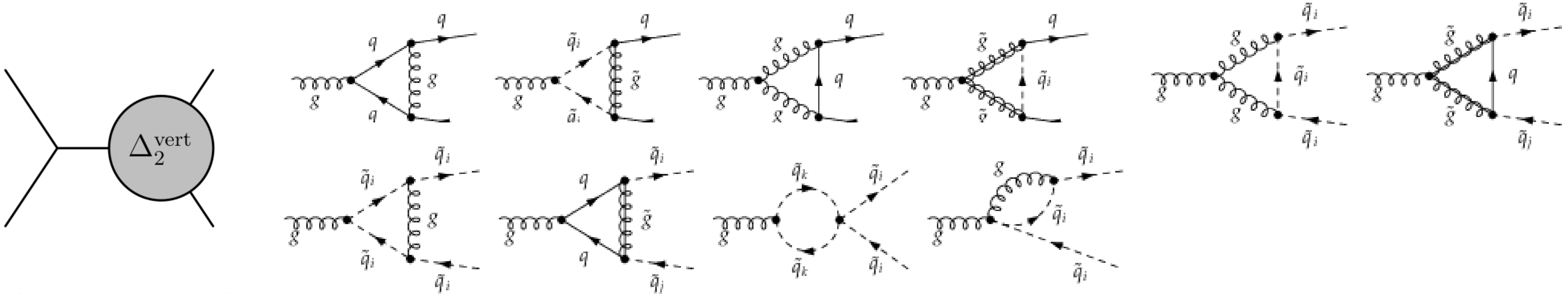
- tree level with gluon in the final state

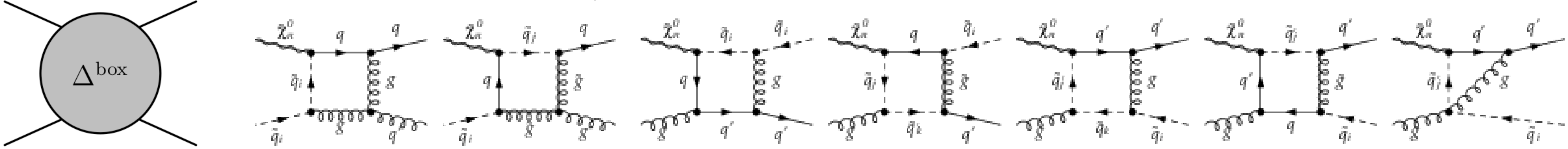


- NLO corrections give rise to propagator corrections, vertex corrections and box diagrams









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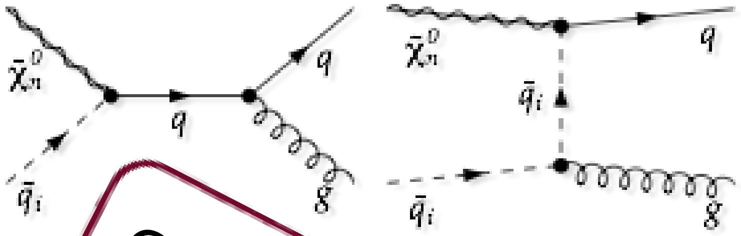

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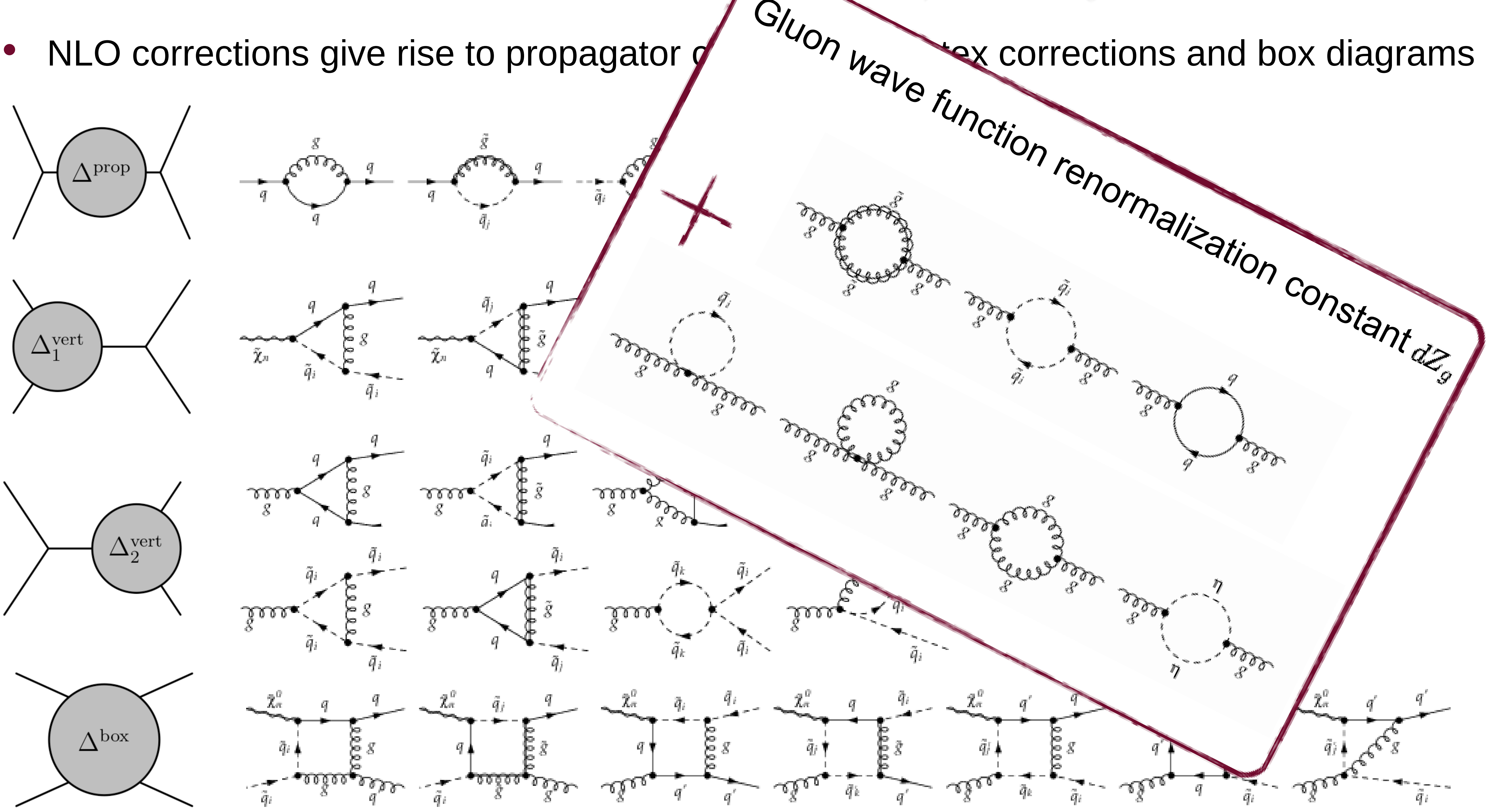
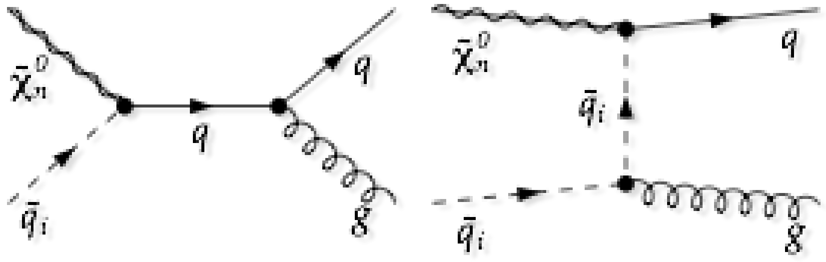
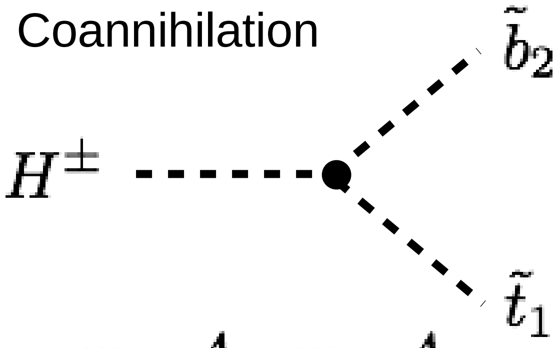


Gluon wave function renormalization constant dZ_g

Renormalisation

- Aim: Renormalisation scheme which is valid over a wide parameter space for all (co)annihilation




Coannihilation

$\sim m_b, A_b, m_t, A_t$

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

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

input parameters

dependent parameters

c.p. S. Heinemeyer, H. Rzehak, C. Schappacher, Phys. Rev. D82 075010 (2010)

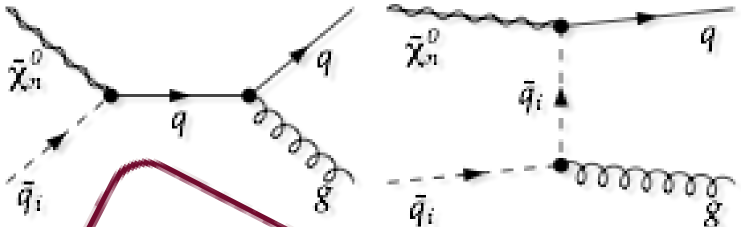
- α_s renormalisation

$$\alpha_s^{\overline{\text{MS}},\text{SM},(5)}(m_Z^2) \xrightarrow{(1)} \alpha_s^{\overline{\text{MS}},\text{SM},(5)}(Q^2) \xrightarrow{(2)} \alpha_s^{\overline{\text{DR}},\text{SM},(5)}(Q^2) \xrightarrow{(3)} \alpha_s^{\overline{\text{DR}},\text{MSSM},(6)}(Q^2)$$

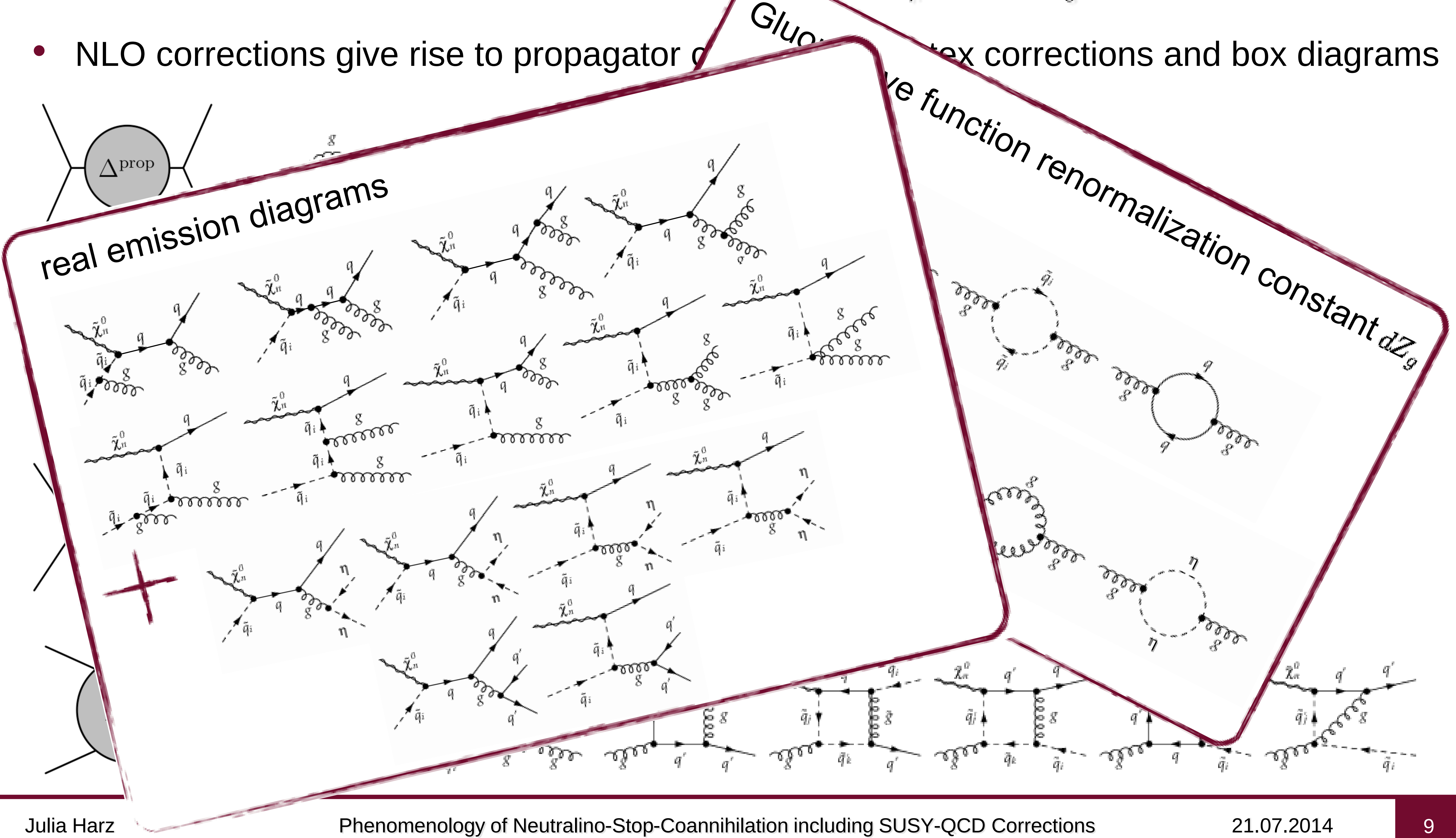
J. Vermaseren, S. Larin, T. Ritbergen, Phys. Lett. B405 (1997)
R. Harlander, L. Mihaila, M. Steinhauser, Phys. Rev. D (2005)
A. Bauer, L. Mihaila, J. Salomon, JHEP 0902:037 (2009)

… and at one-loop level including SUSY-QCD

- tree level with gluon in the final state



- NLO corrections give rise to propagator c tex corrections and box diagrams



real emission diagrams

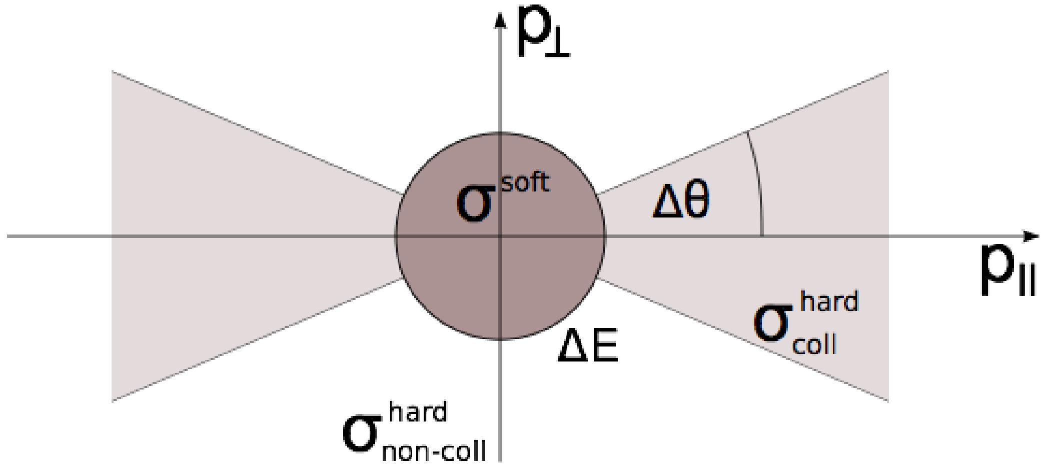
Gluo ve function renormalization constant dZ_g

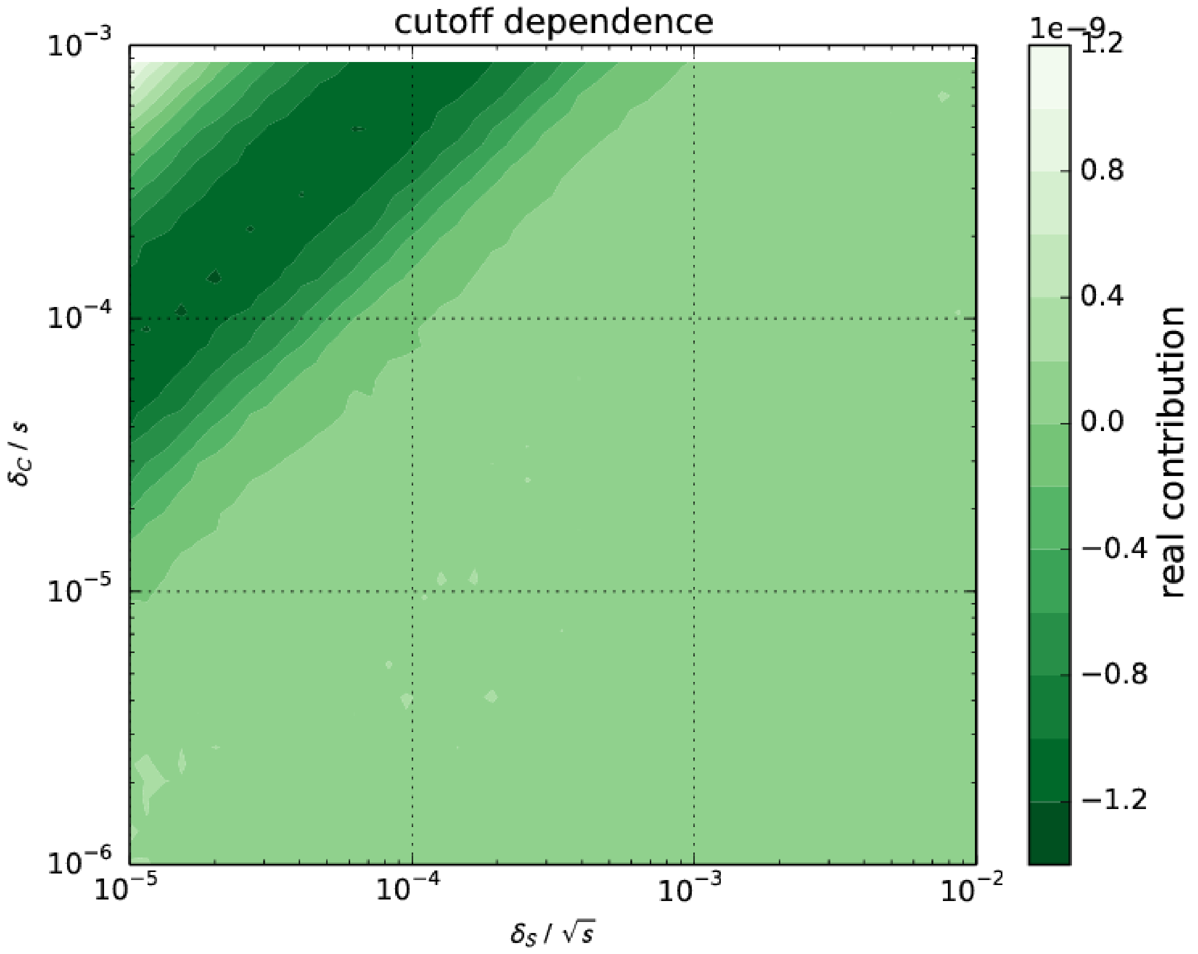
IR divergences

$$\sigma^{\text{NLO}} = \int_{2\to2} d\sigma^{\text{virtual}} + \int_{2\to3} d\sigma^{\text{real}} = \text{finite}$$

- 2-cutoff phase space slicing

B. W. Harris, J. F. Owens, Phys. Rev. D65 (2002)



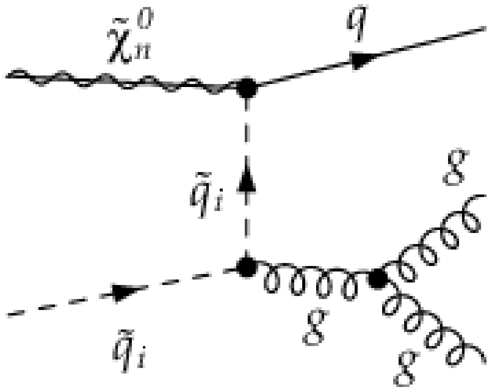


$$\sigma^{real} = \sigma^{\text{soft}}(\Delta E) + \sigma^{\text{hard}}_{\text{coll}}(\Delta E, \Delta\theta) + \sigma^{\text{hard}}_{\text{non-coll}}(\Delta E, \Delta\theta)$$

eikonal approximation

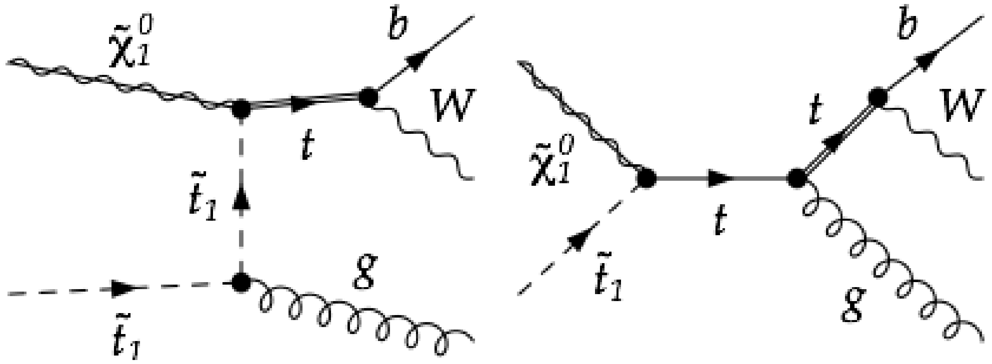
hard-collinear approximation

pure 2 ⟶ 3 processes



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)

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

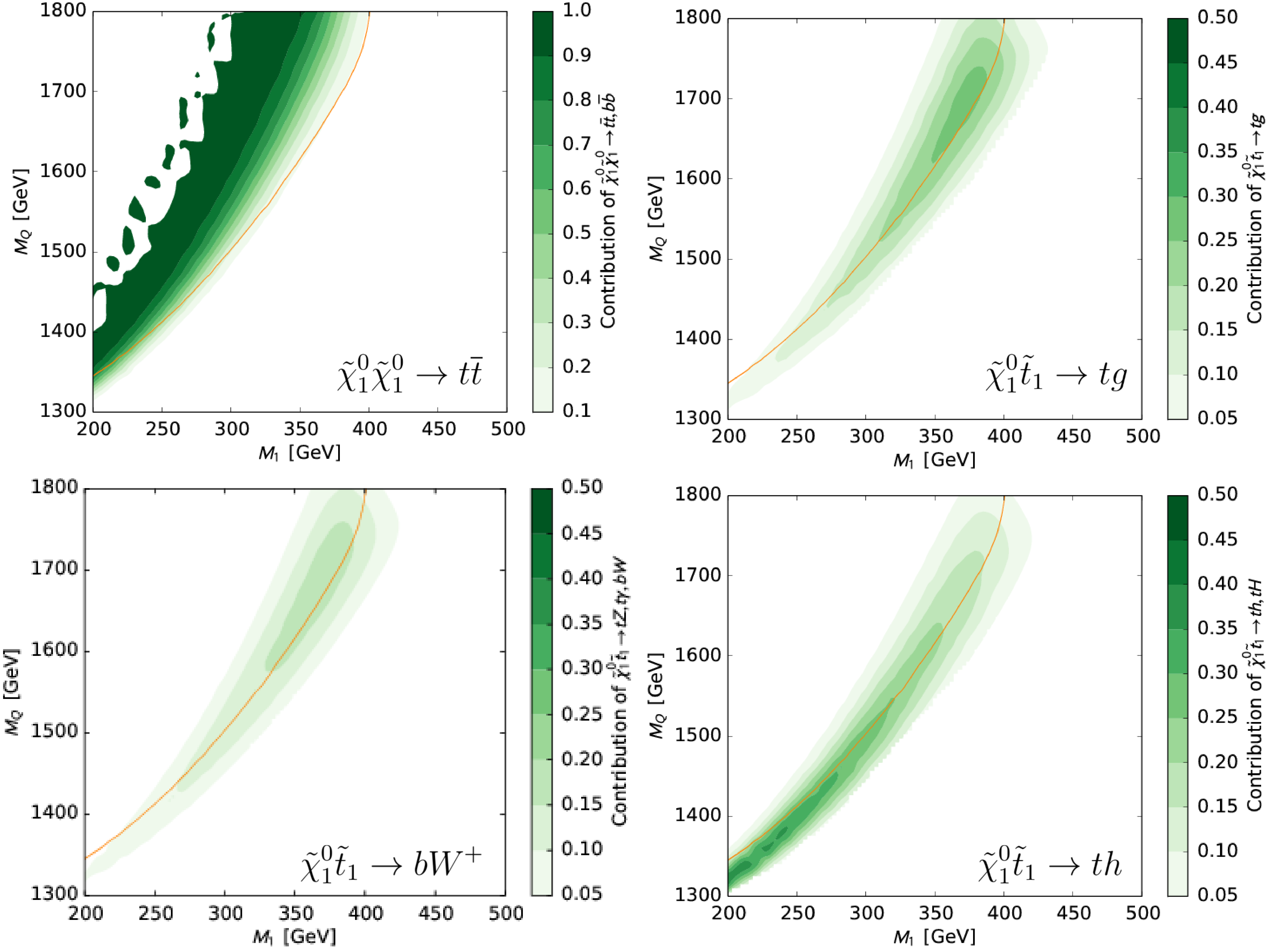
- “counterterm” consists of Breit-Wigner weighted on-shell squared matrix element

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

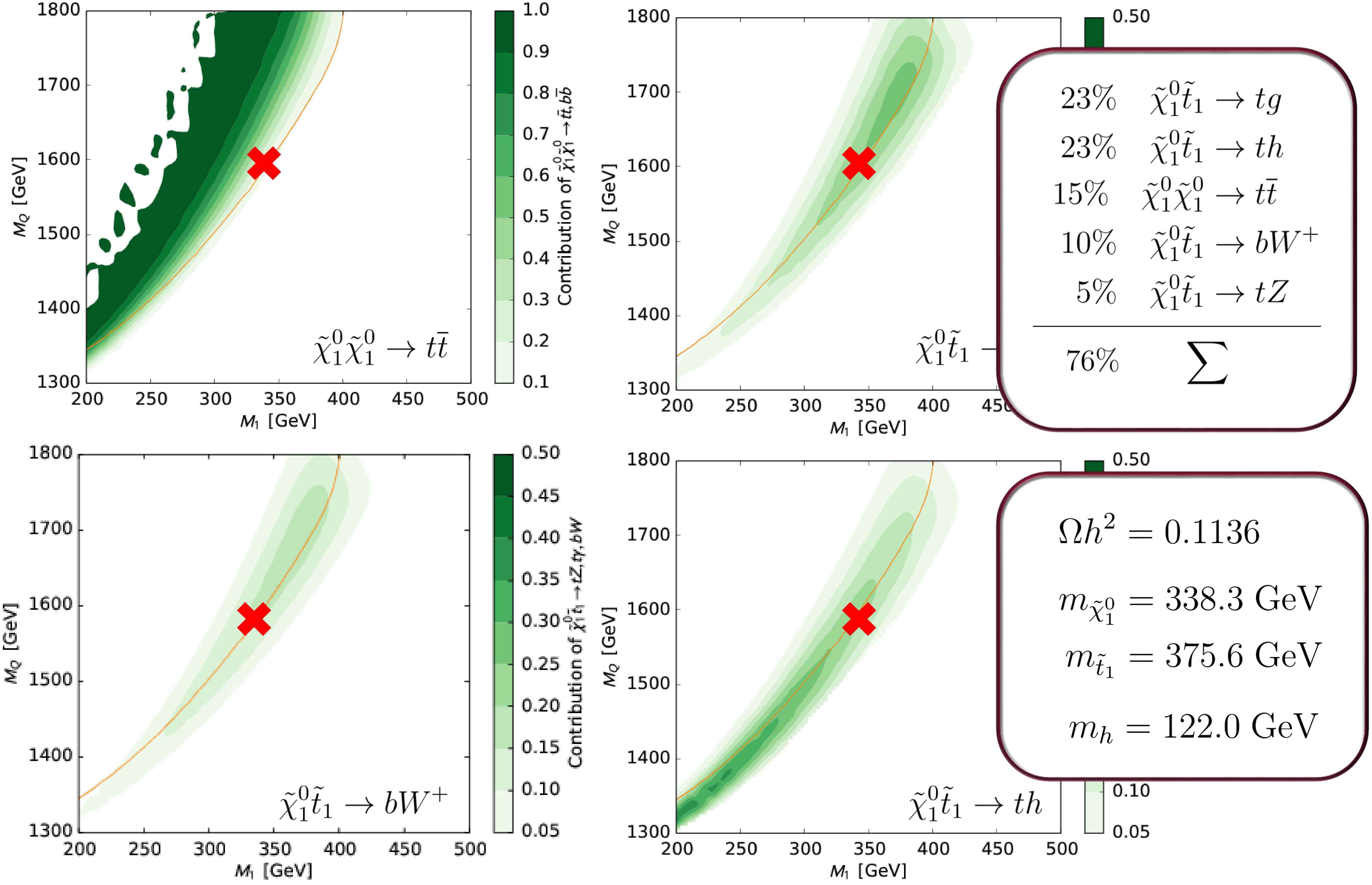
- resonant propagators are regularized by Breit-Wigner propagator

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

Combining different (co)annihilating Channels



Combining different (co)annihilating Channels



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%	$\sum$

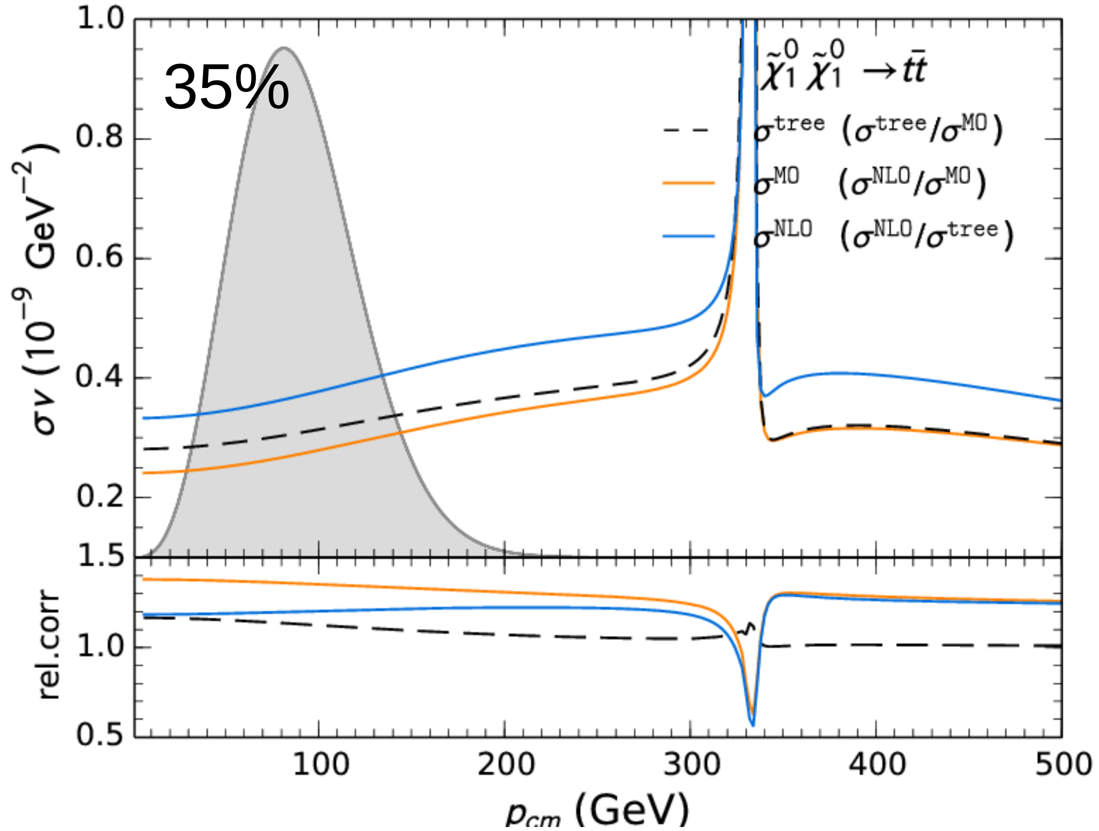
$$\Omega h^2 = 0.1136$$

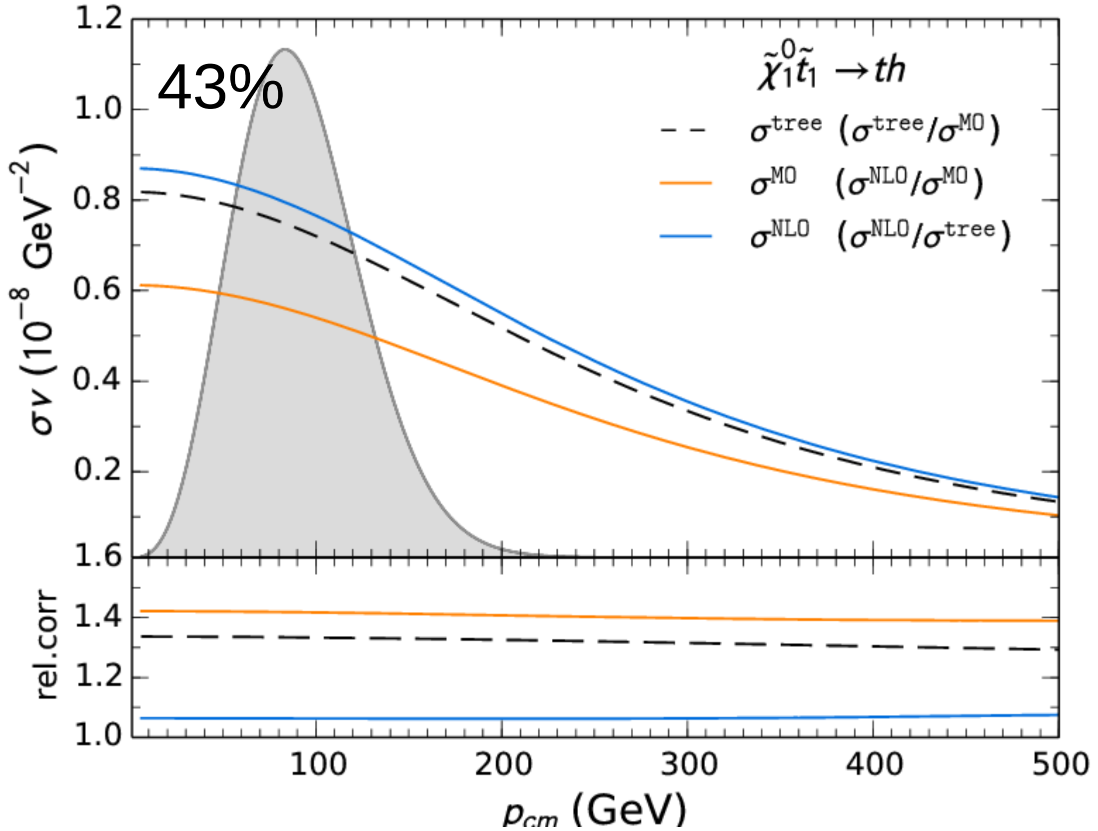
$$m_{\tilde{\chi}_1^0} = 338.3 \text{ GeV}$$

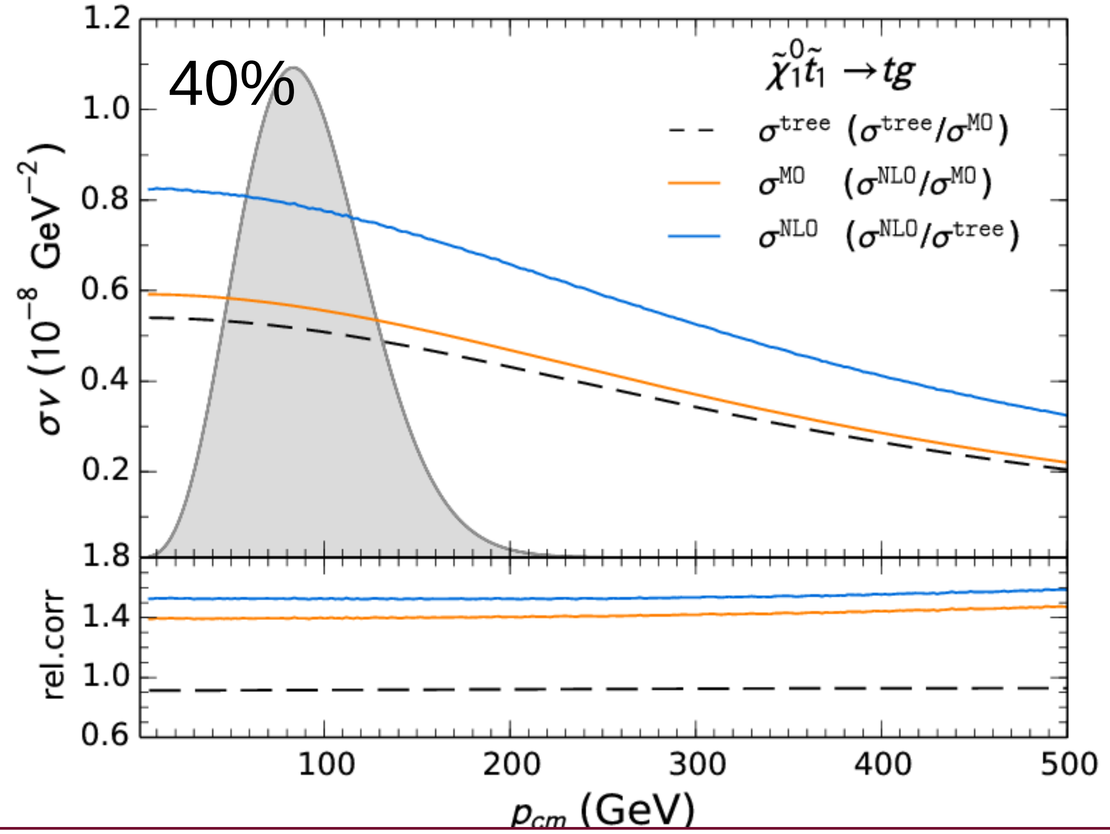
$$m_{\tilde{t}_1} = 375.6 \text{ GeV}$$

$$m_h = 122.0 \text{ GeV}$$

Impact on the (Co)annihilation Cross Section



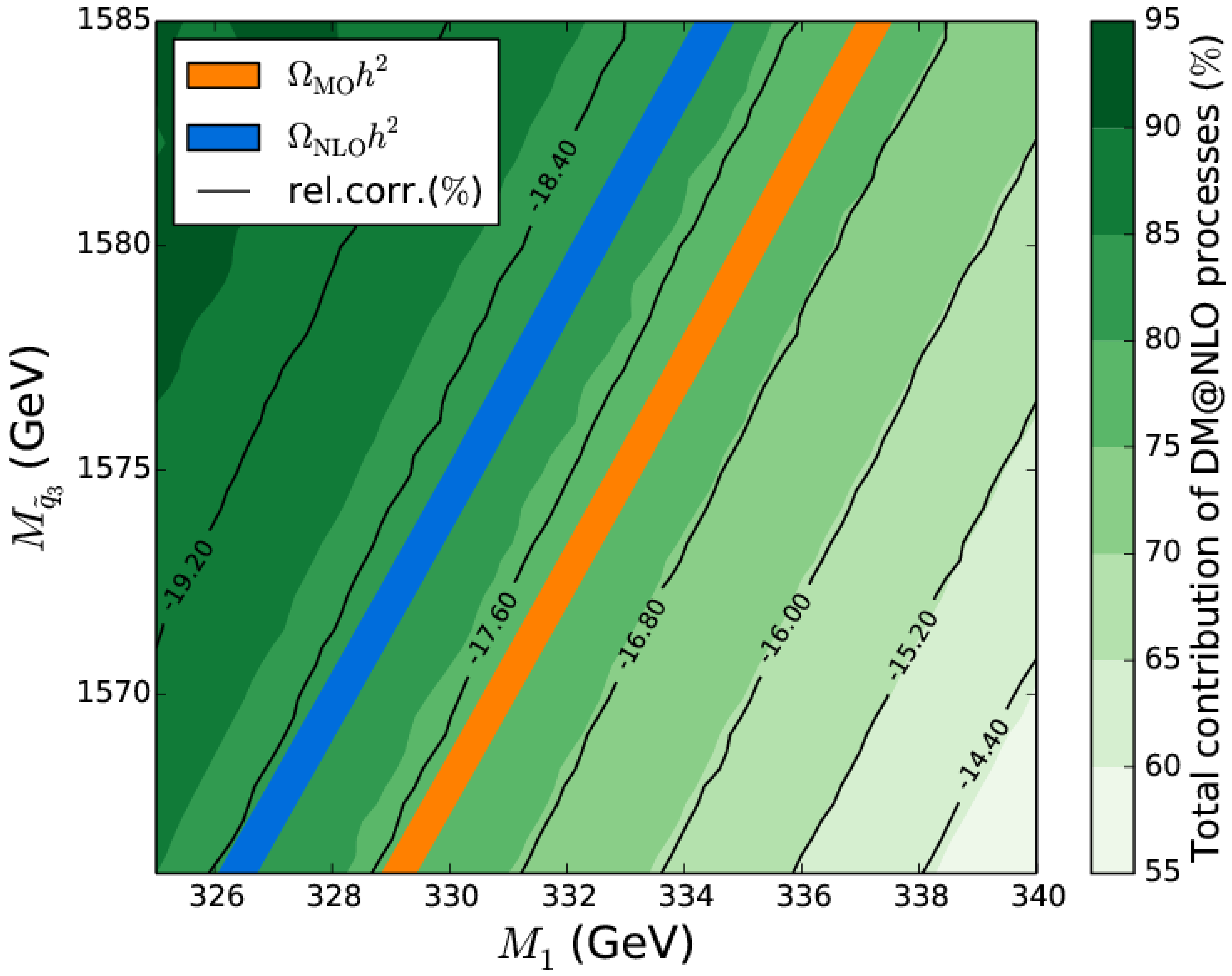




- relative correction with respect to default micrOMEGAs of up to 45 % for each subchannel

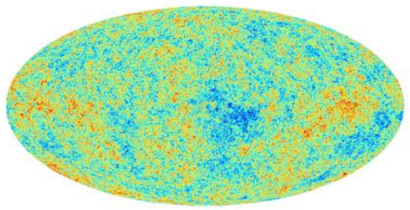
Impact on the Neutralino Relic Density

Impact of all combined channels on the relic density

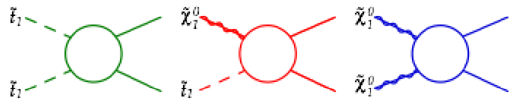


large relative corrections with respect to default MicrOMEGAs (~ 20%)

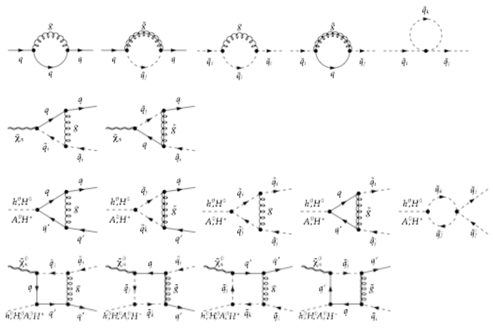
Conclusions



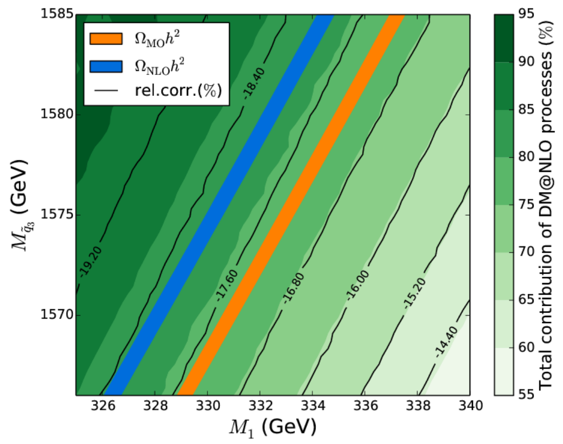
- SUSY might be hiding in the light stop region



- neutralino-stop coannihilation can be important in order to obtain the relic density in the right ballpark



- calculation of neutralino-stop coannihilation and neutralino annihilation at full next-to-leading order



- impact larger than current experimental uncertainties

DM@NLO

http://dmnlo.hepforge.org/

Backup

Interesting for a 126 GeV Higgs …

- Stop mixing matrix

$$\begin{pmatrix} m_{\tilde{t}_1}^2 & 0 \\ 0 & m_{\tilde{t}_2}^2 \end{pmatrix} = U^{\tilde{q}} \begin{pmatrix} M_{\tilde{Q}}^2 + m_t^2 + (I_q^{3L} - e_q \sin_W^2) \cos 2\beta m_Z^2 & m_t X_t \\ m_t X_t & M_{\tilde{U}}^2 + m_t^2 + e_q \sin_W^2 \cos 2\beta m_Z^2 \end{pmatrix} (U^{\tilde{q}})^\dagger$$

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

maximal contribution from stop mixing for $|X_t| \approx \sqrt{6}/M_{\mathrm{SUSY}}$

- Higgs mass corrected by dominant one-loop corrections

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

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

Light stops interesting for collider phenomenology
as well as for dark matter relic density!

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}

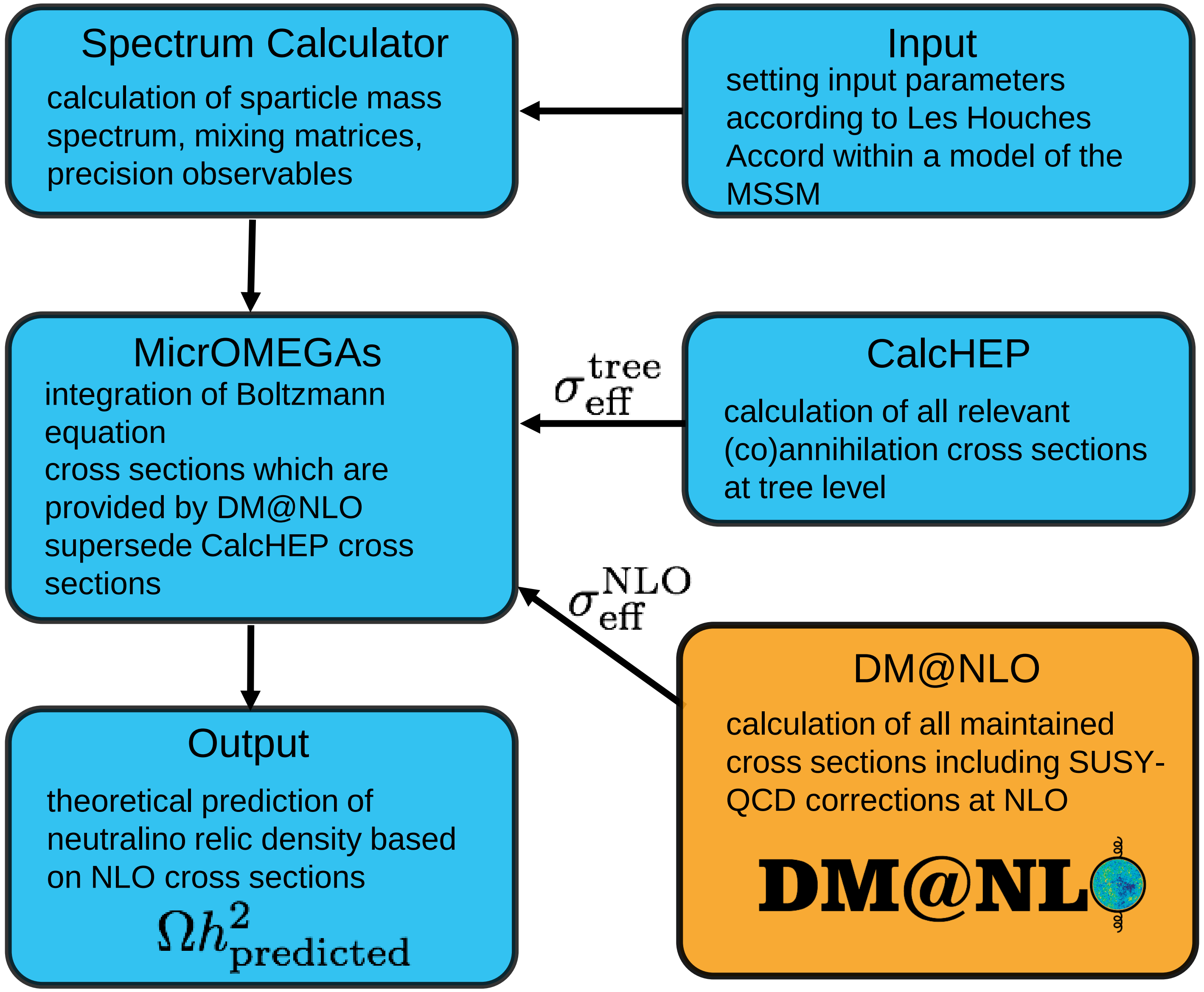
DM@NLO

Precision data from CMB measurements

PLANCK: ~ 2% uncertainty

DM@NLO – a Tool for an improved Relic Density Prediction

- current public tools: calculation based on max. effective tree level
- DM@NLO provides (co)annihilation processes including O(α_s) SUSY-QCD corrections
- DM@NLO will be publically available as Fortran library
- interface to MicrOMEGAs
- ability to perform broad parameter scans



Spectrum Calculator
calculation of sparticle mass spectrum, mixing matrices, precision observables

Input
setting input parameters according to Les Houches Accord within a model of the MSSM

MicrOMEGAs
integration of Boltzmann equation
cross sections which are provided by DM@NLO supersede CalcHEP cross sections

$\sigma_{\text{eff}}^{\text{tree}}$

CalcHEP
calculation of all relevant (co)annihilation cross sections at tree level

$\sigma_{\text{eff}}^{\text{NLO}}$

DM@NLO
calculation of all maintained cross sections including SUSY-QCD corrections at NLO

DM@NLO

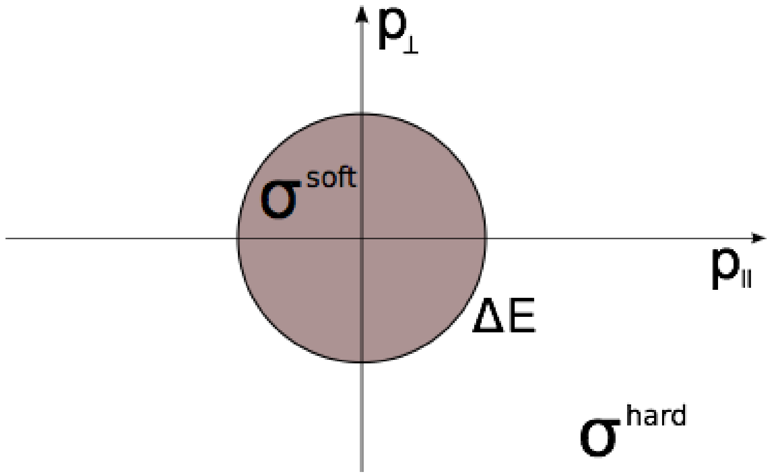
Output
theoretical prediction of neutralino relic density based on NLO cross sections

$\Omega h^2_{\text{predicted}}$

Phase Space Slicing (one cutoff)

- phase space is devided in soft and hard part by cut off ΔE

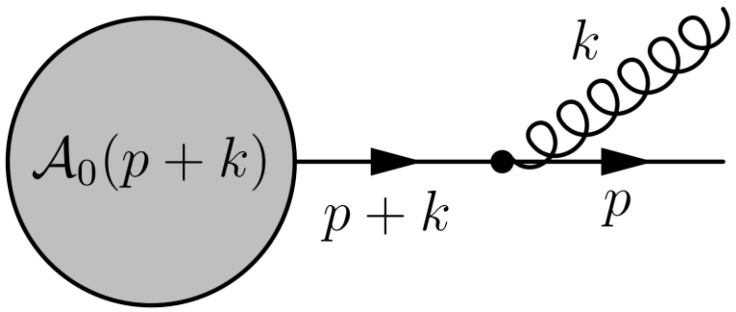
$$\sigma^{\text{real}} = \sigma^{\text{soft}}(\Delta E) + \sigma^{\text{hard}}(\Delta E)$$



- use eikonal approximation in soft limit

$$\mathcal{M} = \mathcal{A}_0(p+k)\frac{i(\not{p}+\not{k}+m)}{(p+k)^2-m^2}(-ig_sT^a\gamma^\mu)\overline{u}(p)\varepsilon^*_\mu(k)$$

$$\mathcal{M} = \mathcal{A}_0(p)\overline{u}(p)\frac{p\cdot\varepsilon^*}{p\cdot k}(g_sT^a) \qquad \text{with} \qquad k^\mu \to 0$$



$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{soft}} = -\left(\frac{d\sigma}{d\Omega}\right)_0 \times \frac{g_s^2C_F\mu^{4-D}}{8\pi^3}\int_{|\vec{k}|\leq\Delta E}\frac{d^{D-1}k}{(2\pi)^{D-4}}\frac{1}{2E_k}\left[-\frac{2p_1\cdot p_2}{(p_1\cdot k)(k\cdot p_2)}\right]$$

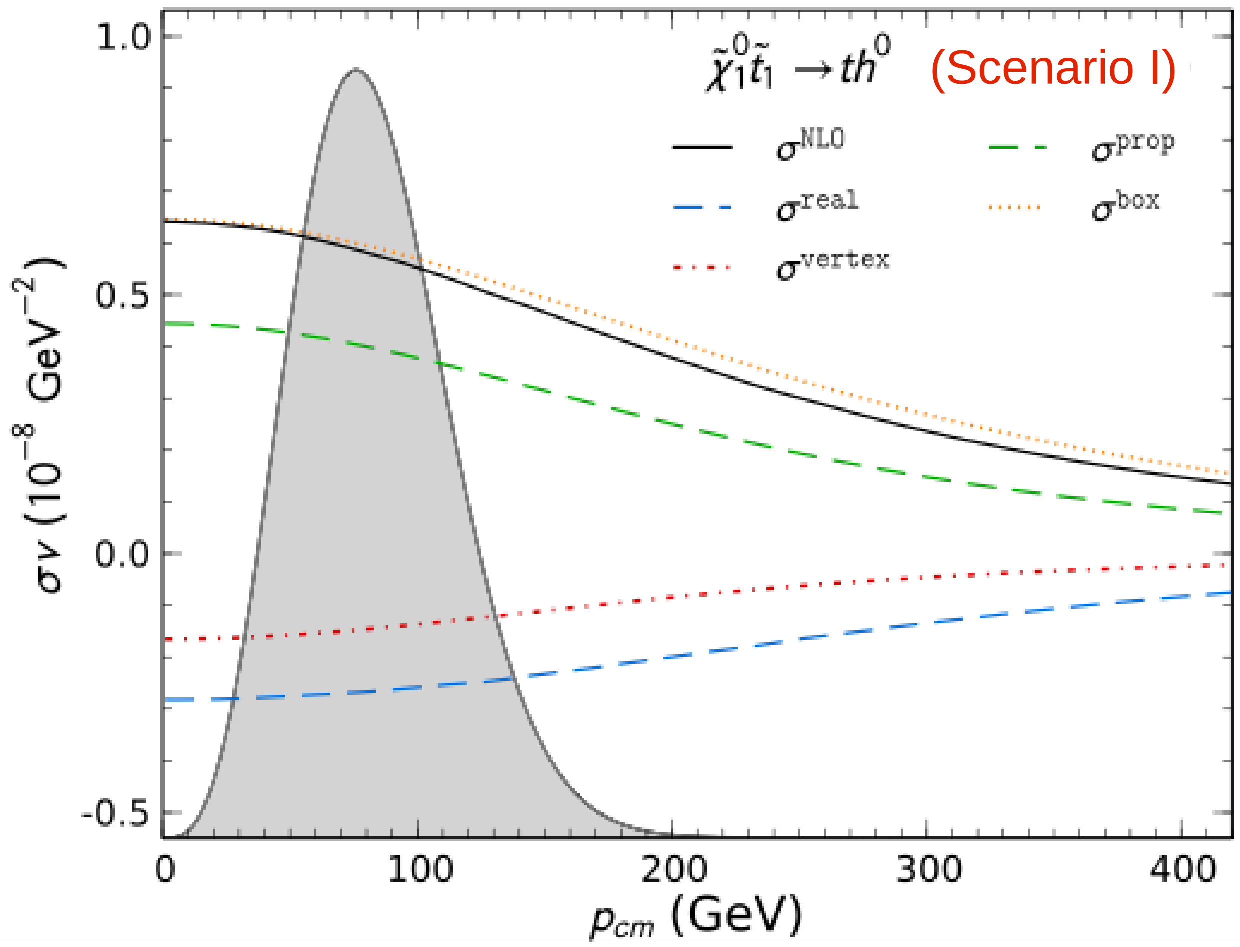
Veltmann, `t Hooft, Nuclear Physics B 153 (1979)

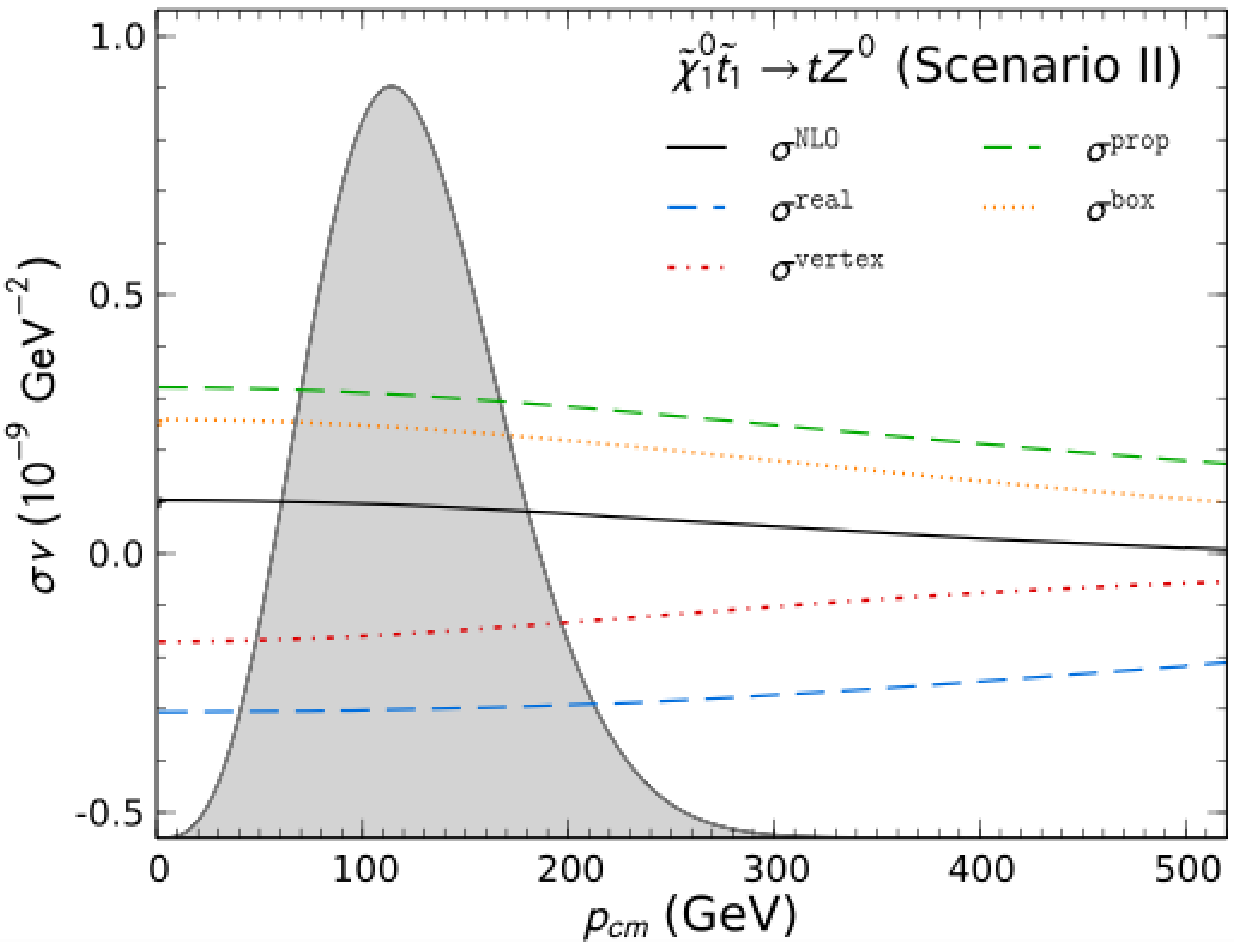
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{soft}} = \left(\frac{d\sigma}{d\Omega}\right)_0 \times \frac{-g_s^2C_F}{8\pi^2}\left[-\frac{1}{\epsilon}+\dots\right]$$

⇨ a finite total cross section is achieved

Interplay of Virtual and Real Corrections

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

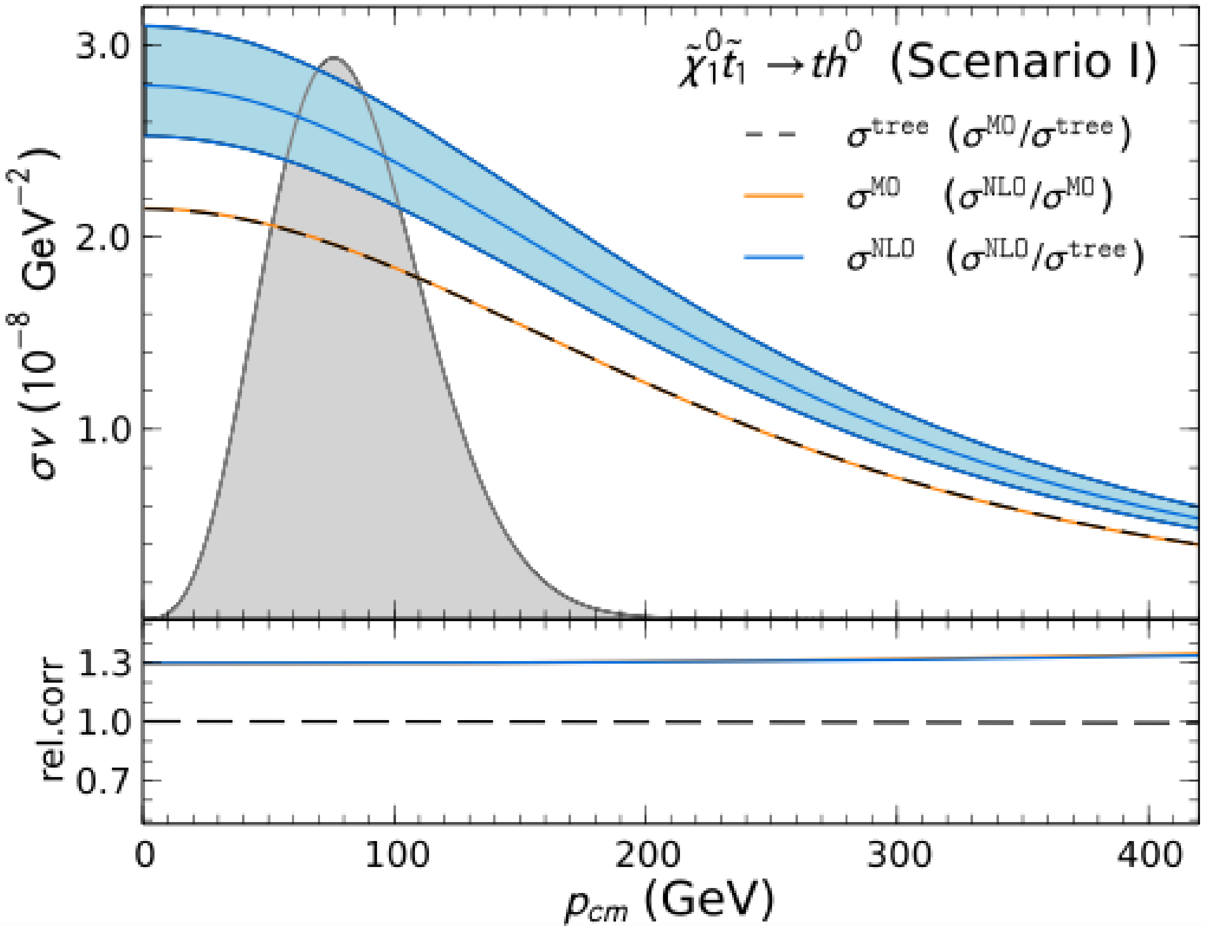


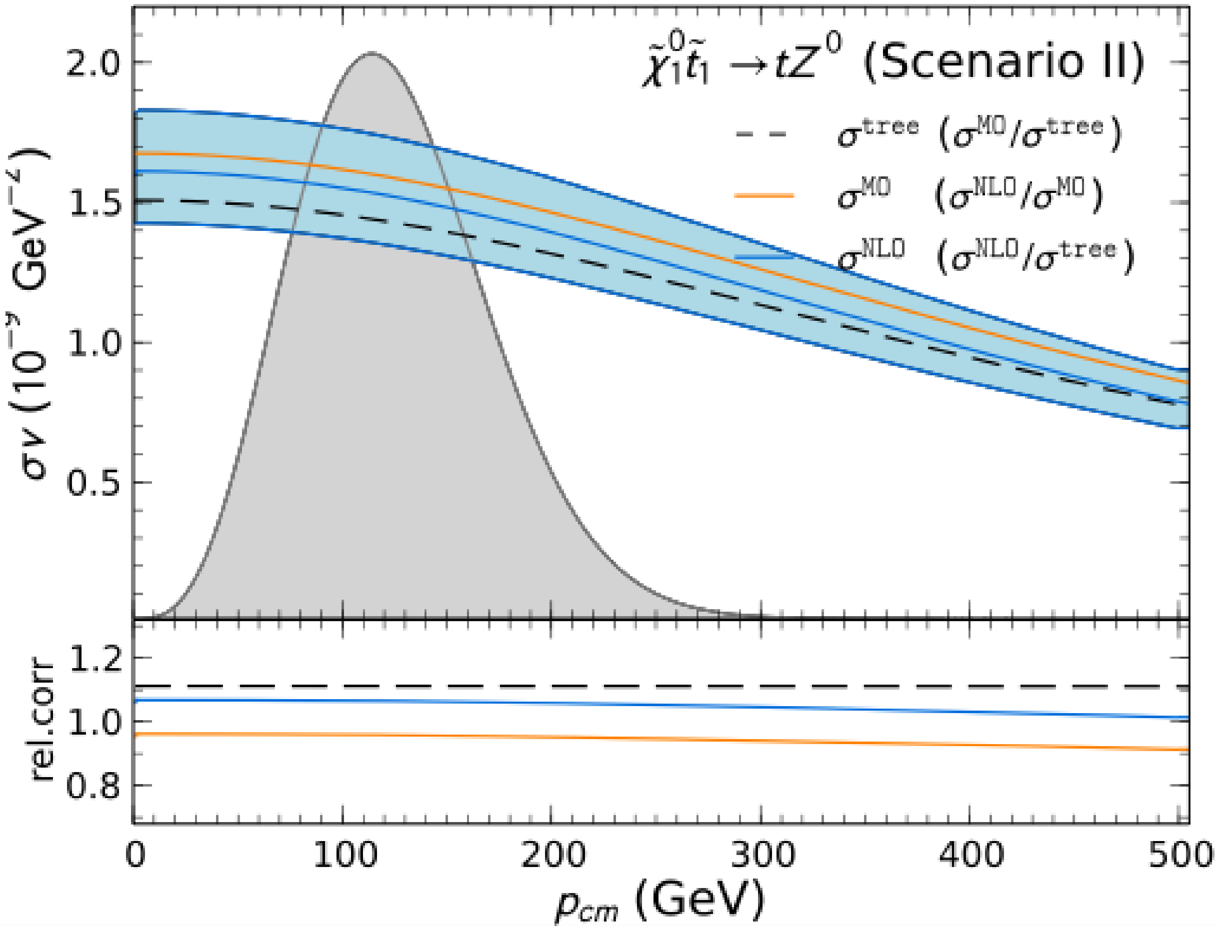


contributions still contain uncancelled logarithms

Scale Variation

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

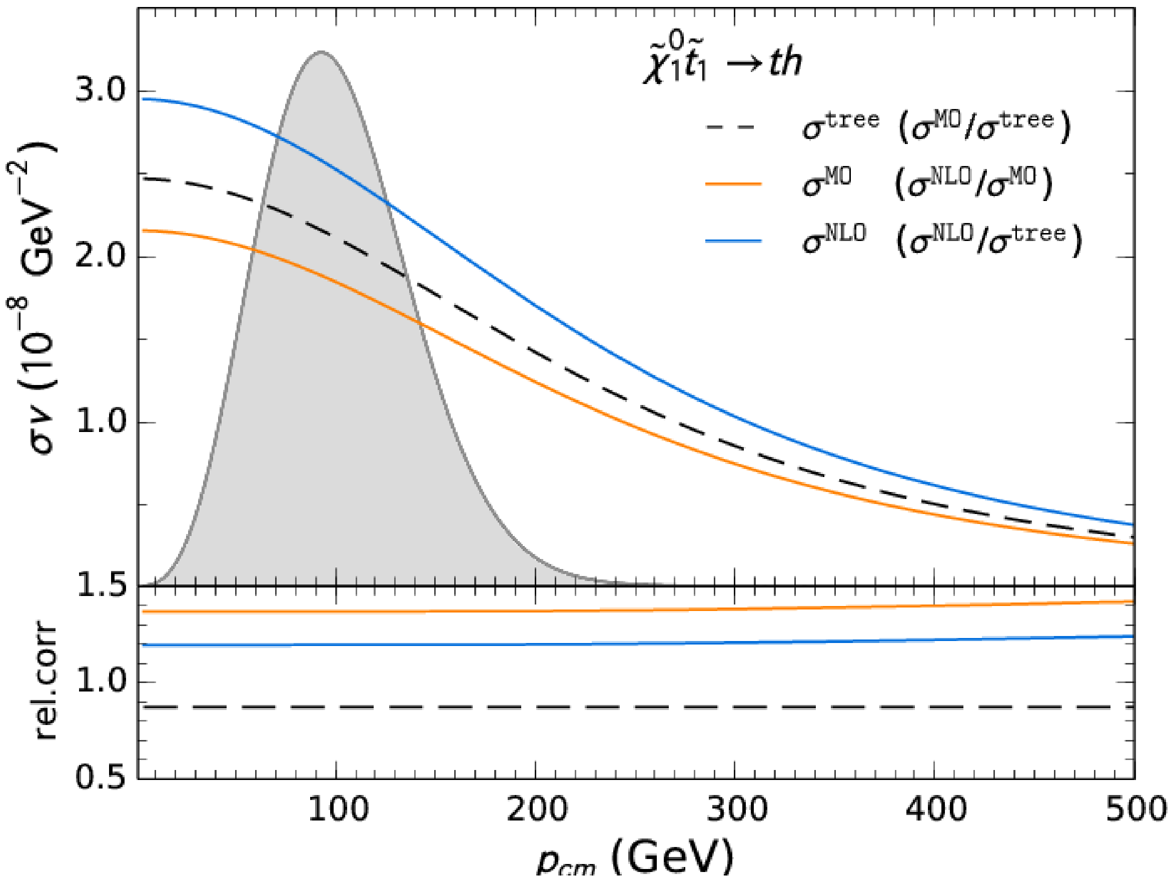


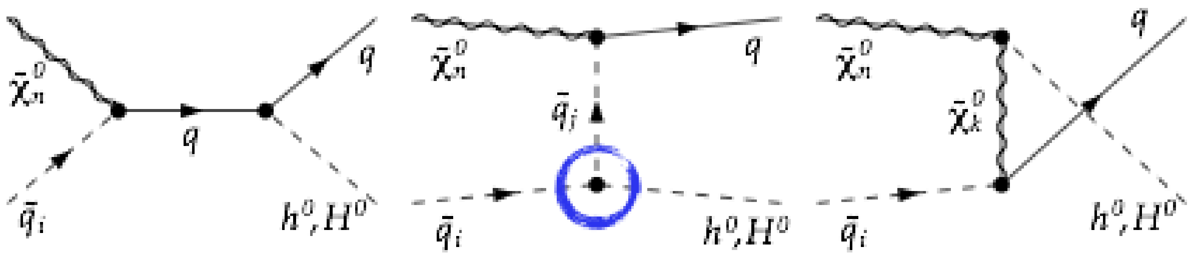


Impact on the Coannihilation Cross Section

Comparison of tree-level, one-loop and MicrOMEGAs result

cross section





th° final state: 38.5 %

large relative corrections comparing NLO cross section with MicrOMEGAs

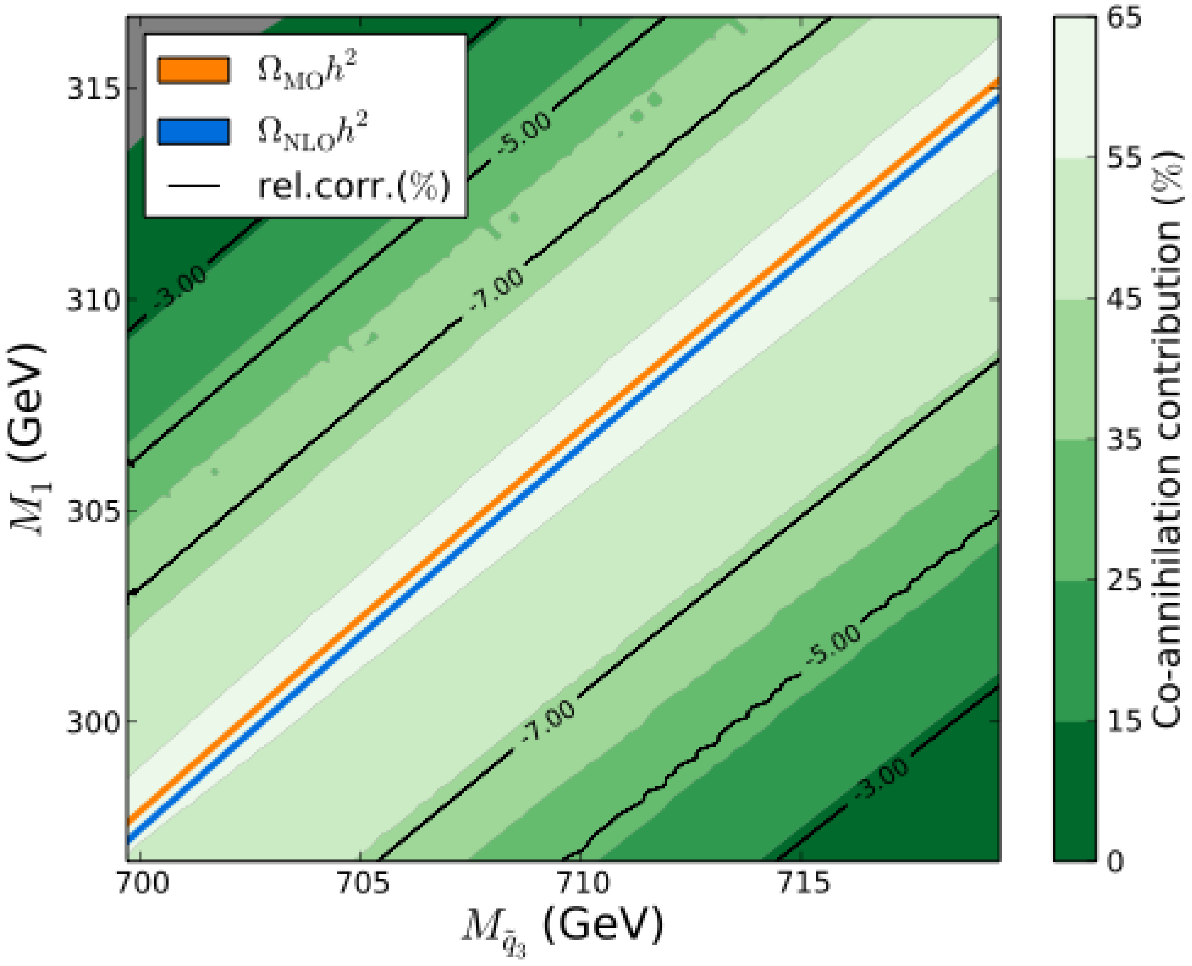
M_1	$M_{\tilde{q}_{1,2}}$	$M_{\tilde{q}_3}$	$M_{\tilde{\ell}}$	T_t	m_A	μ	$\tan\beta$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{t}_1}$	m_{h^0}	m_{H^0}
306.9	2037.7	709.7	1499.3	1806.5	1495.6	2616.1	9.0	307.1	350.0	124.43	1530.72

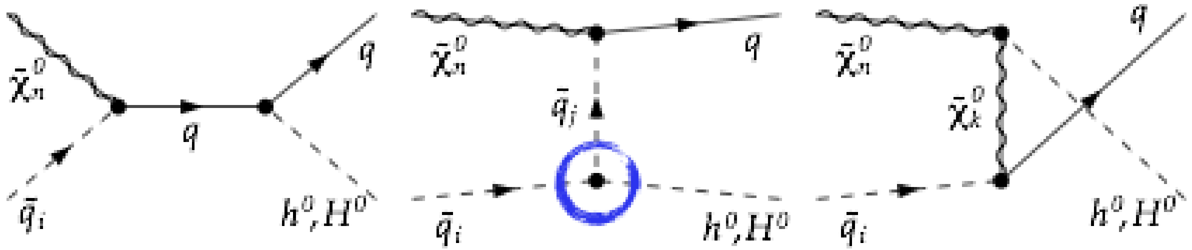
$\Omega_\chi h^2$	$\tilde{\chi}_1^0\tilde{t}_1 \to th^0$	$\tilde{\chi}_1^0\tilde{t}_1 \to tZ^0$	$\tilde{\chi}_1^0\tilde{t}_1 \to bW^+$	$\sum$
0.114	38.5%	3.4%	5.9%	47.8%

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

Impact on the Neutralino Relic Density

One-loop and MicrOMEGAs result in 2D parameter plane





th° final state: 38.5 %

- „right“ relic density in the range of maximal coannihilation contribution
- mass difference of around 40-45 GeV
- relative NLO correction of around 9 %

impact larger than current experimental uncertainties

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