Neutralino Annihilation into Quarks Pairs with SUSY-QCD Corrections

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Work realized in collaboration with Karol Kovařík and Michael Klasen
(to be published)

Orsay, 3 December 2008

Outline

1. Introduction
2. Neutralino annihilation into quarks
3. SUSY-QCD corrections
4. Numerical results
5. Conclusion

Observational Evidence for Dark Matter

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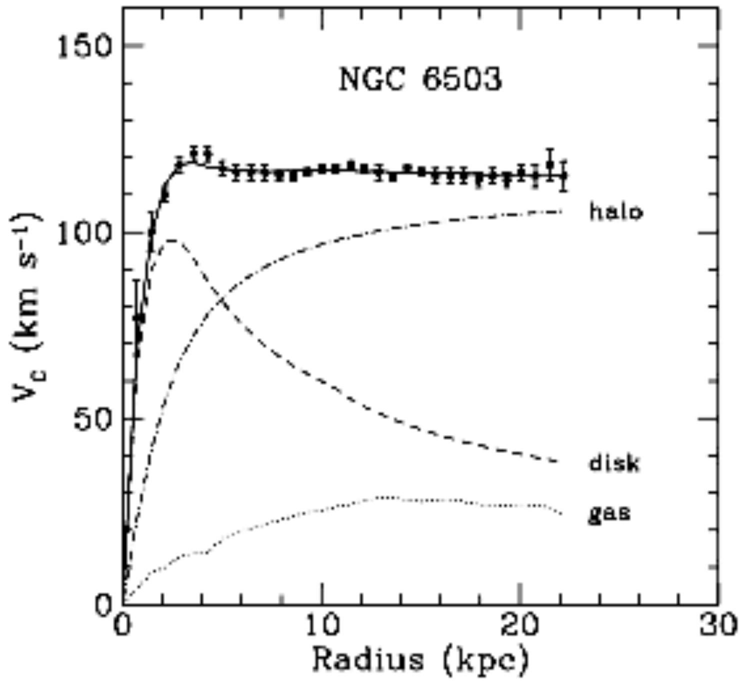
First observational hints

Velocity dispersion and rotation curves

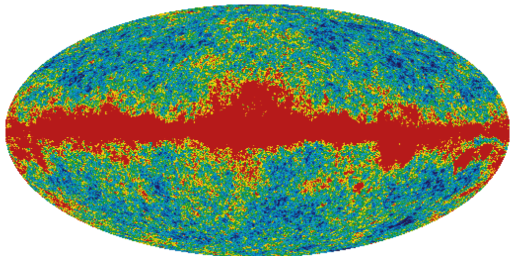
[Zwicky 1933, Rubin *et al.* 1970]



CMB anisotropies

Cosmological parameters from WMAP mission

[Komatsu *et al.* (WMAP) 2008]



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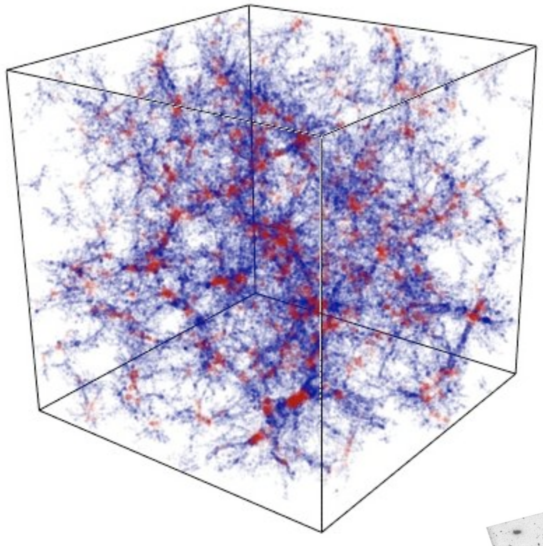
$$\Omega_{\rm CDM} = 0.223 \pm 0.013$$



Structure formation

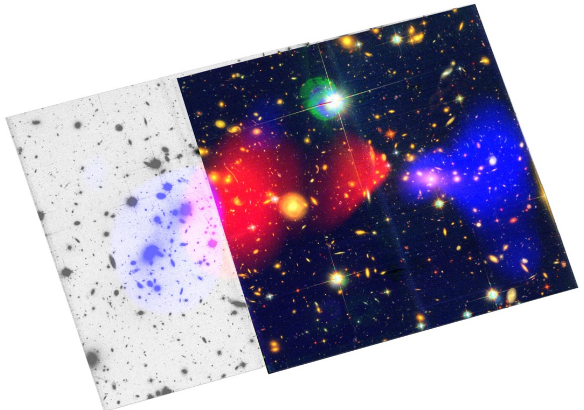
Cold dark matter needed to explain large structures

[Blumenthal *et al.* 1984]

First direct observation

Observation of "Bullet Cluster" proofs existence of dark matter

[Clowe *et al.* 2006]



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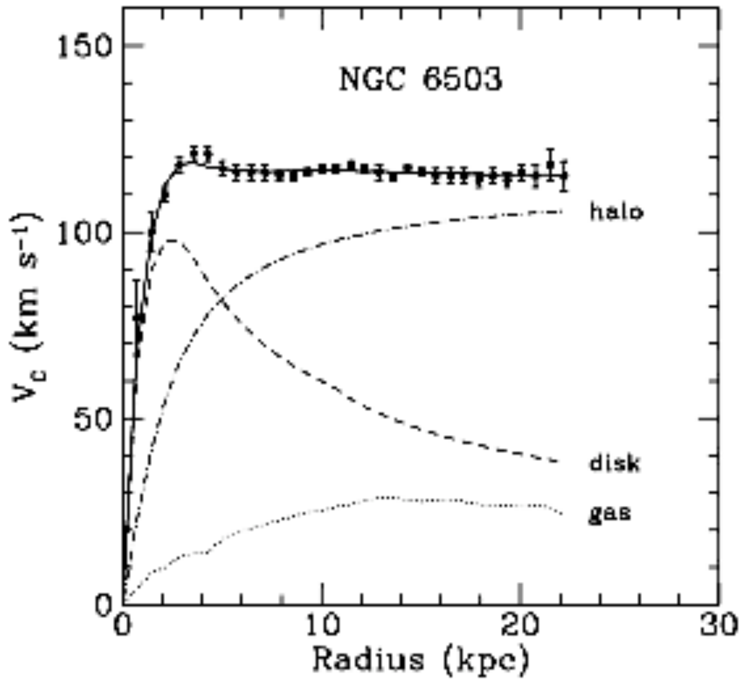

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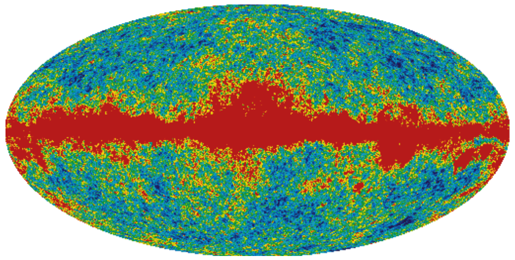

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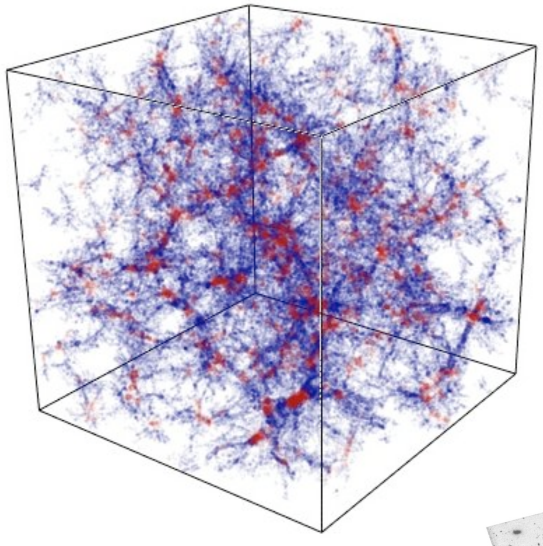

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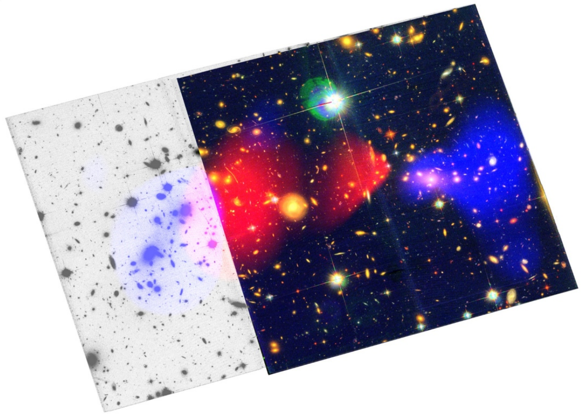

New physics, e.g. Supersymmetry, provides interesting candidates for cold dark matter...

The Minimal Supersymmetric Standard Model (MSSM)

Supersymmetry relates bosons and fermions

$$\mathcal{Q}\,|b\rangle \;=\; |f\rangle \qquad \mathcal{Q}\,|f\rangle \;=\; |b\rangle$$

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Minimal supersymmetric theory including the Standard Model particles

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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Particle mixing after electroweak symmetry breaking gives rise to neutralinos and charginos

Supersymmetric Dark Matter

R-parity conservation implies that lightest supersymmetric particle (LSP) is stable

→ interesting candidate for dark matter

$$P_R = (-1)^{3(B-L)+2s} = \begin{cases} +1 & \text{for Standard Model particles} \\ -1 & \text{for their superpartners} \end{cases}$$

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Here: Focus on minimal supergravity (mSUGRA)

→ SUSY breaking mediated between hidden and observable sectors by gravity

→ five universal parameters at the grand unification scale

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Relic density of cold dark matter candidate required to agree with WMAP+SN+BAO data

→ indentify (dis)favoured regions of the parameter space

$$0.094 \ \leq \ \Omega_{\mathrm{CDM}} h^2 \ \leq \ 0.136$$

[Hamann *et al.* 2007]

Relic Density Calculation

Number density of relic particle governed by the Boltzmann equation

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

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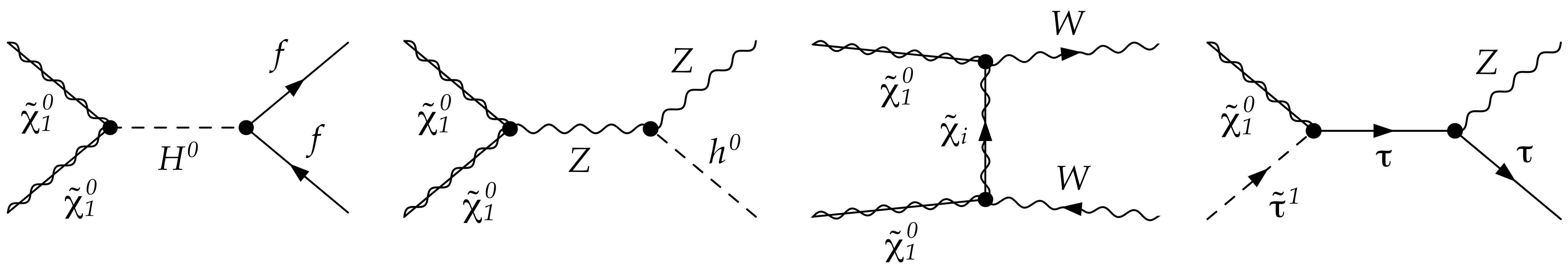
Cross section σ_{ann} includes all annihilation and coannihilation processes



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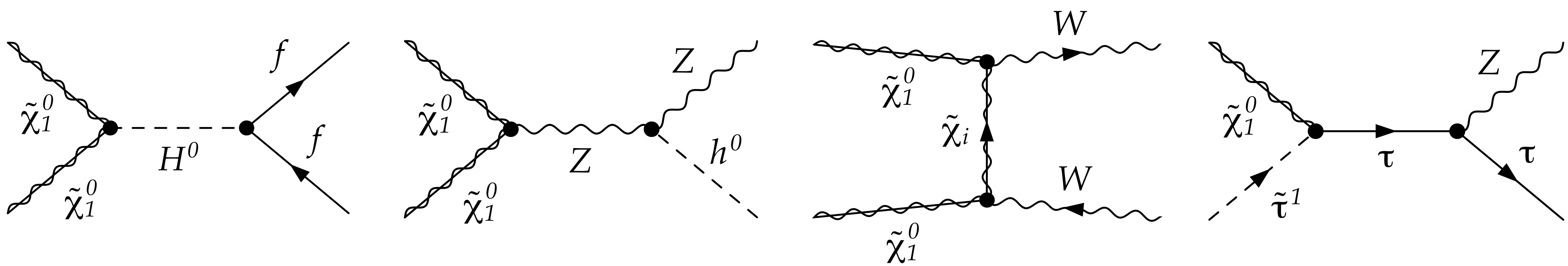

Thermal average involves velocity distribution of the non-relativistic relic particle

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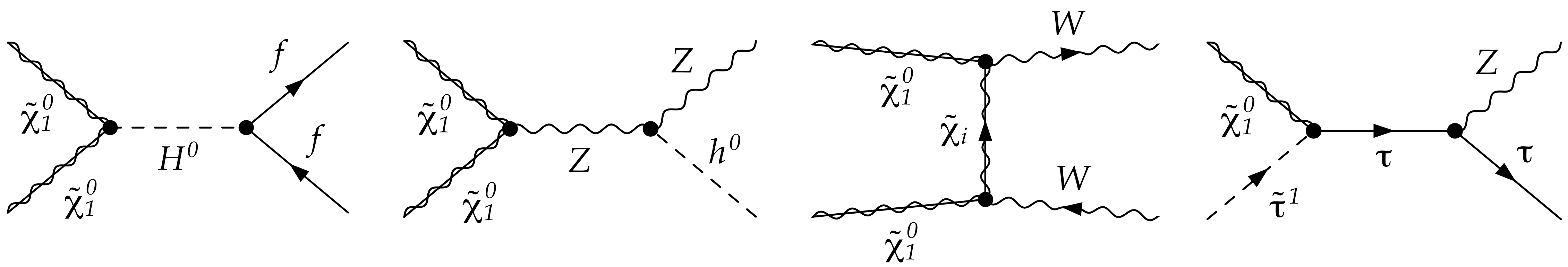

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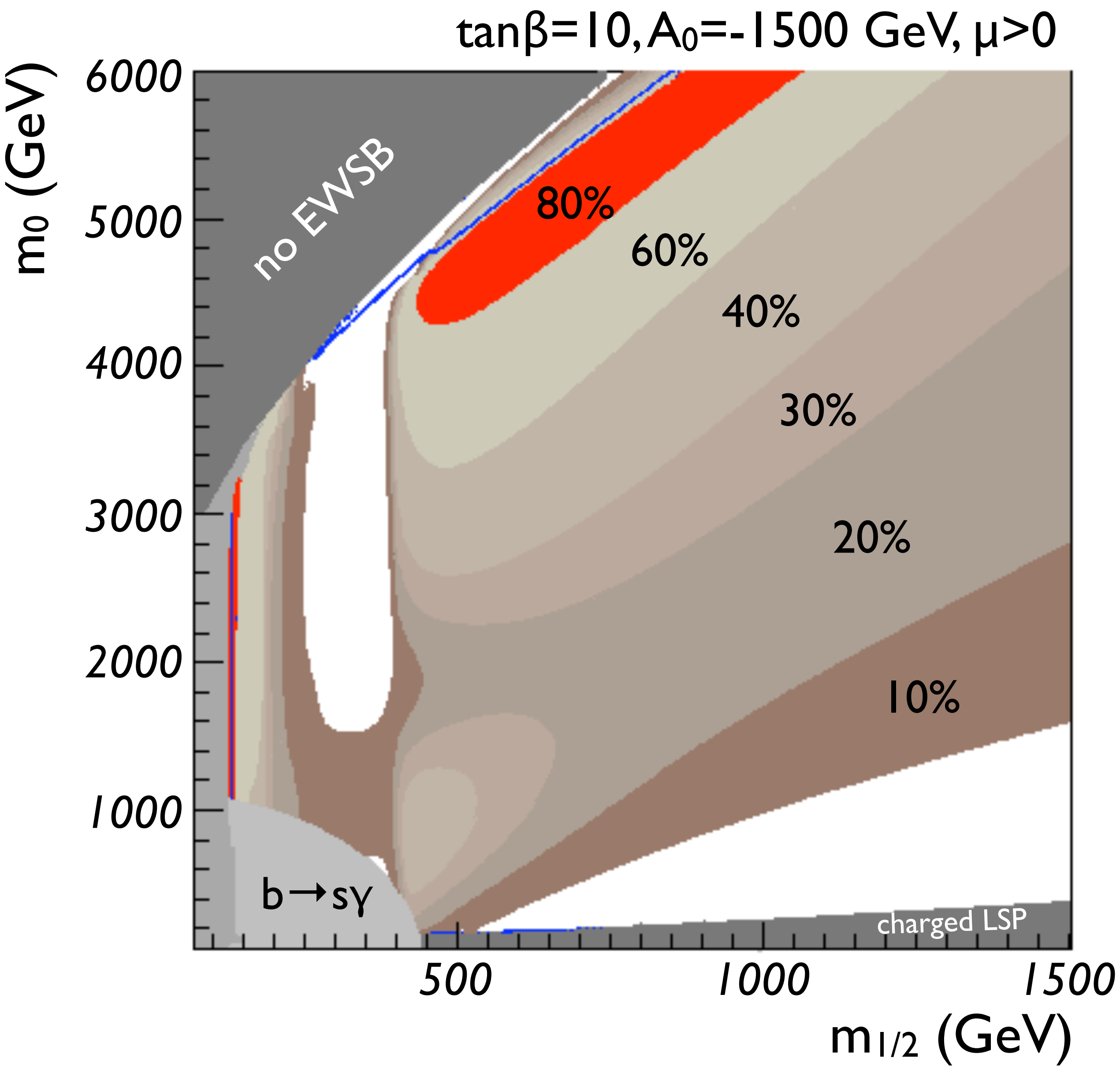
Public codes perform a calculation of the relic density for given scenario

→ DarkSUSY (only neutralino) [Gondolo *et al.* 2004]

→ micrOMEGAs (all kinds of LSP) [Bélanger *et al.* 2006]

Neutralino Annihilation into Quarks



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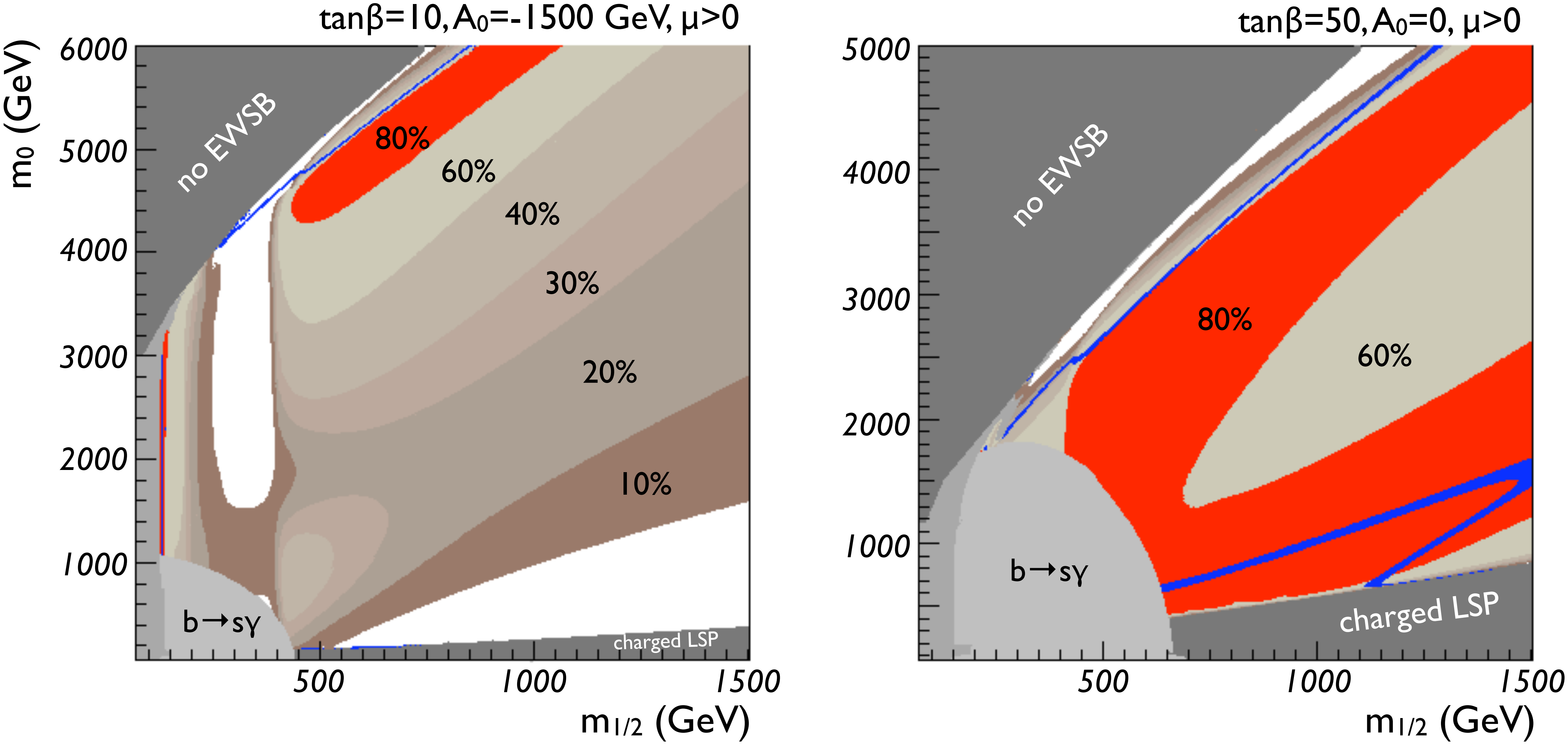

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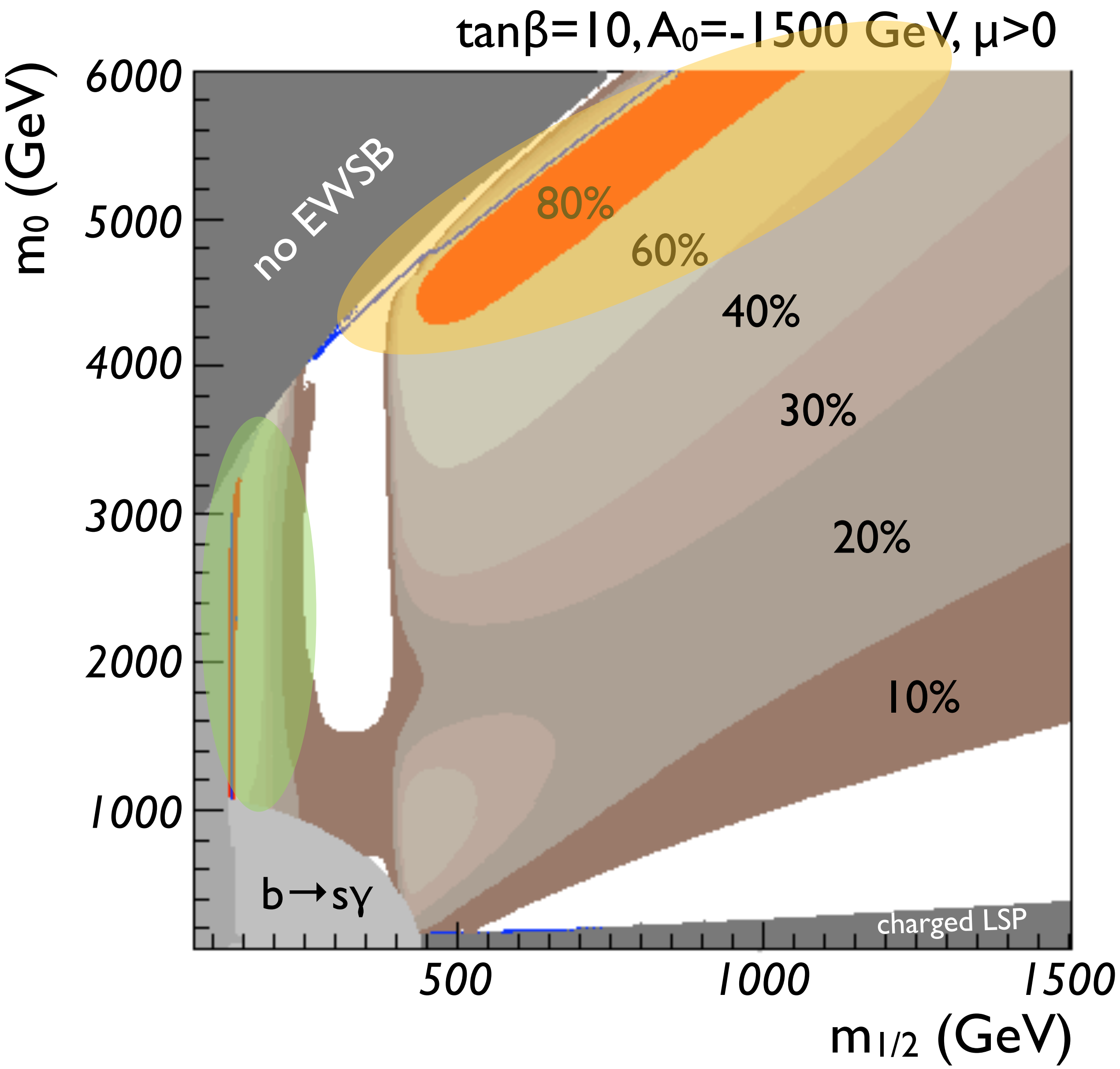

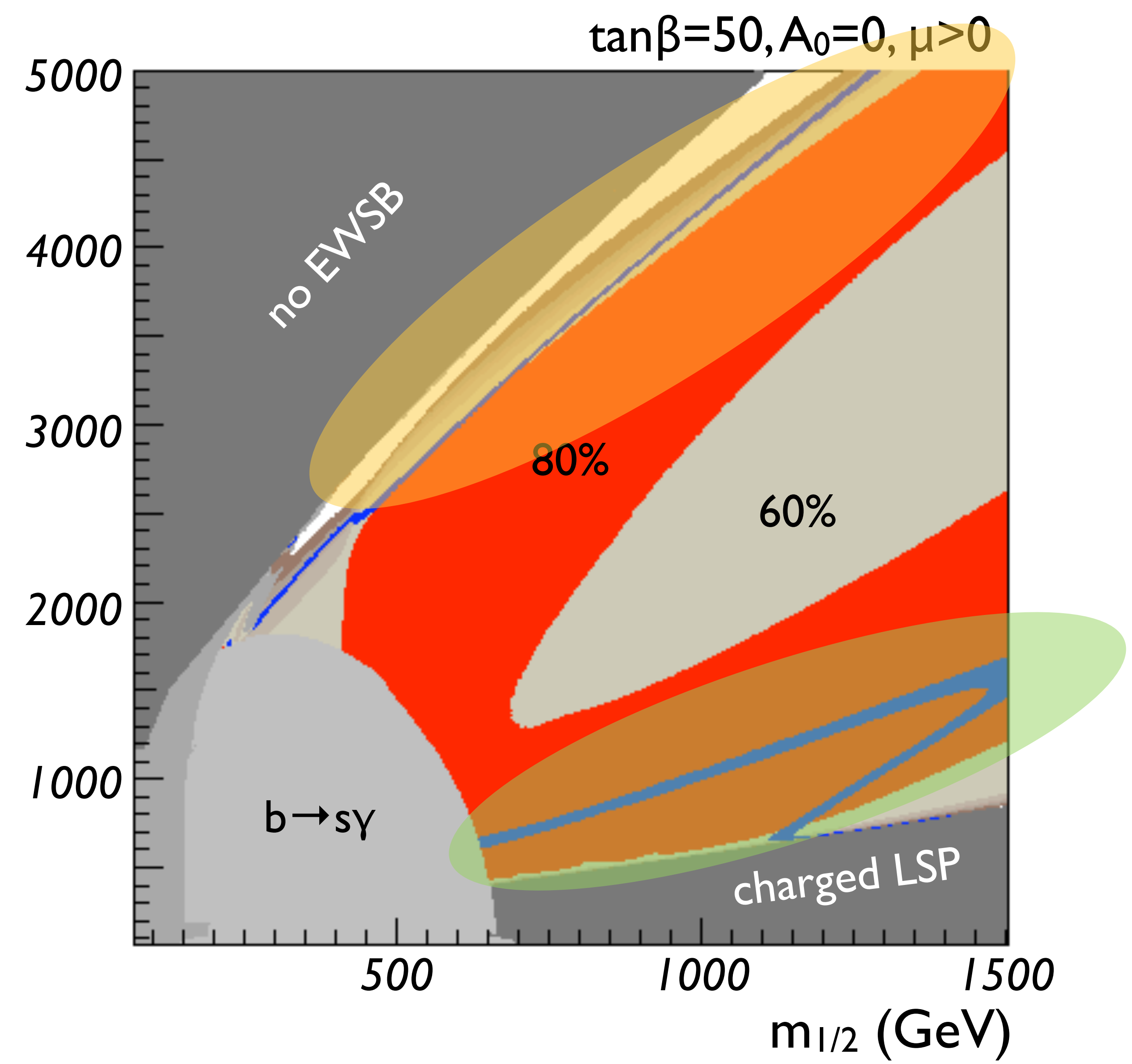

Interesting regions:

- Focus point region ($t\bar{t}$ dominated)
- Higgs resonances ($b\bar{b}$ dominated)

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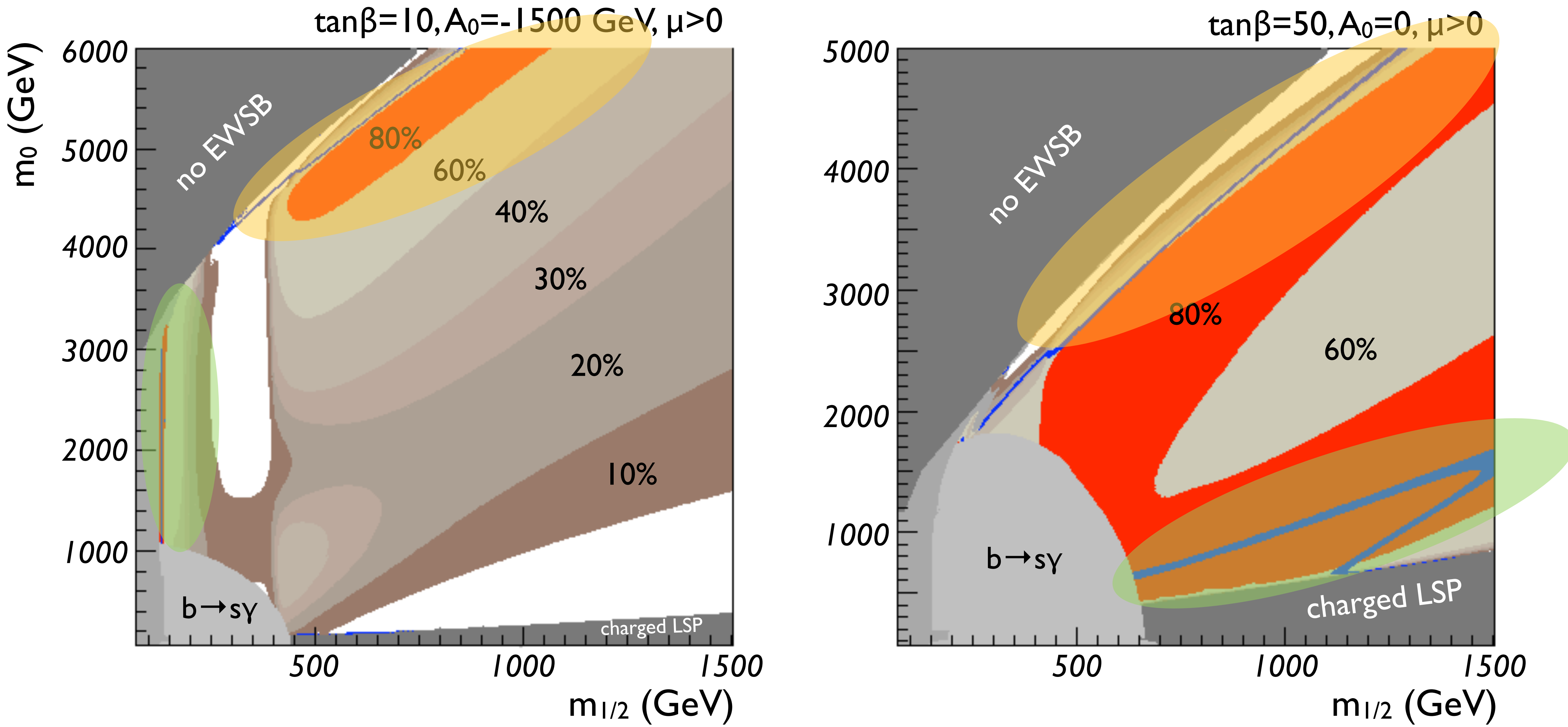

Interesting regions:

- Focus point region ($t\bar{t}$ dominated)
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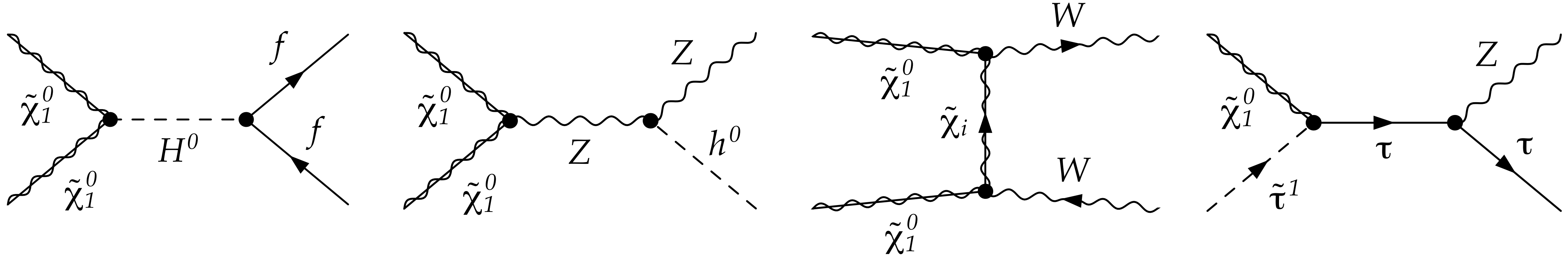
Light quark final states do not play a significant role in mSUGRA scenarios

Motivation for SUSY-QCD Corrections

Most (co)annihilation processes only implemented at leading order in public codes



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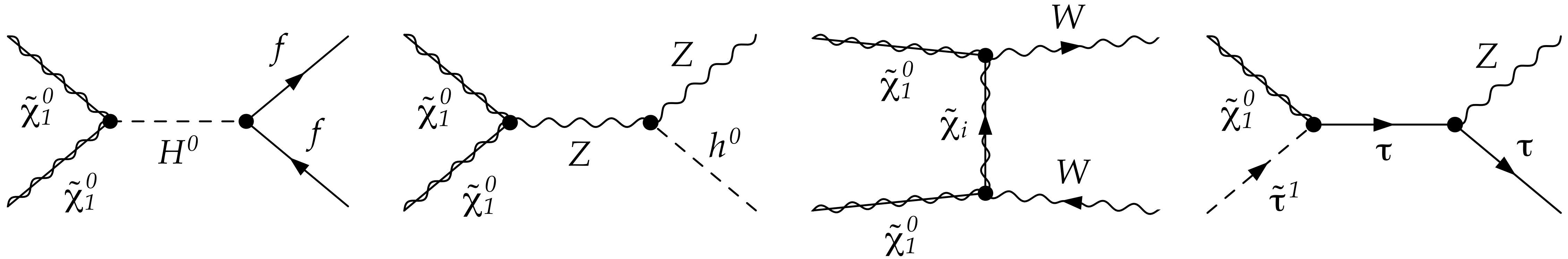

Higher order corrections can have important contributions to cross sections

→ QCD corrections significant due to strong coupling constant

→ modification of preferred regions in parameter space

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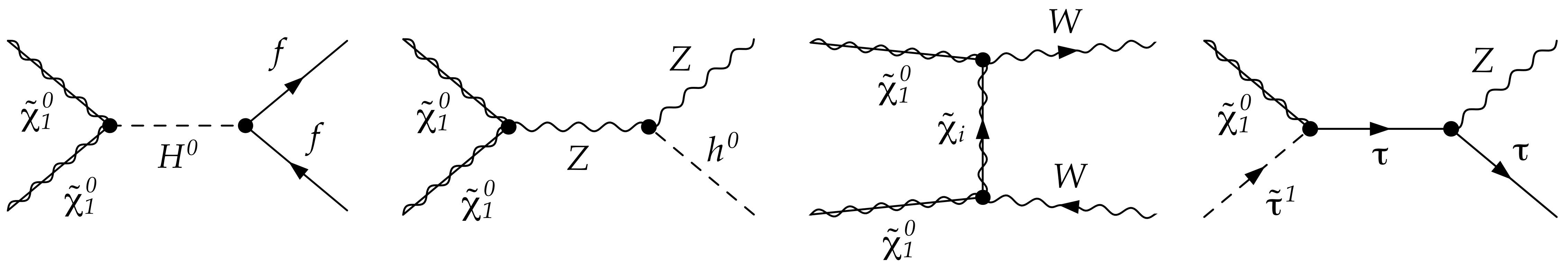

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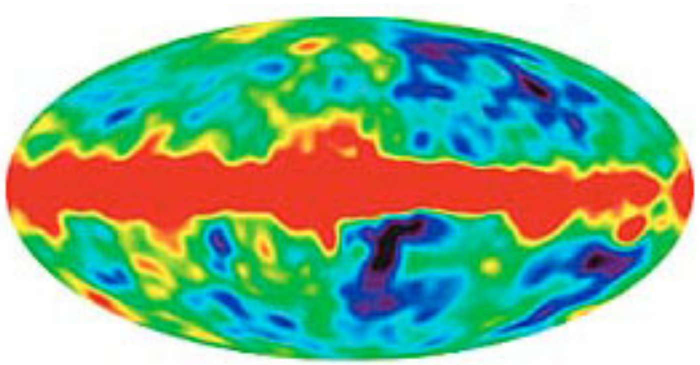
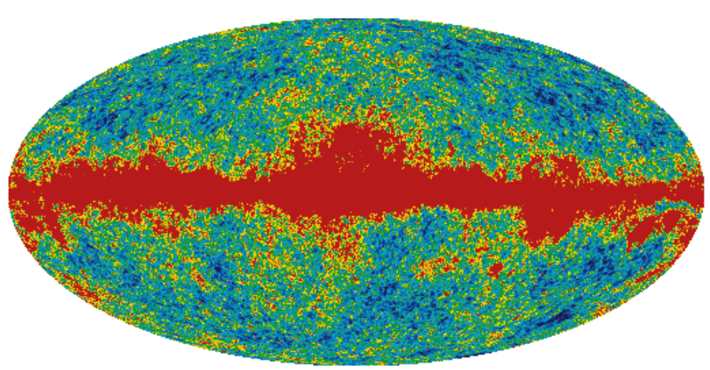
Planck satellite will deliver new cosmological data in near future

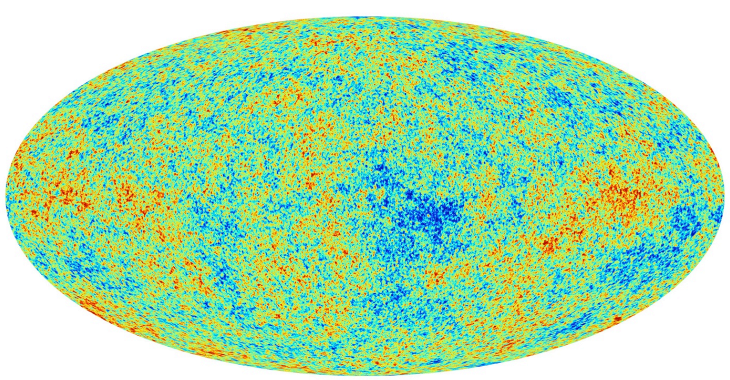
→ higher precision in theoretical predictions needed to match experimental improvements



COBE
1989



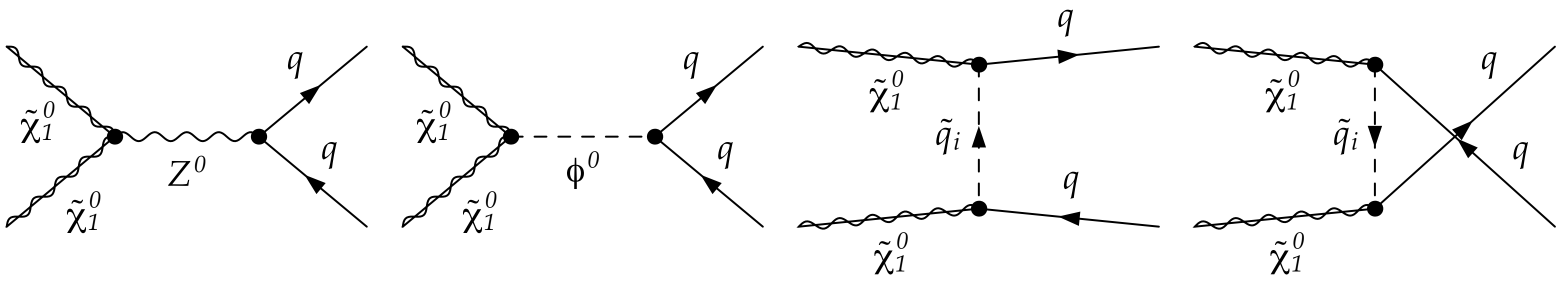
WMAP
2002



Planck
2009 ?

QCD and SUSY-QCD Corrections

Tree-level Feynman diagrams



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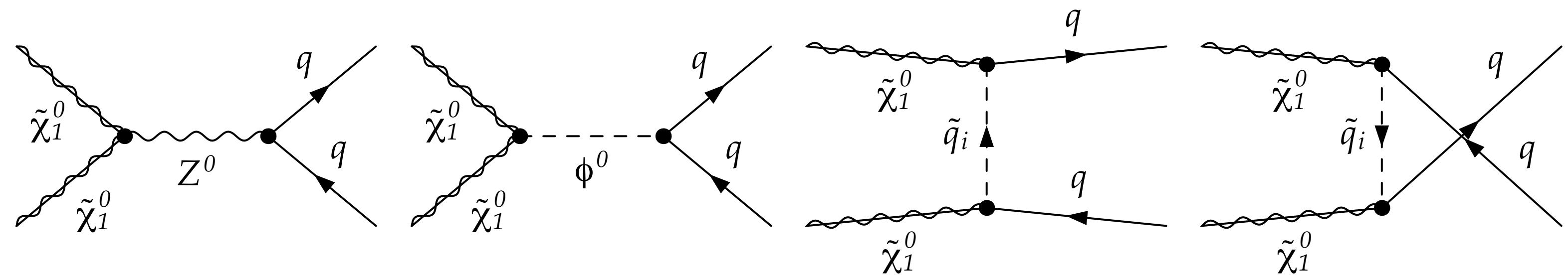
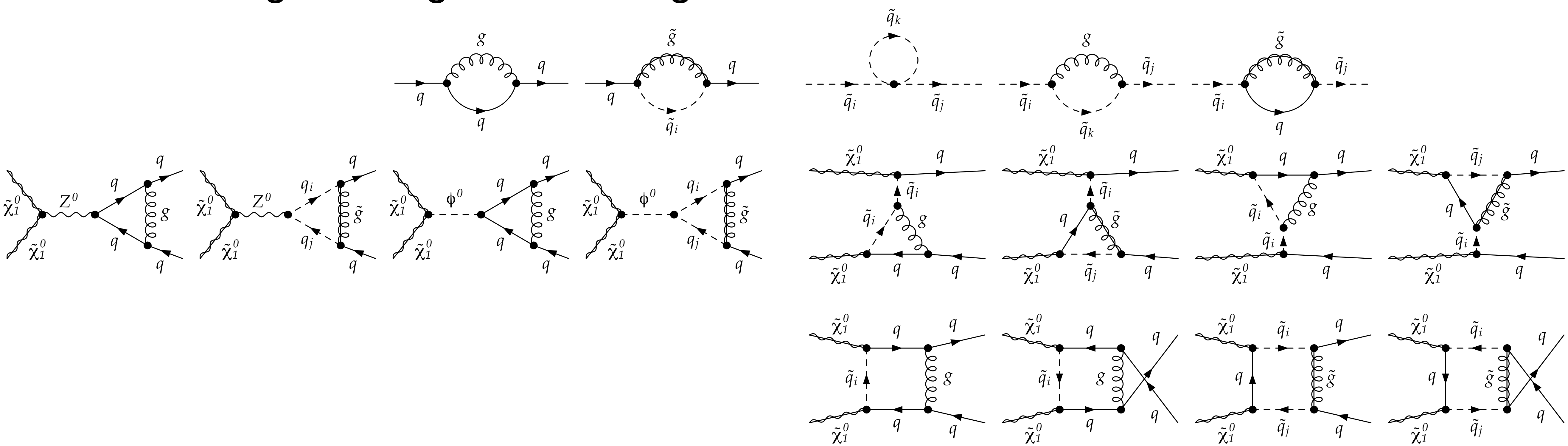


Virtual loop corrections

→ Loop integrals calculated in $\overline{\text{DR}}$ regularization scheme (preserves Supersymmetry)

→ UV-divergencies regularized through on-shell renormalization



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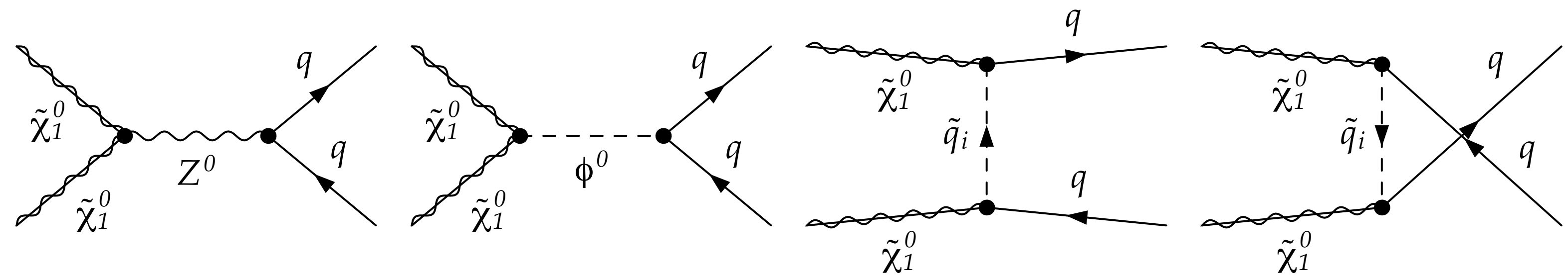

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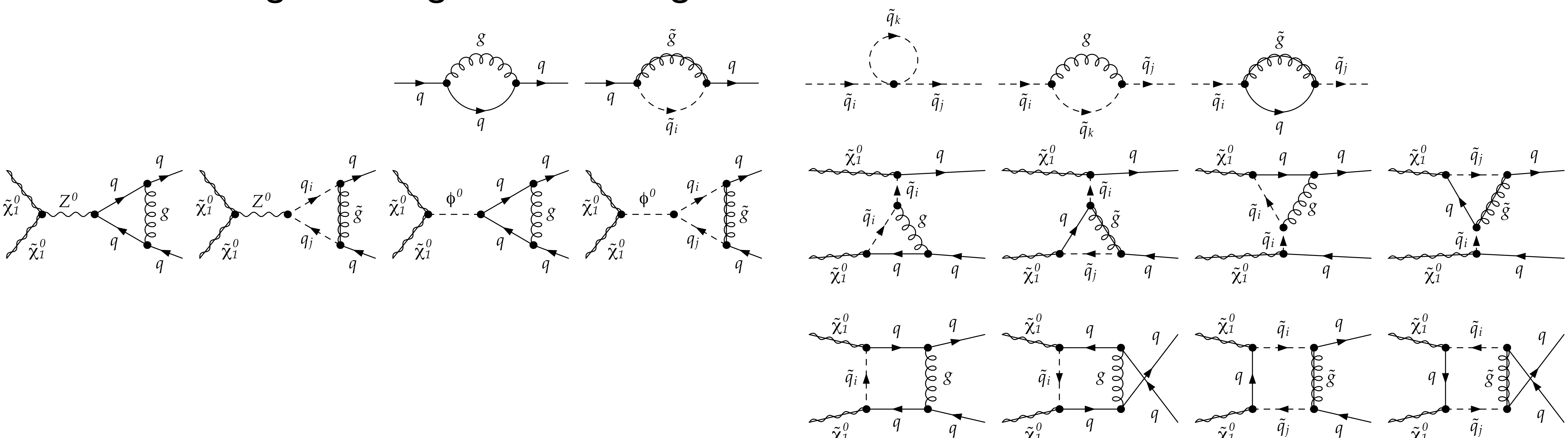
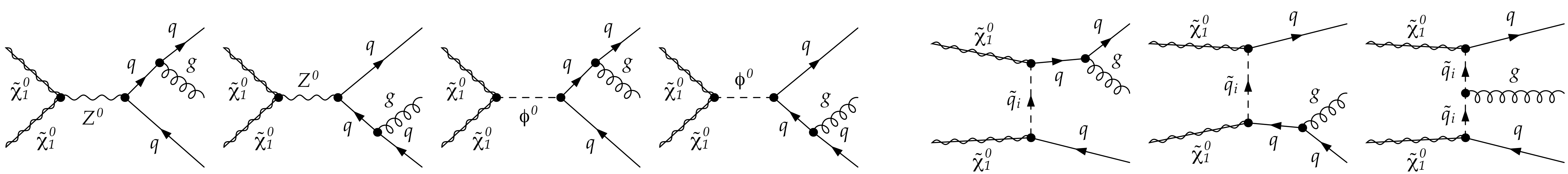


Real gluon emission corrections

→ IR-divergencies calculated in $\overline{\text{DR}}$ regularization scheme



QCD and SUSY-QCD Corrections

Dipole subtraction method to combine virtual and real emission contributions [Catani *et al.* 2000]

→ auxiliary cross section cancels IR-divergence in both the virtual and real part

$$\sigma_{\rm NLO} \;=\; \Big[\sigma_{\rm V} + \int {\rm d}\sigma_{\rm aux}\Big]_{\epsilon=0} + \int \Big[{\rm d}\sigma_{\rm R} - {\rm d}\sigma_{\rm aux}\Big]_{\epsilon=0}$$

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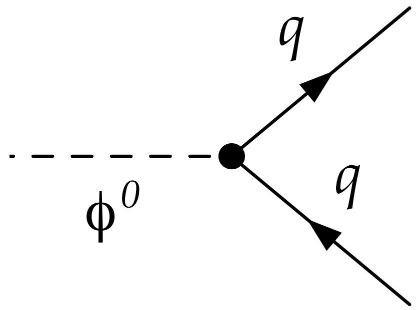
Yukawa couplings in Higgs exchange diagrams



→ Higgs resonances enhance annihilation cross section significantly

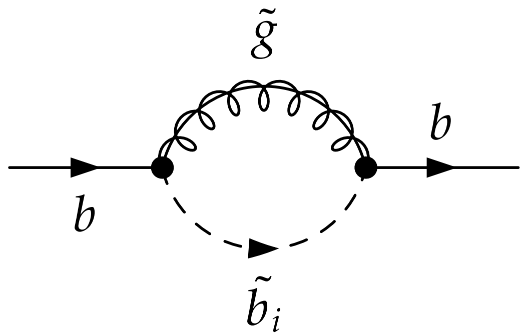
→ radiative corrections to Higgs boson decay into fermions well known

→ include QCD corrections up to $O(\alpha_s^4)$ [Chetyrkin *et al.* 1995-2006]

→ include SUSY-QCD bottom quark mass resummation (important at large tanβ or A_b)

[Carena *et al.* 2000, Spira *et al.* 2003]

$$\left(\frac{\Delta m_b}{m_b}\right)_{\tilde{g}\tilde{b}} = \frac{\alpha_s(s)}{\pi} C_F \frac{m_{\tilde{g}}}{2} \Big(A_b - \mu \tan\beta\Big) I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}})$$



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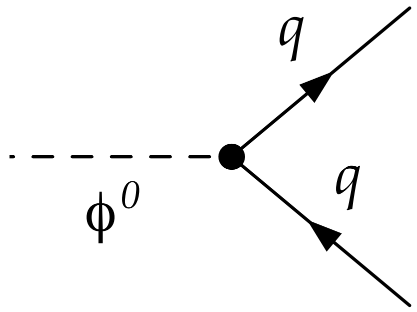

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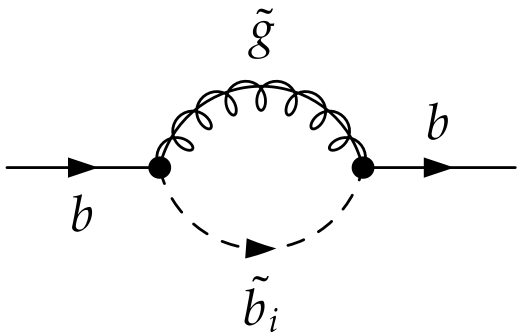
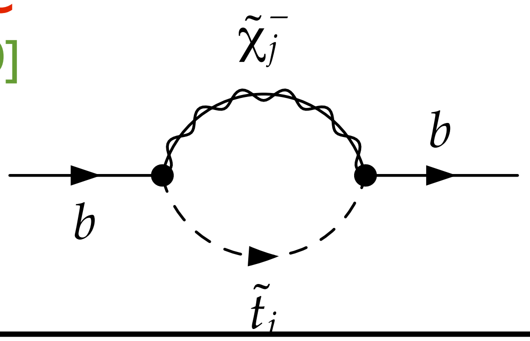


Stop-chargino loop correction to bottom mass of same order of magnitude

[Carena *et al.* 2000]

$$\left(\frac{\Delta m_b}{m_b}\right)_{\tilde{t}\tilde{\chi}^\pm} = -\frac{\lambda_t^2}{16\pi^2}\Big[A_t \mu \tan\beta - \mu^2\Big] I(\mu^2, m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2})$$

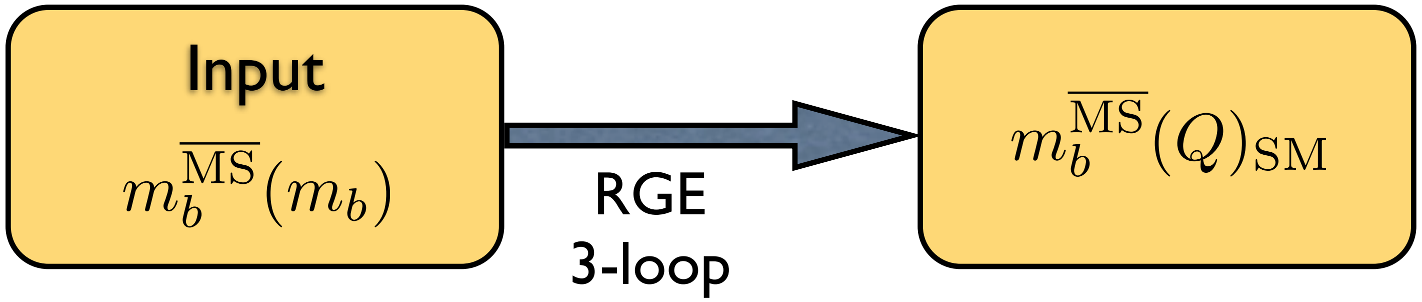


Treatment of Quark Masses

Input

$m_b^{\overline{\mathrm{MS}}}(m_b)$

Treatment of Quark Masses



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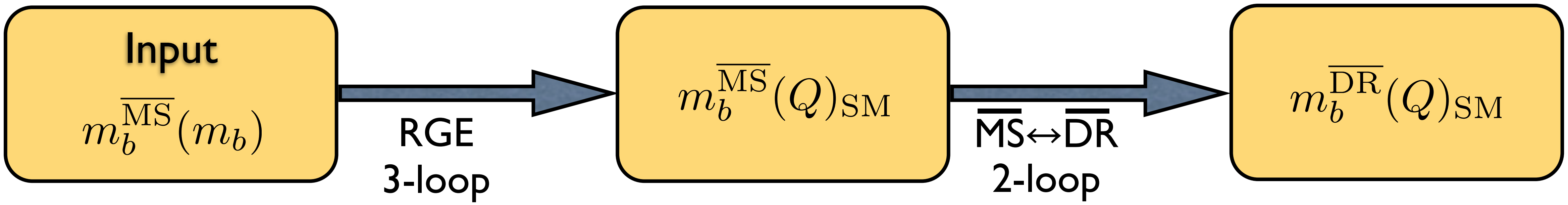

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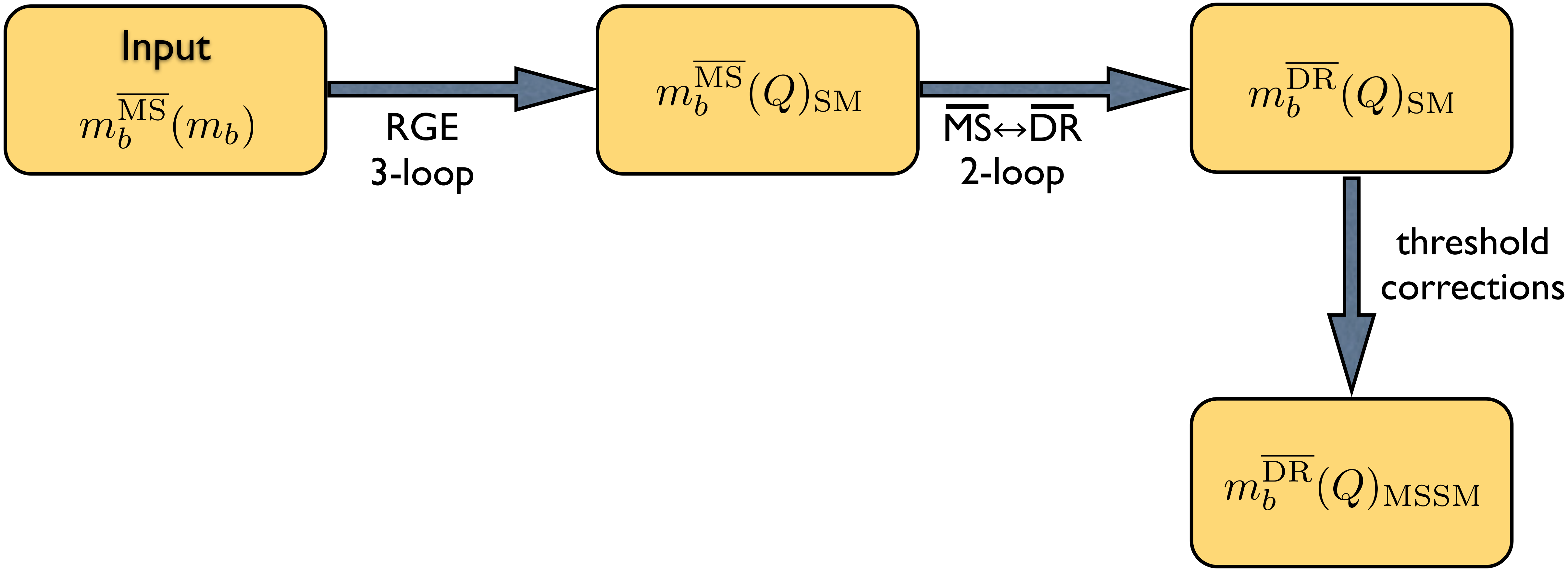

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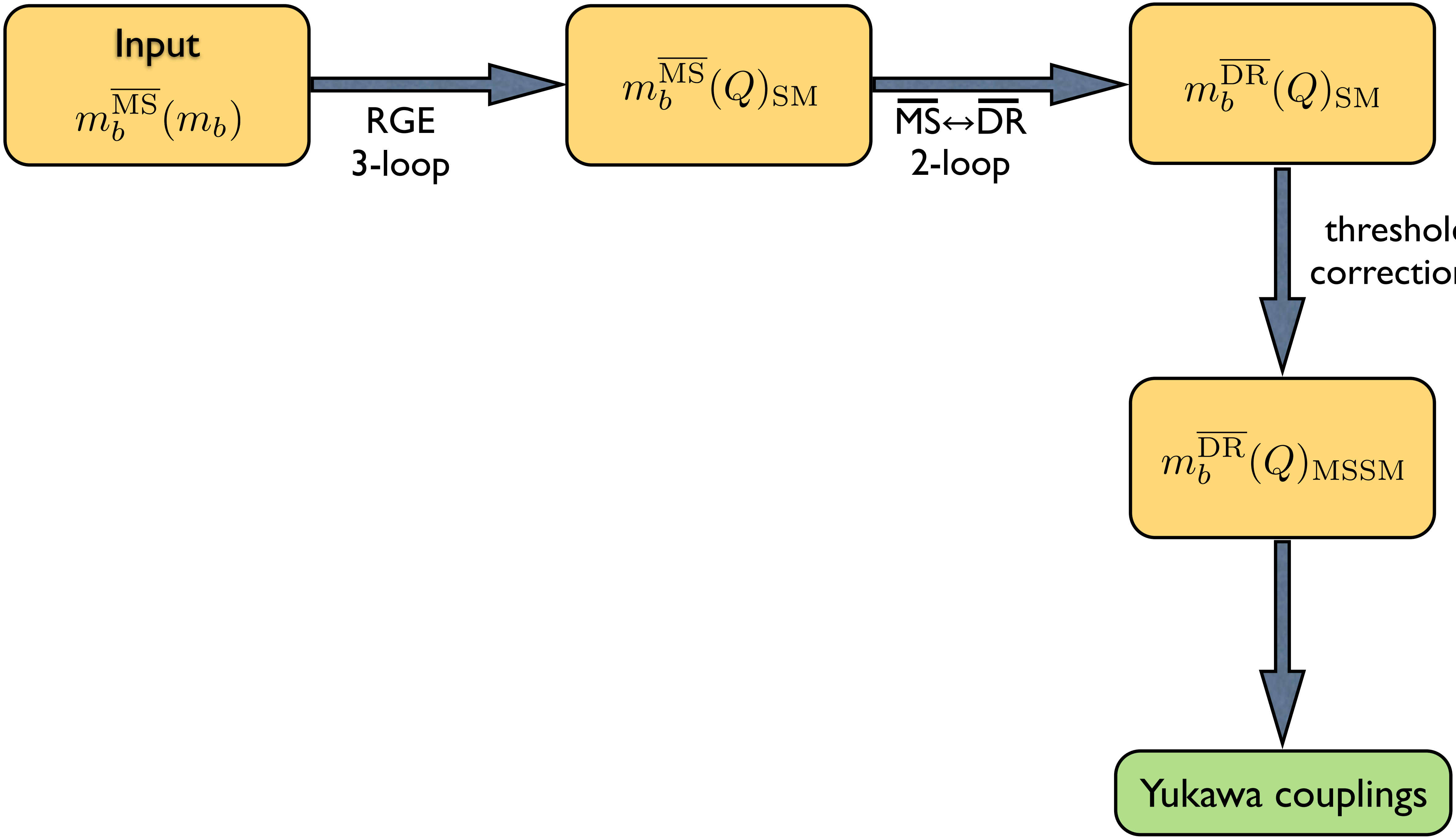

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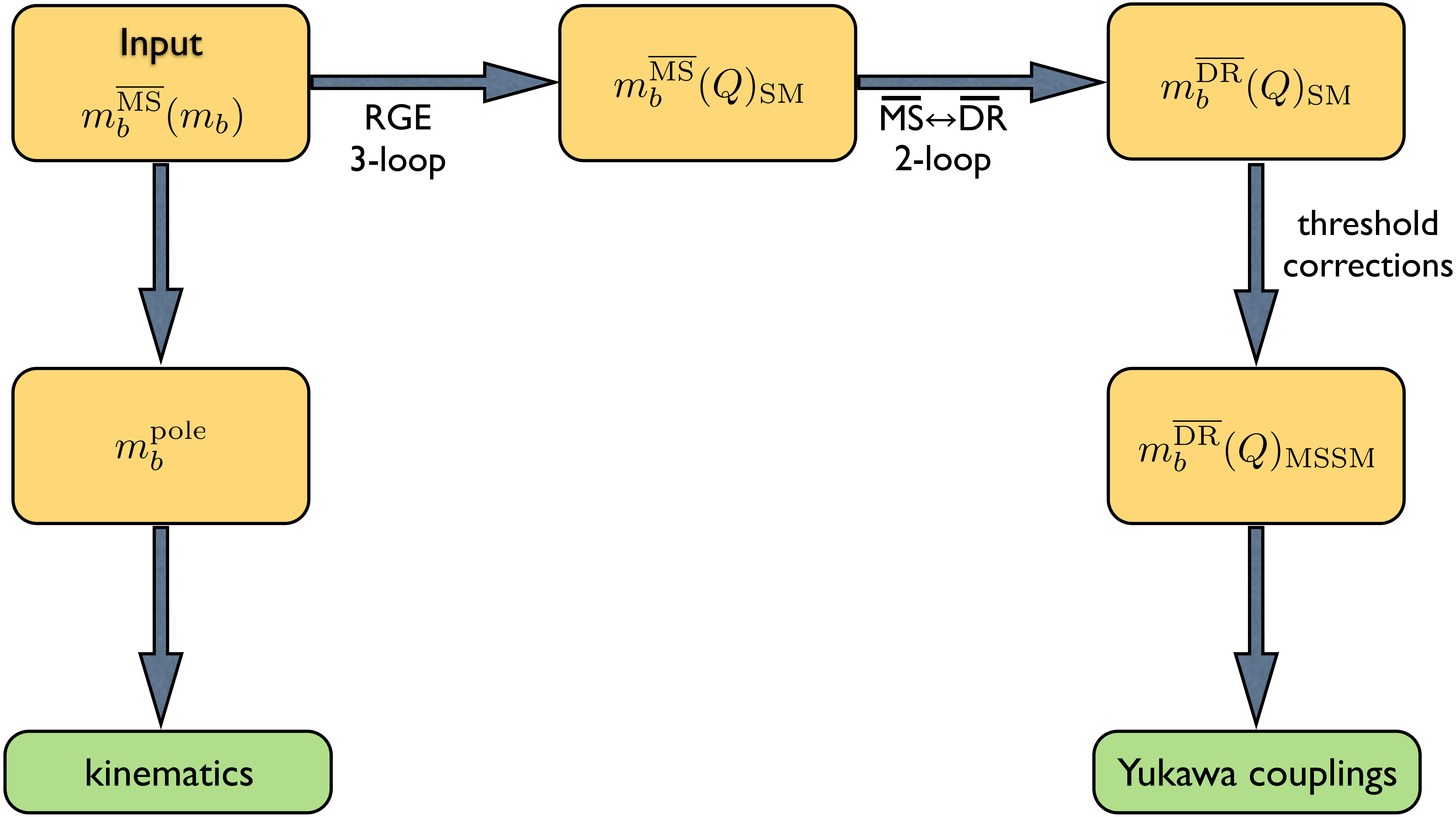

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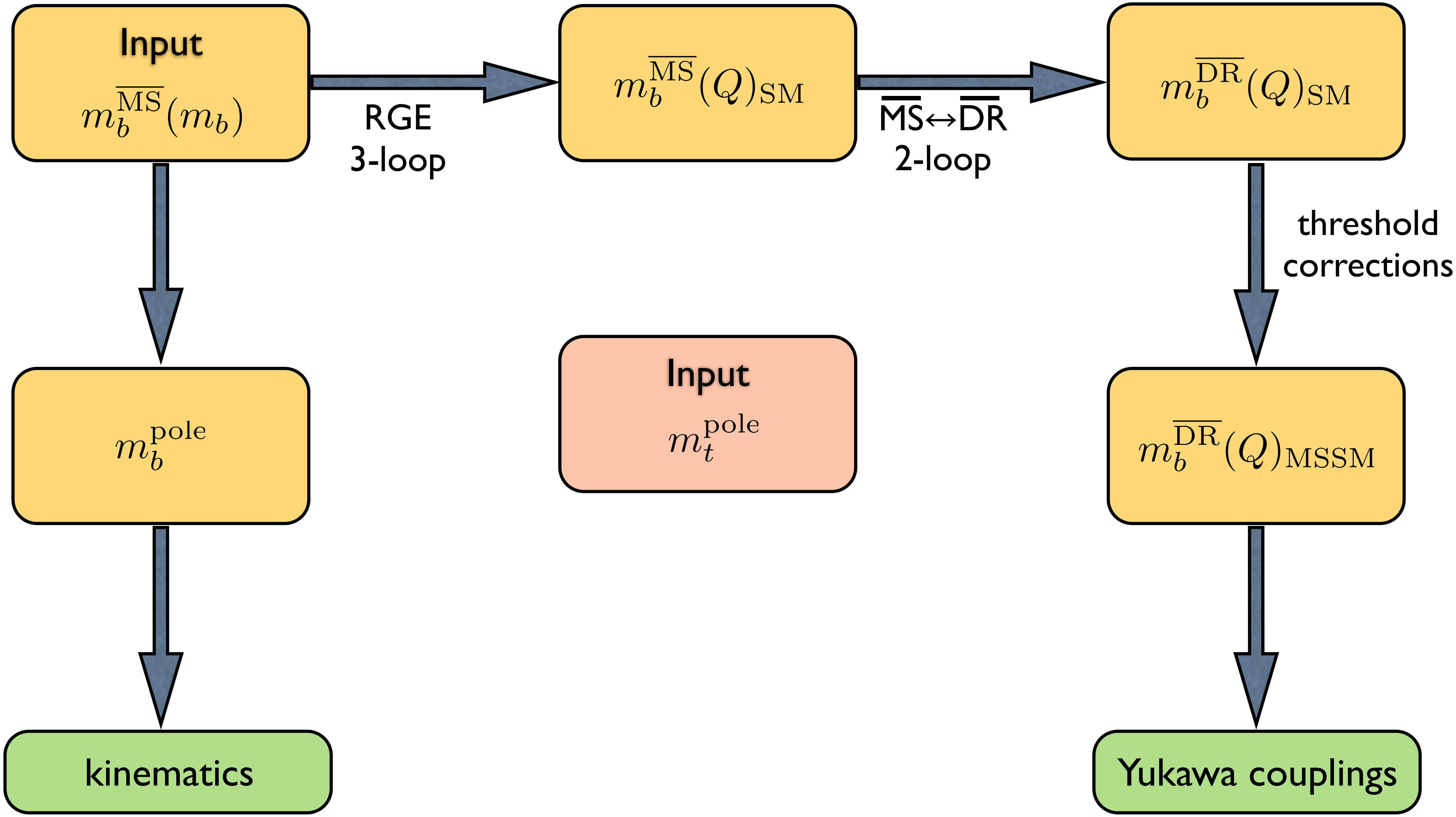

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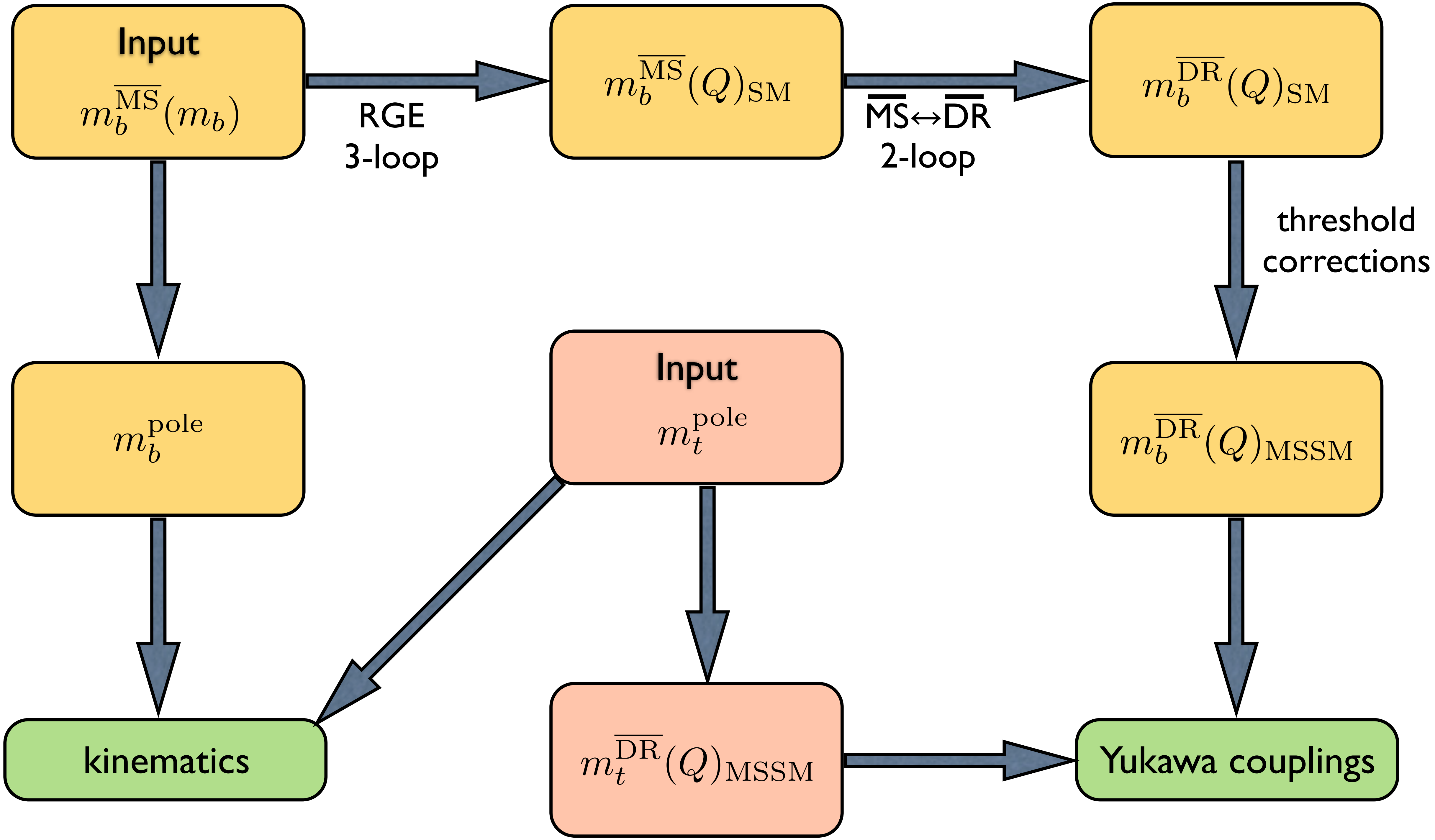
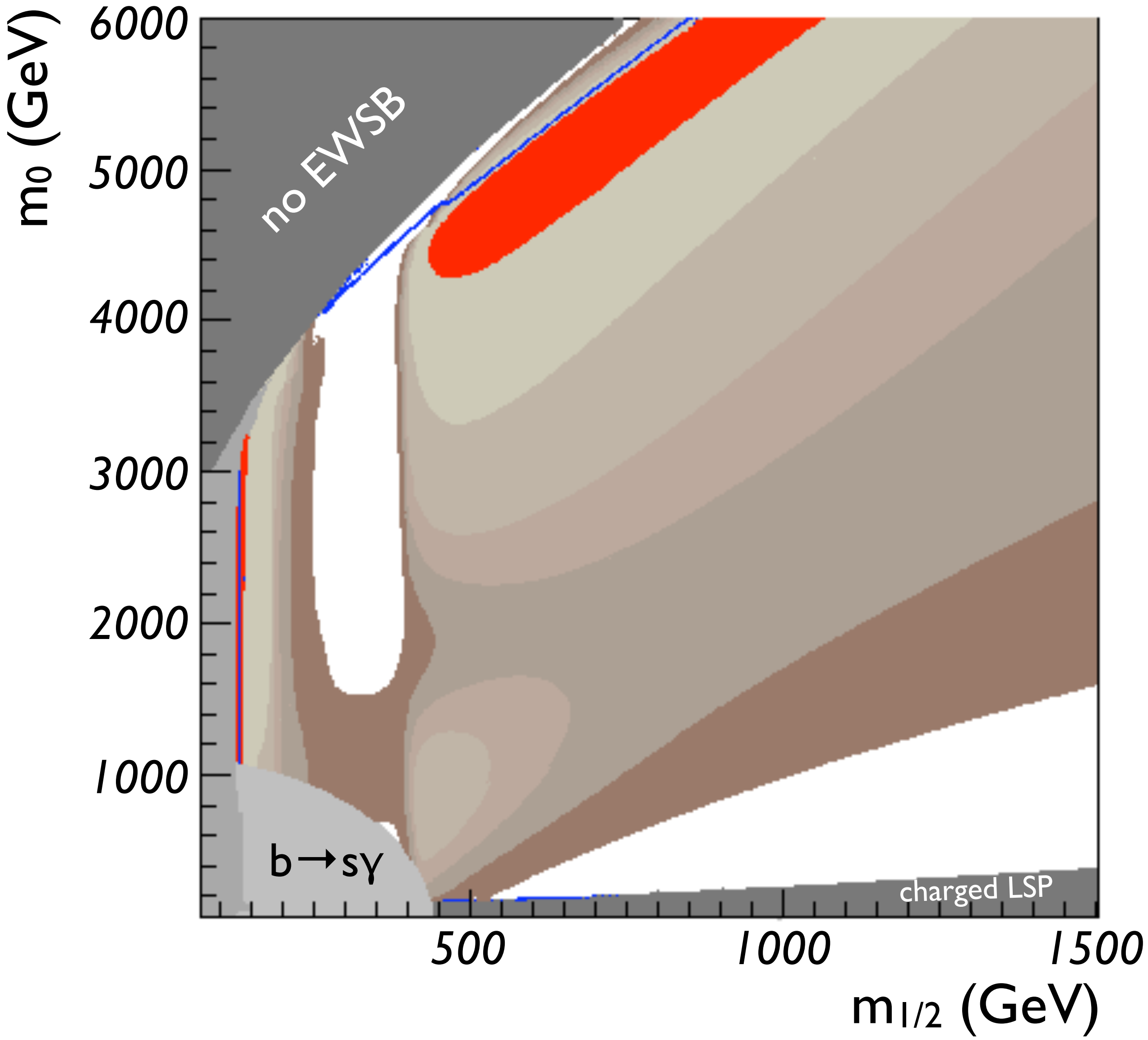


Numerical results: Light Higgs resonance *(preliminary)*

mSUGRA parameters: m_0=1500 GeV, $m_{1/2}$=130 GeV, A_0=-1500 GeV, tanβ=10, μ>0



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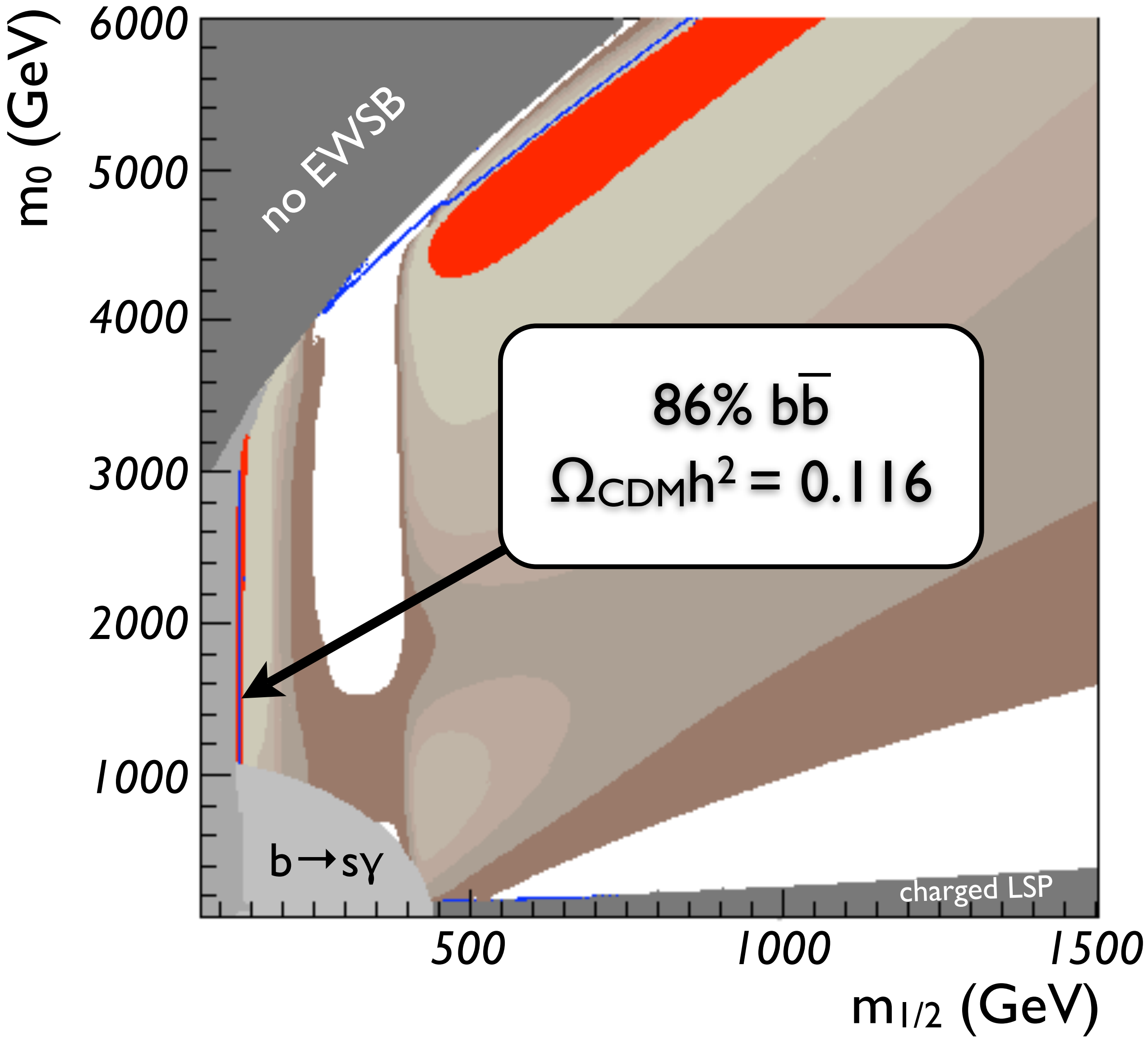

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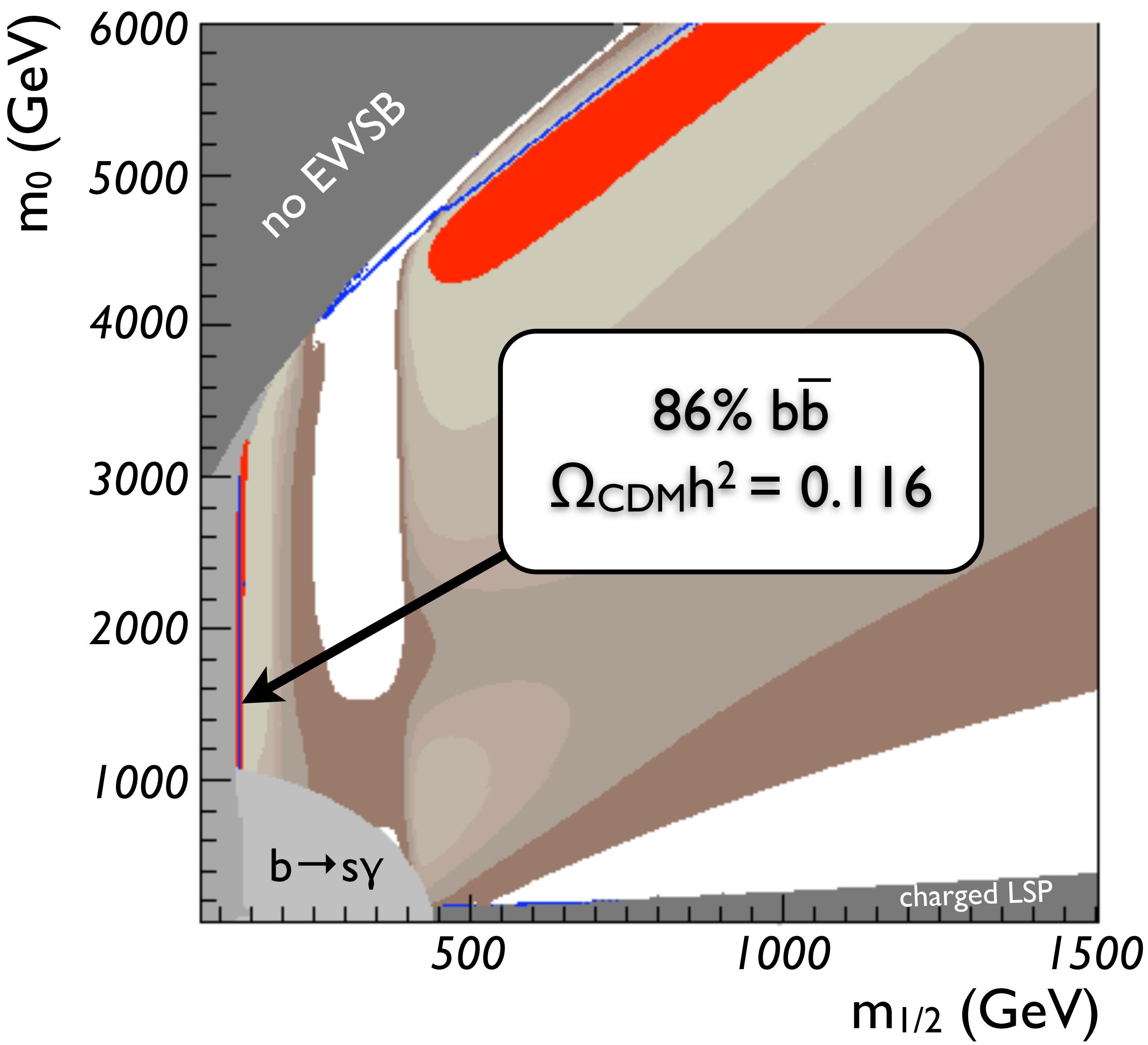

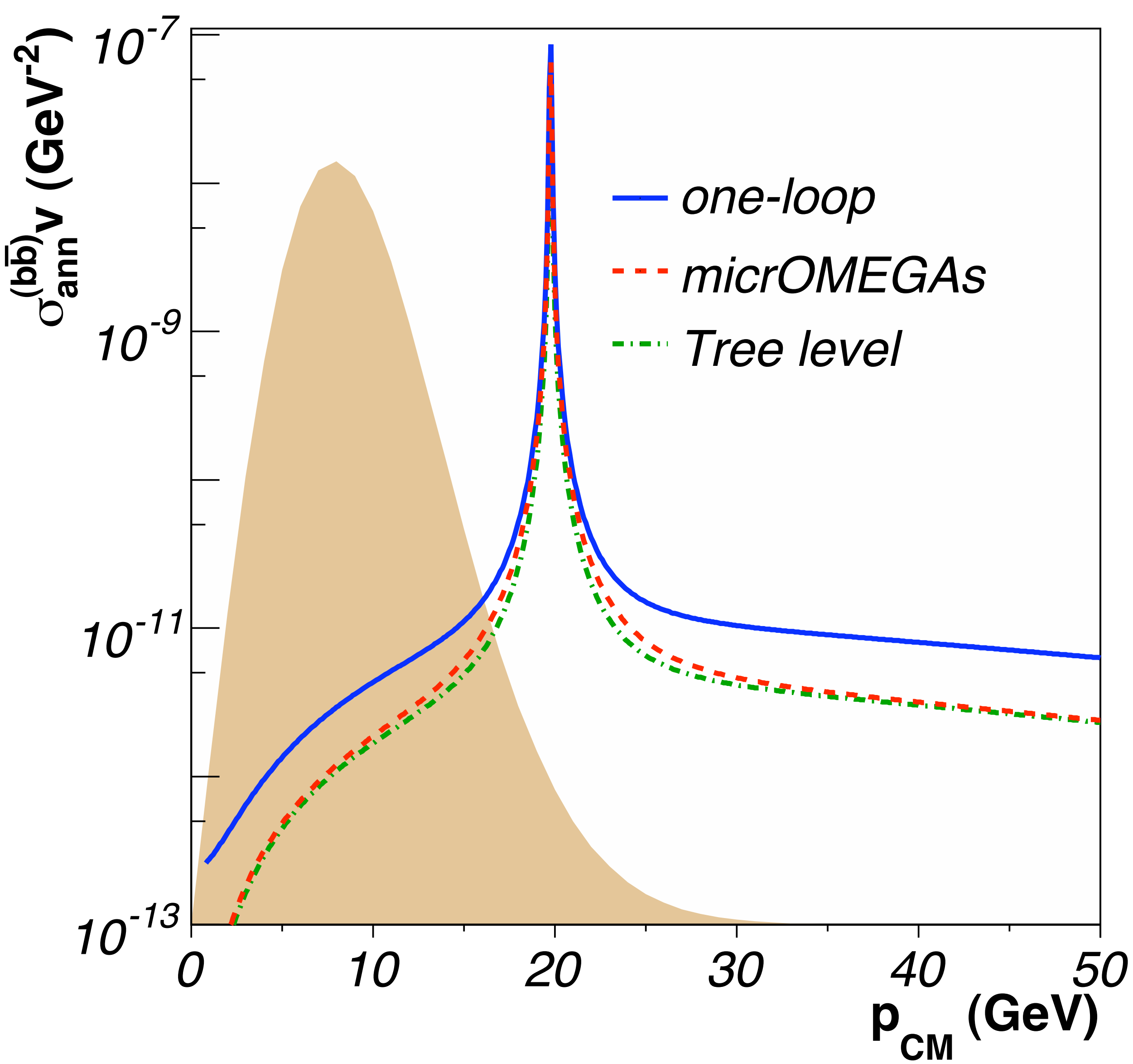

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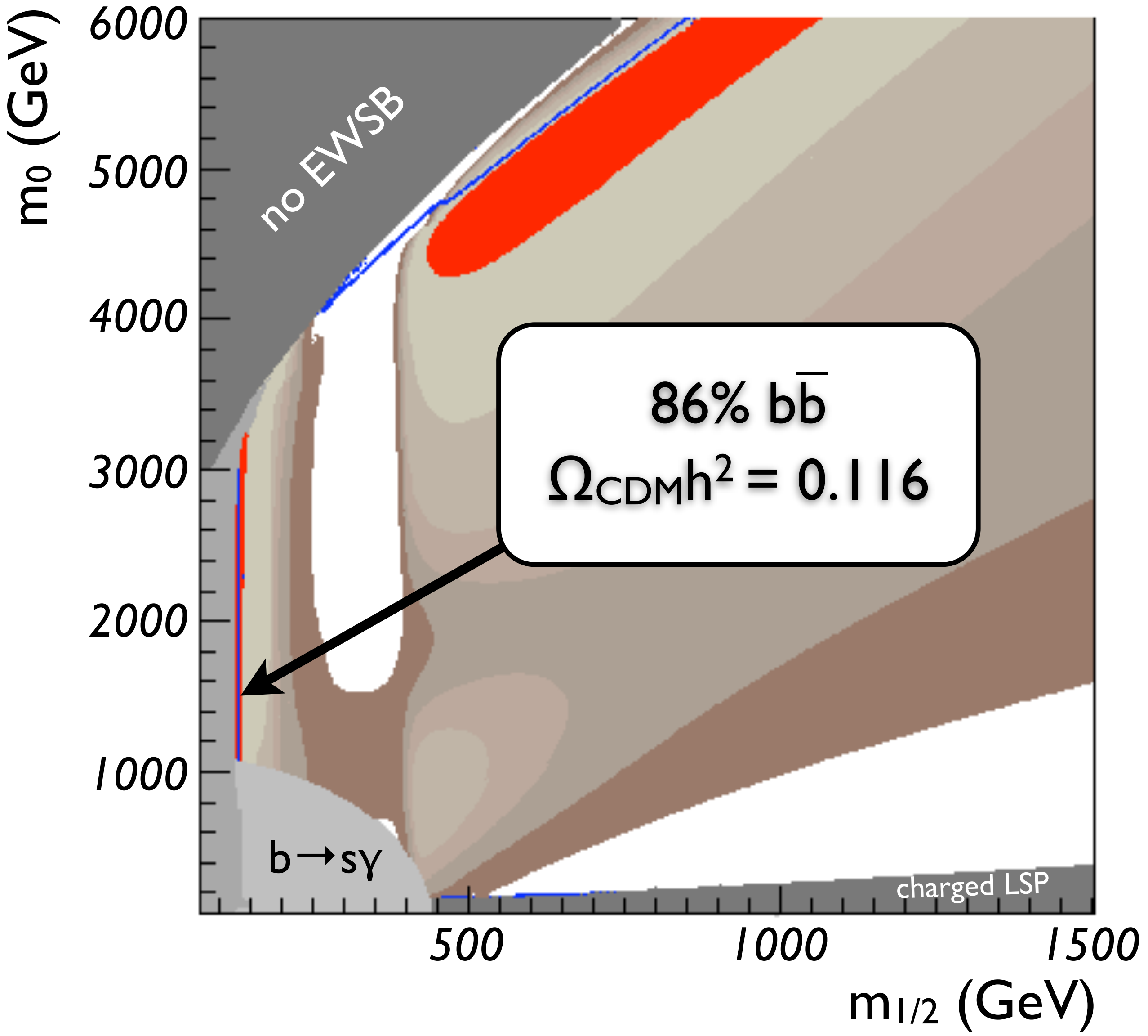

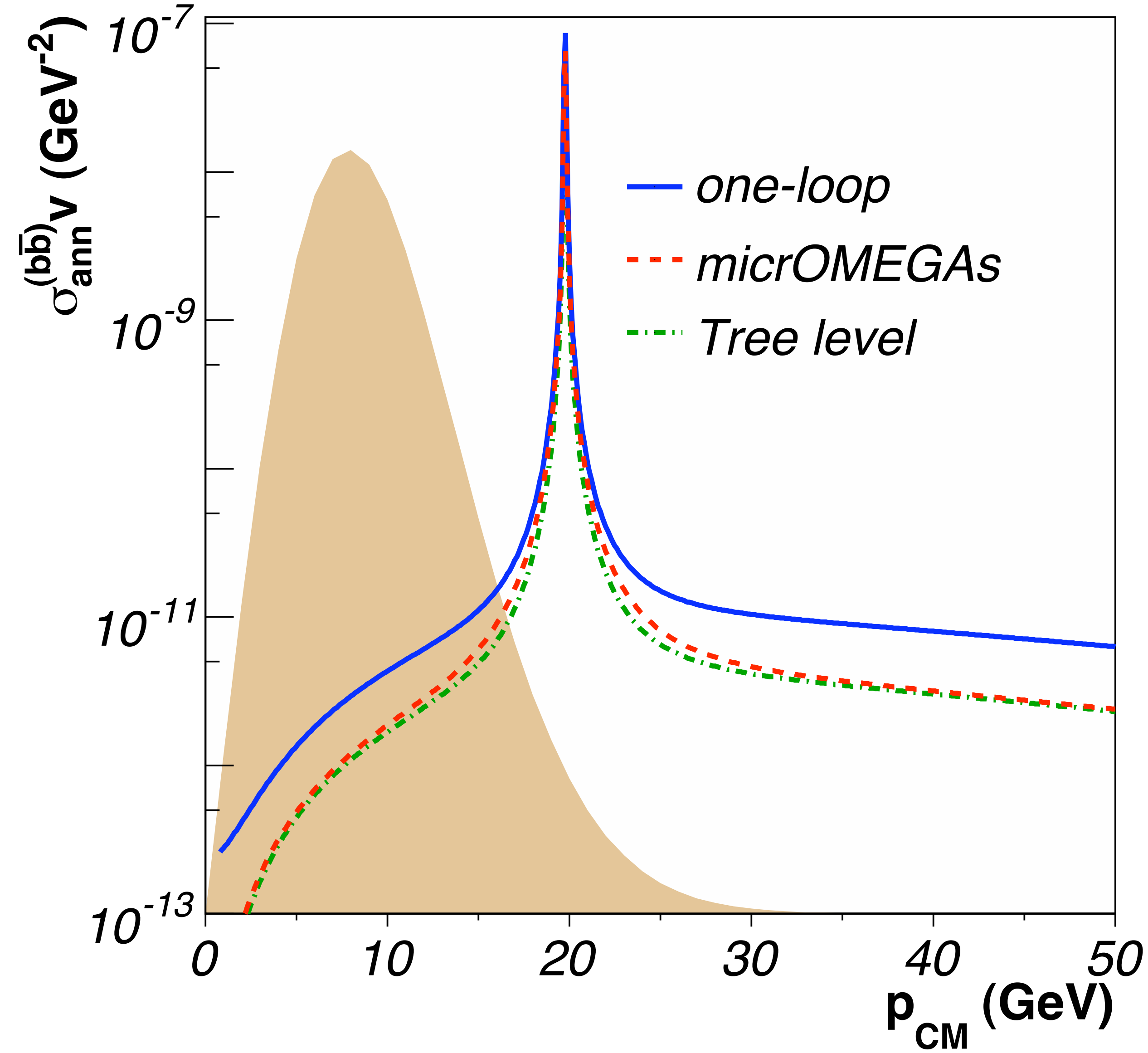

"Effective" Yukawa coupling very good approximation around the Higgs resonance

Position of resonance does not coincide with peak of velocity distribution for thermal average

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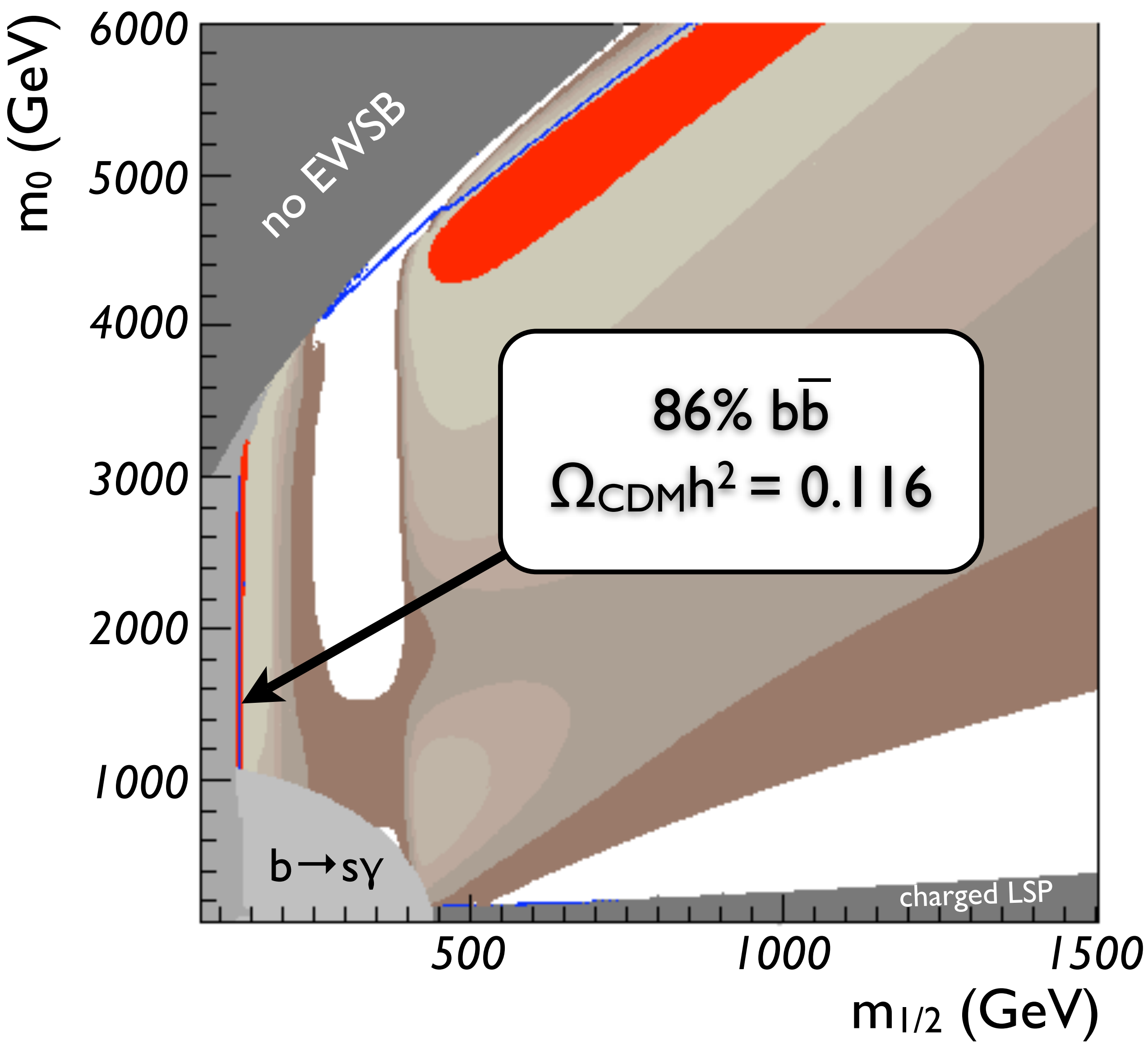

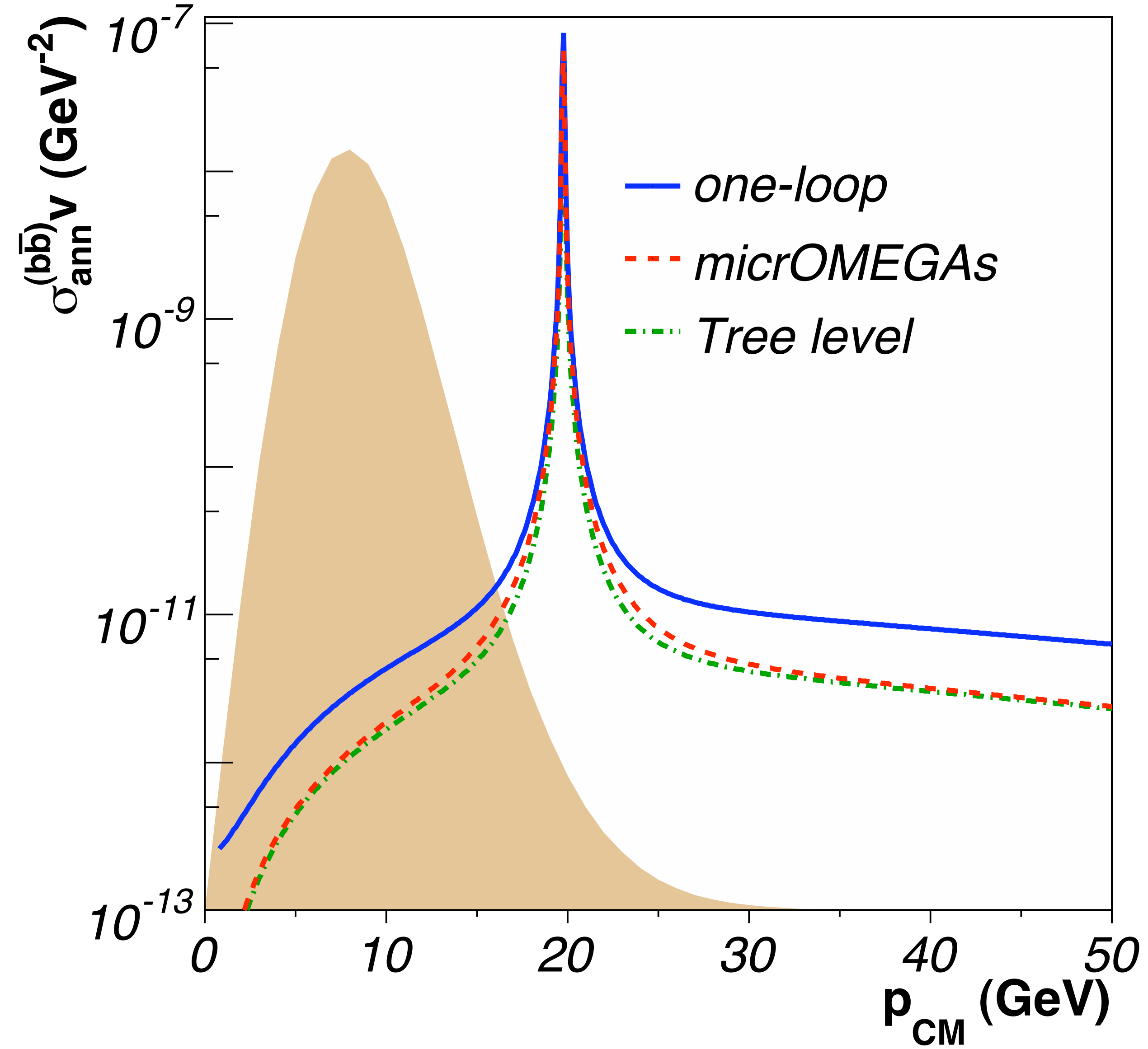

"Effective" Yukawa coupling very good approximation around the Higgs resonance

Position of resonance does not coincide with peak of velocity distribution for thermal average

Cross section enhanced significantly by one-loop QCD and SUSY-QCD corrections

Numerical results: Light Higgs resonance *(preliminary)*

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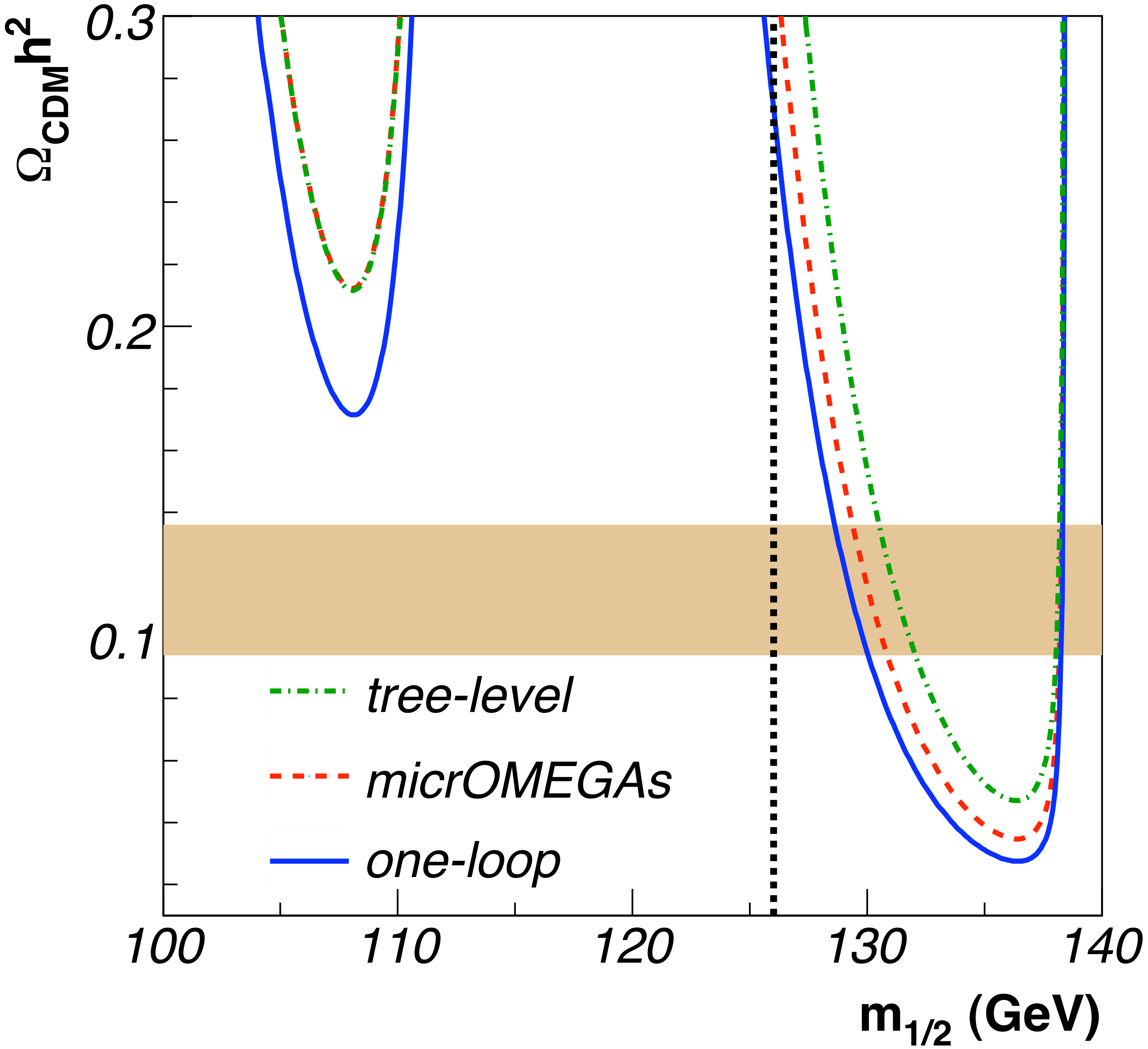

Effect on cross section influences directly the prediction of the relic density

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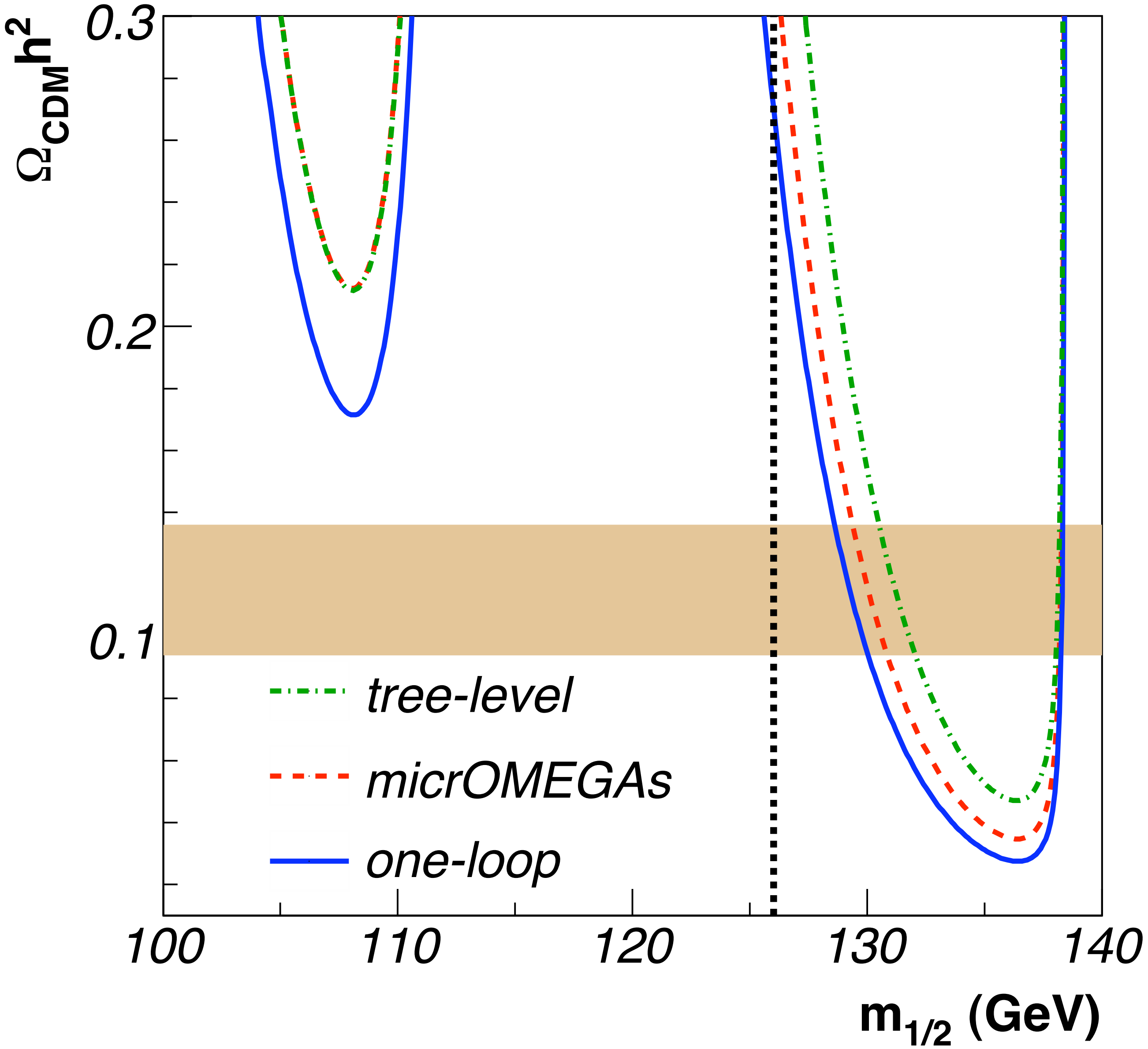

Effect on cross section influences directly the prediction of the relic density

Correction to annihilation through Z-boson exchange significant

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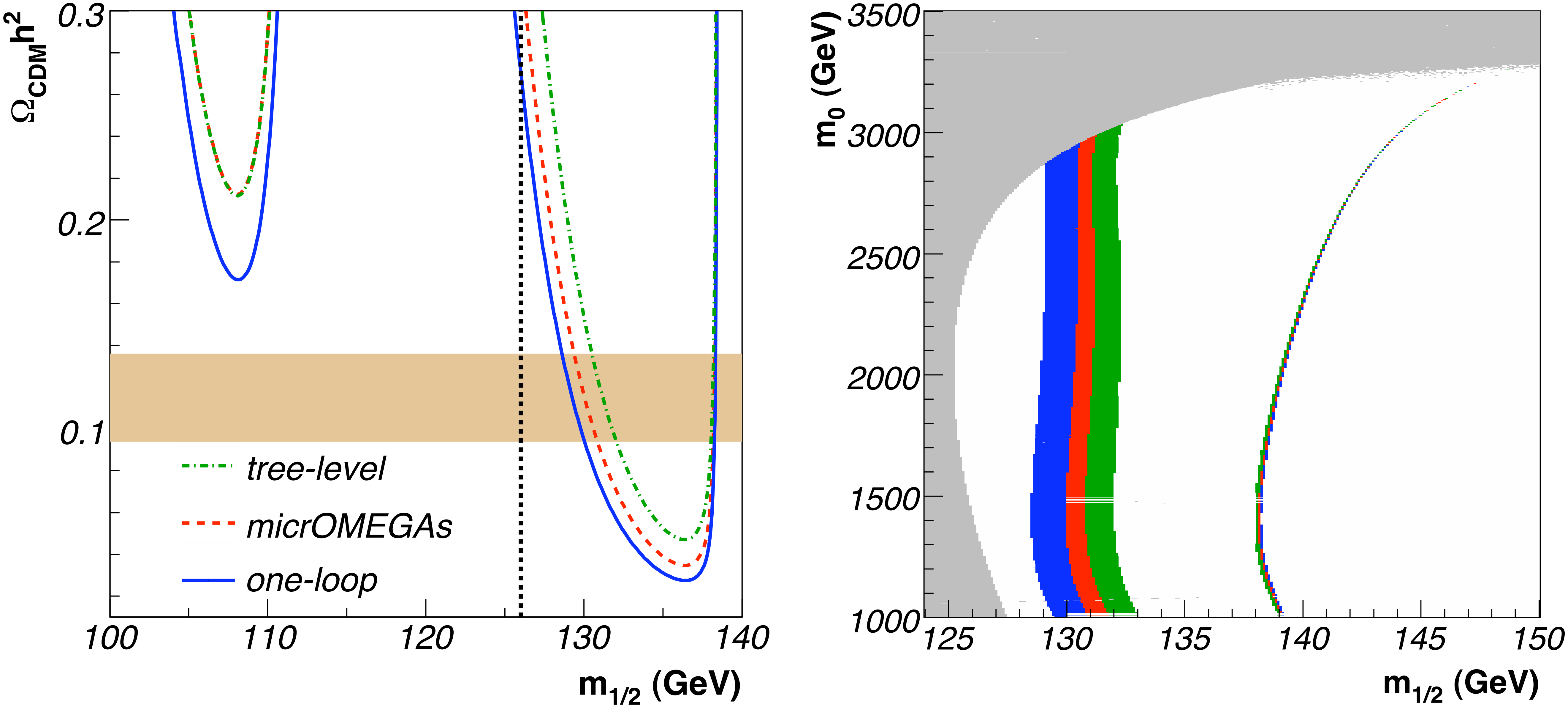

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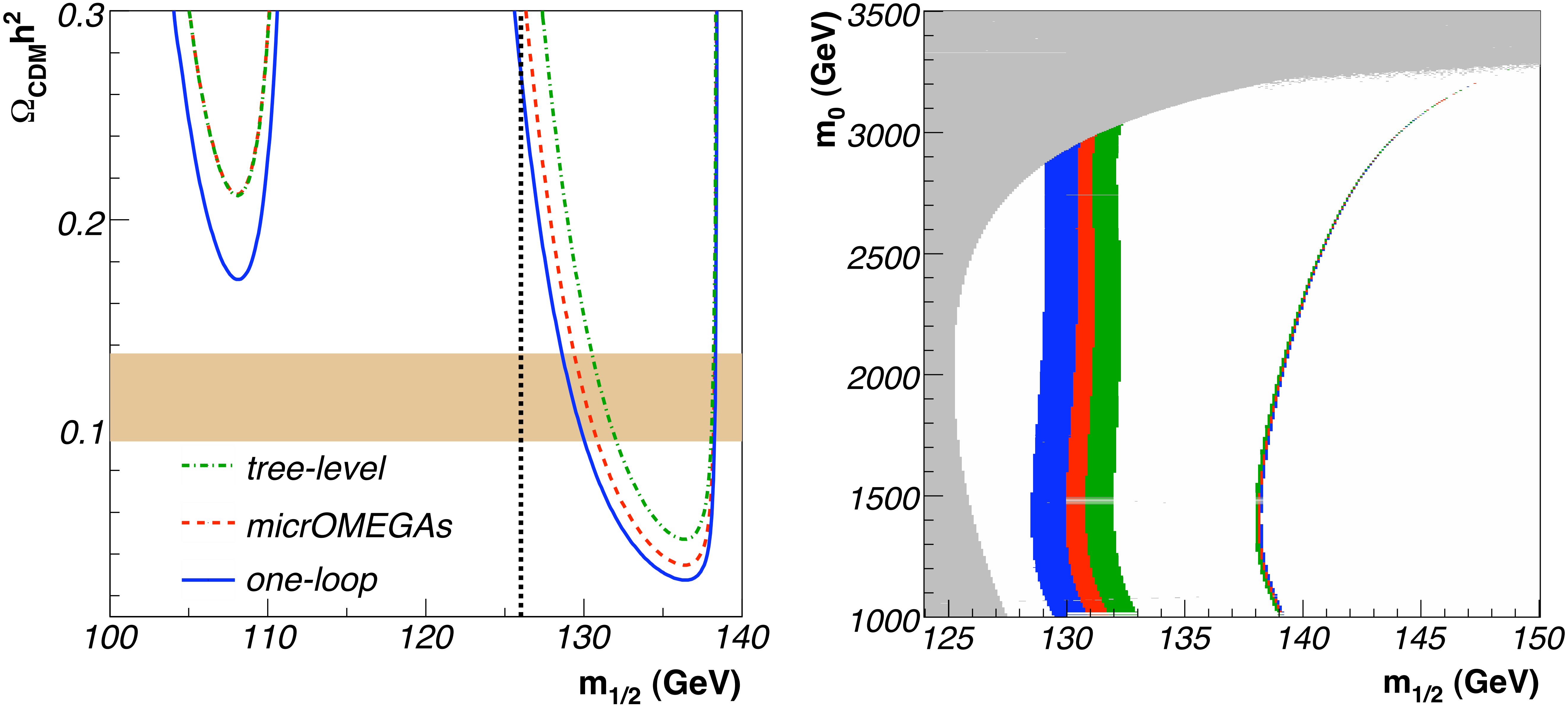


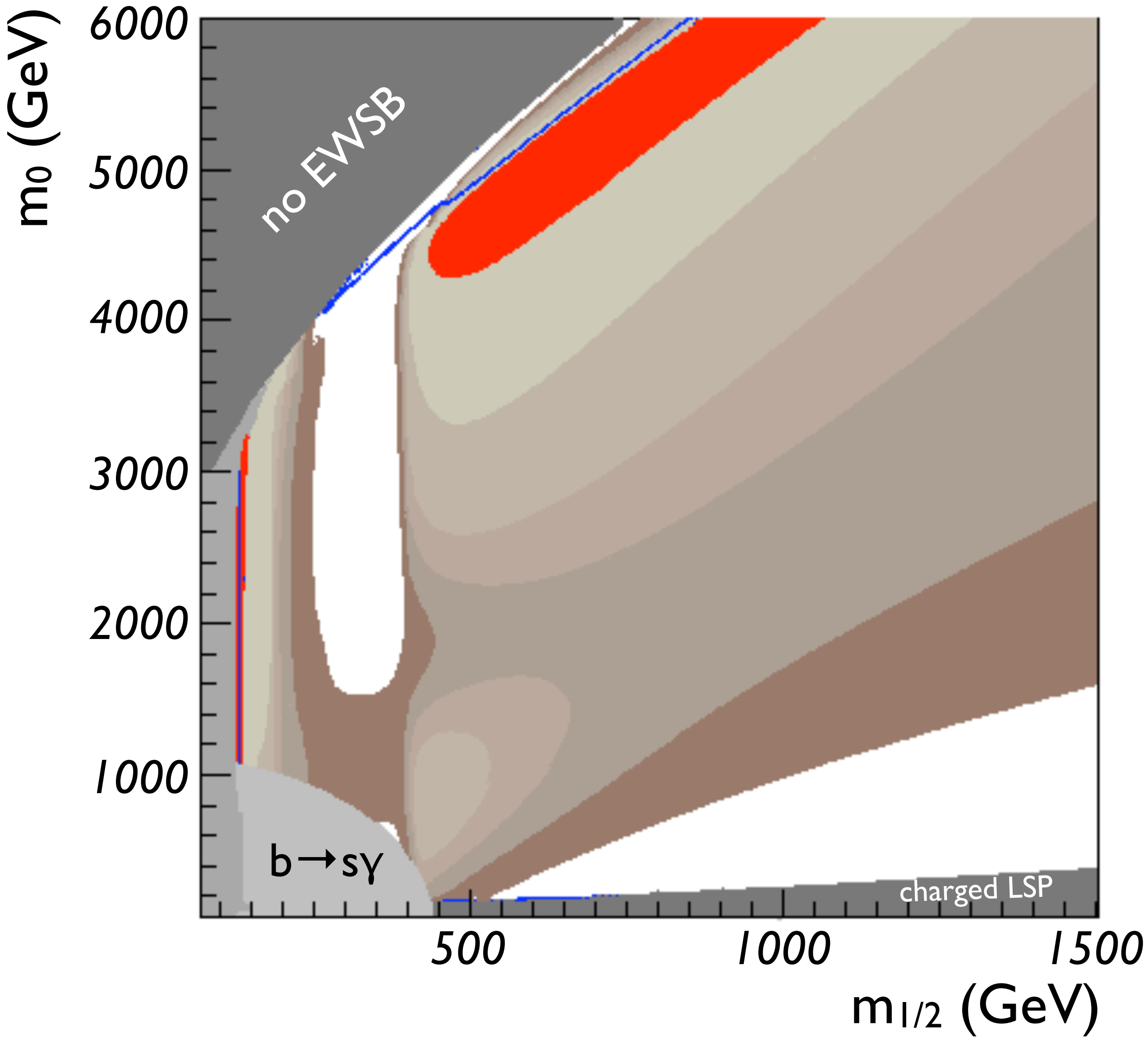
Effect on cross section influences directly the prediction of the relic density

Correction to annihilation through Z-boson exchange significant

Favoured interval shifted towards chargino mass limit $m_{1/2} \geq 126$ GeV

Numerical results: Focus point region *(preliminary)*

mSUGRA parameters: m_0=5300 GeV, $m_{1/2}$=625 GeV, A_0=-1500 GeV, tanβ=10, μ>0



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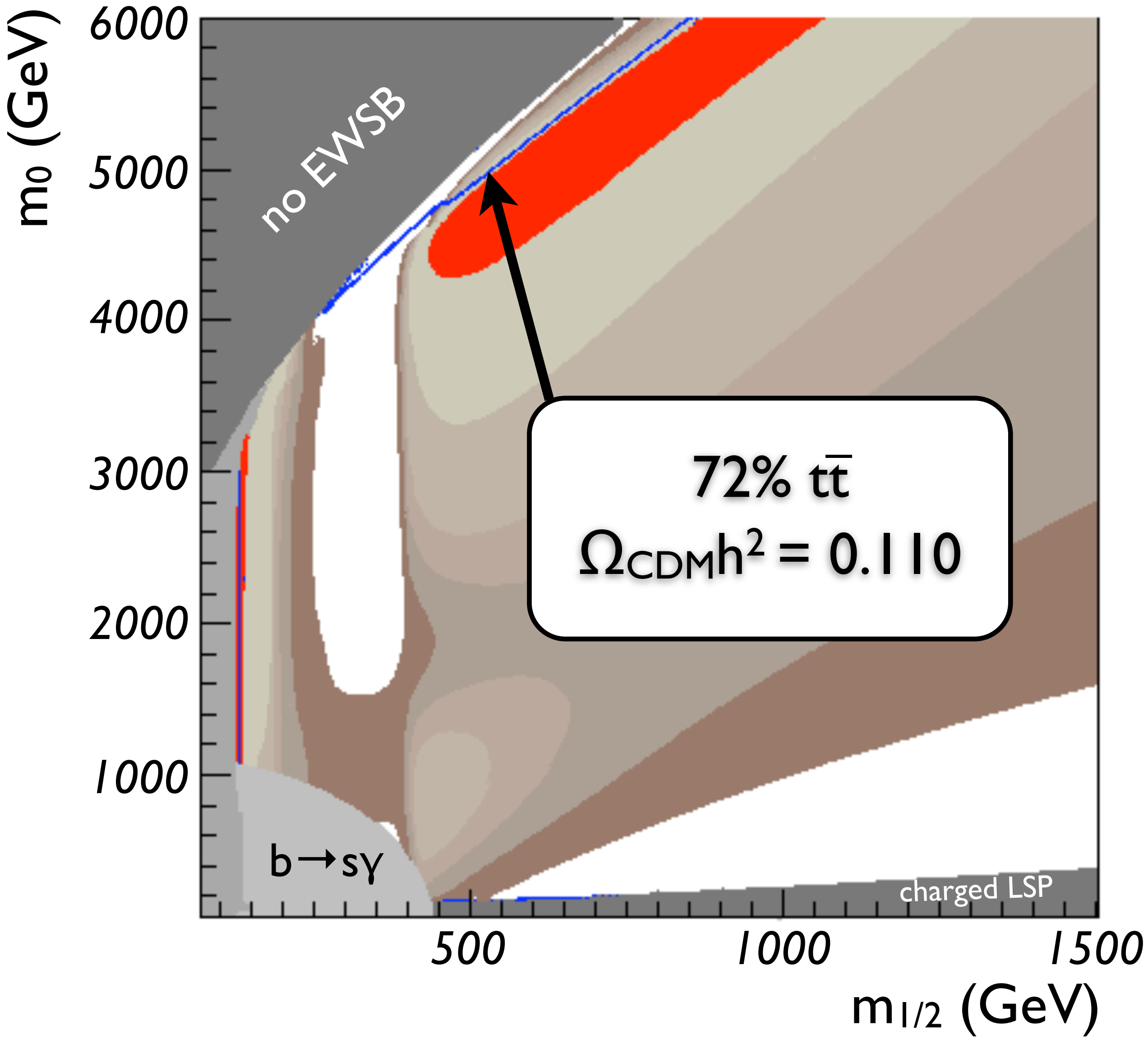

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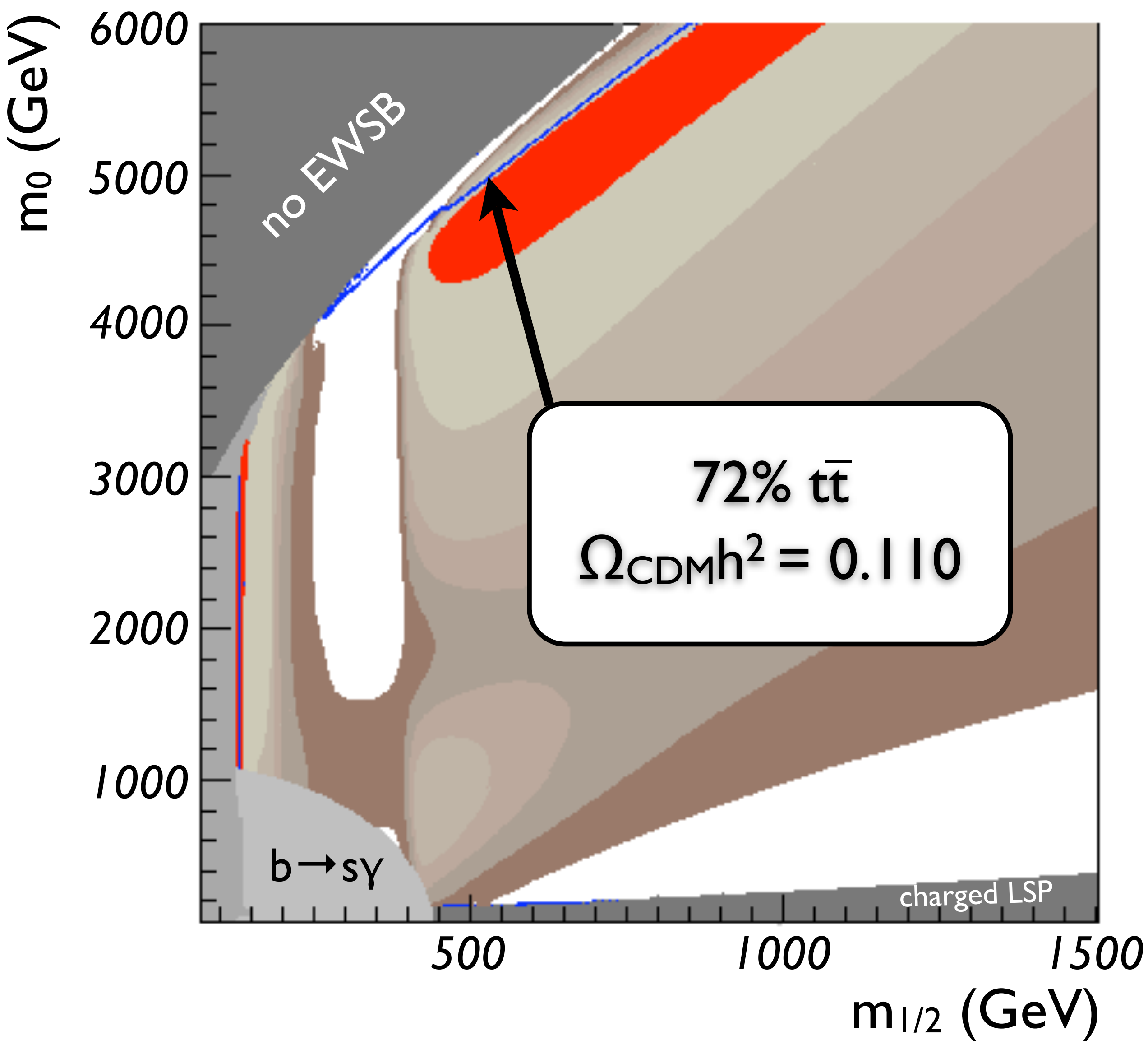

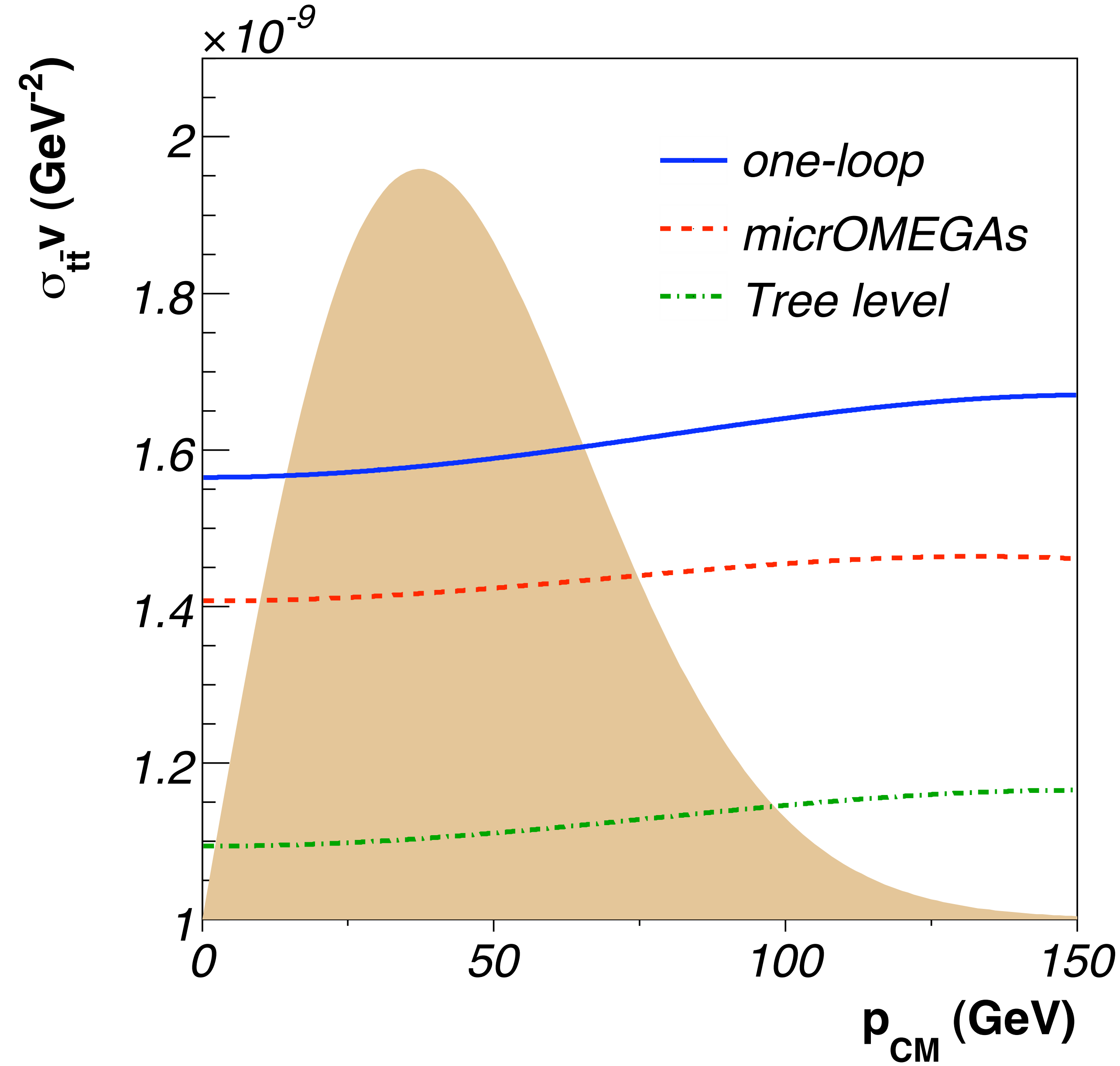

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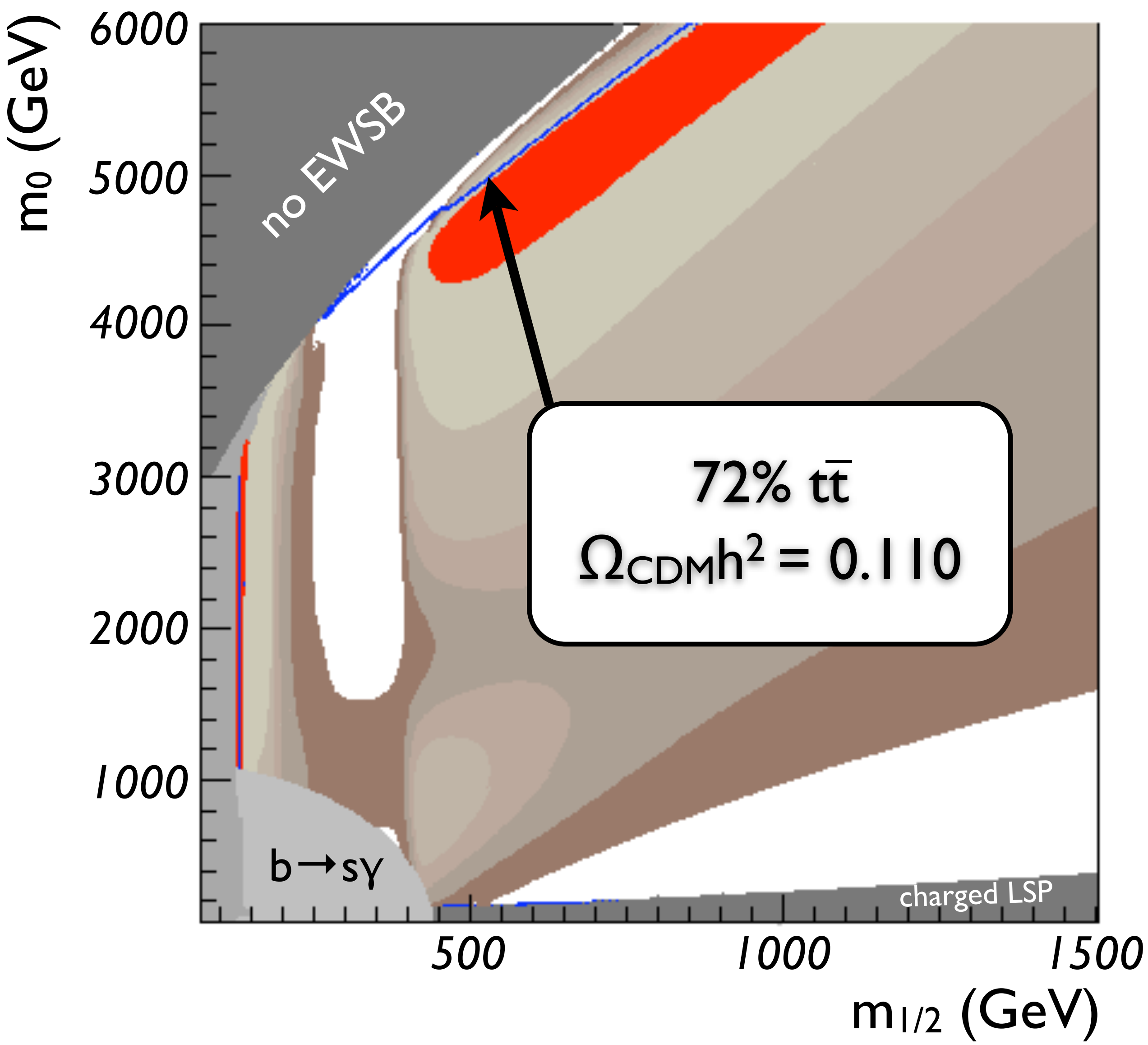
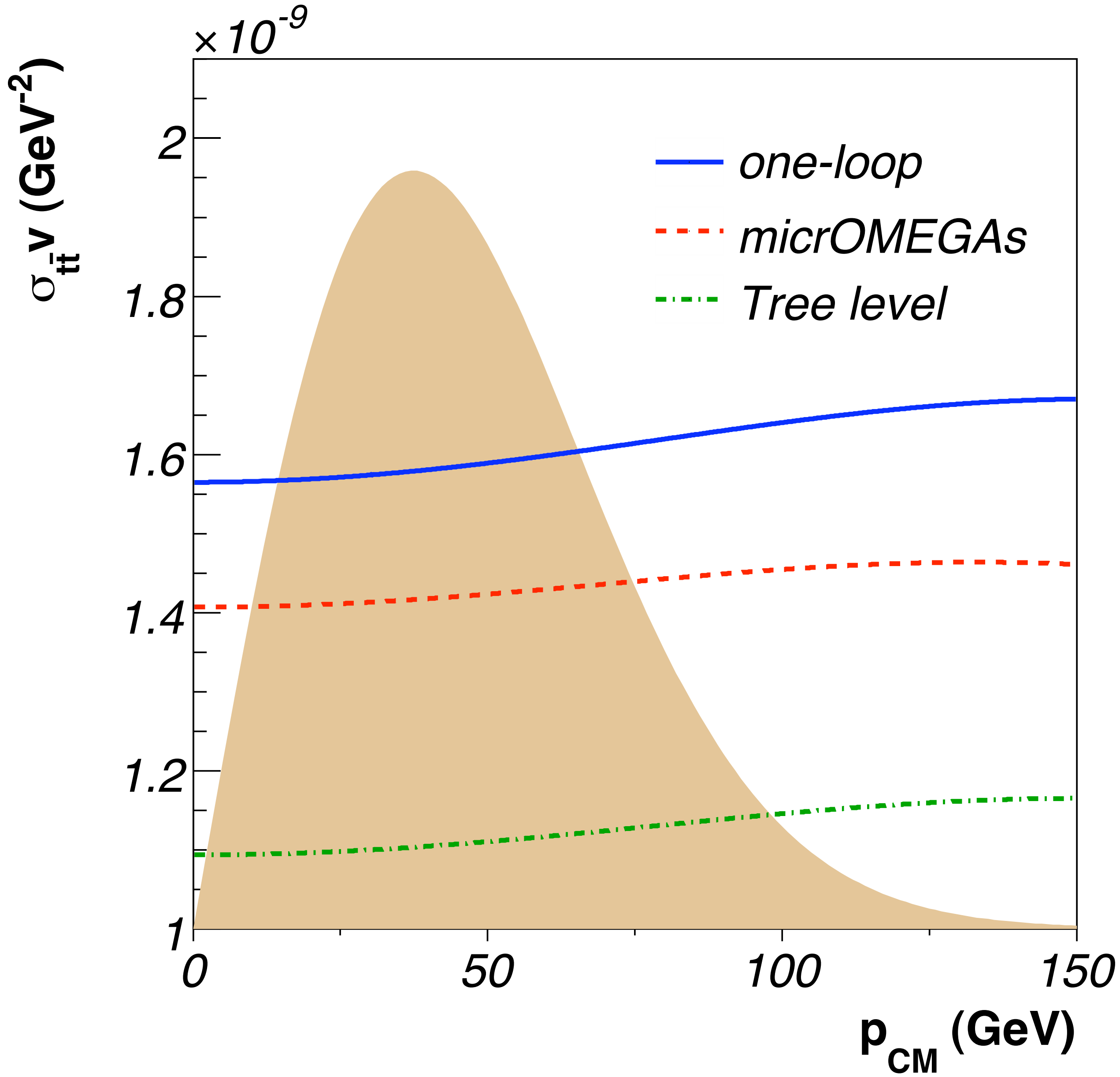


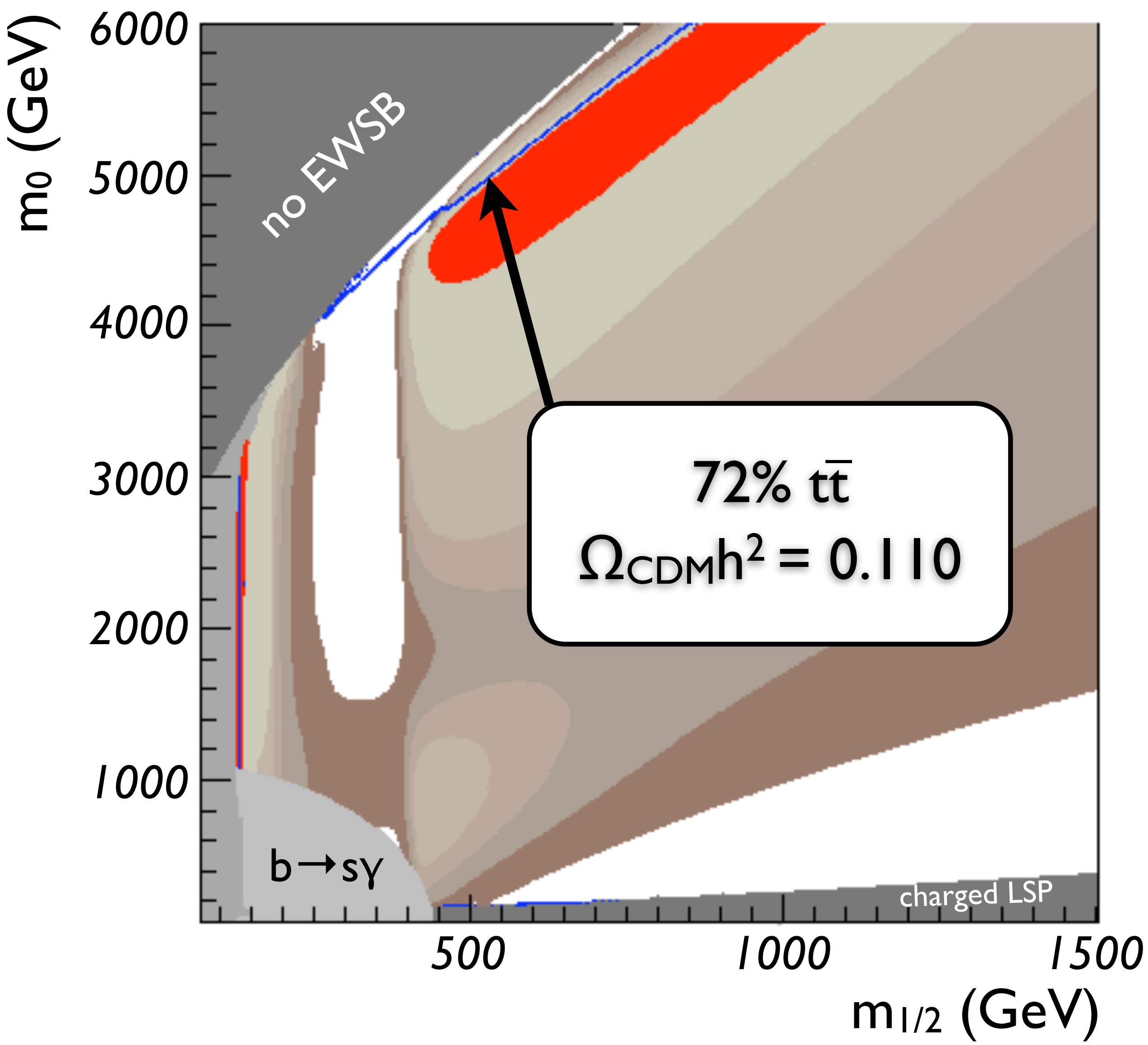


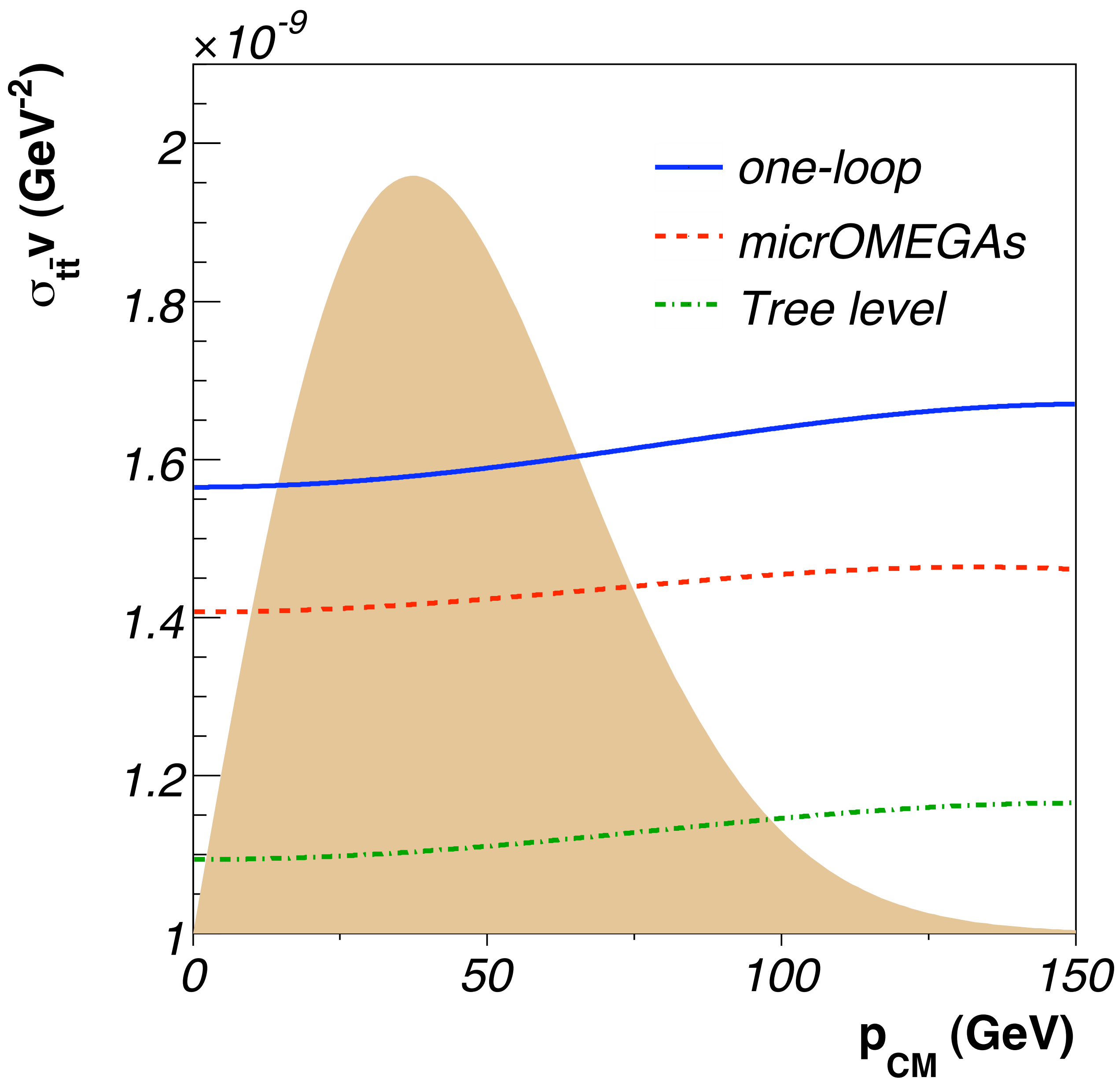
Higgs resonance situated at rather high energies around p_{cm}≈2610 GeV

Annihilation cross section sizeable due to large top quark mass

Numerical results: Focus point region *(preliminary)*

mSUGRA parameters: m_0=5300 GeV, $m_{1/2}$=625 GeV, A_0=-1500 GeV, tanβ=10, μ>0





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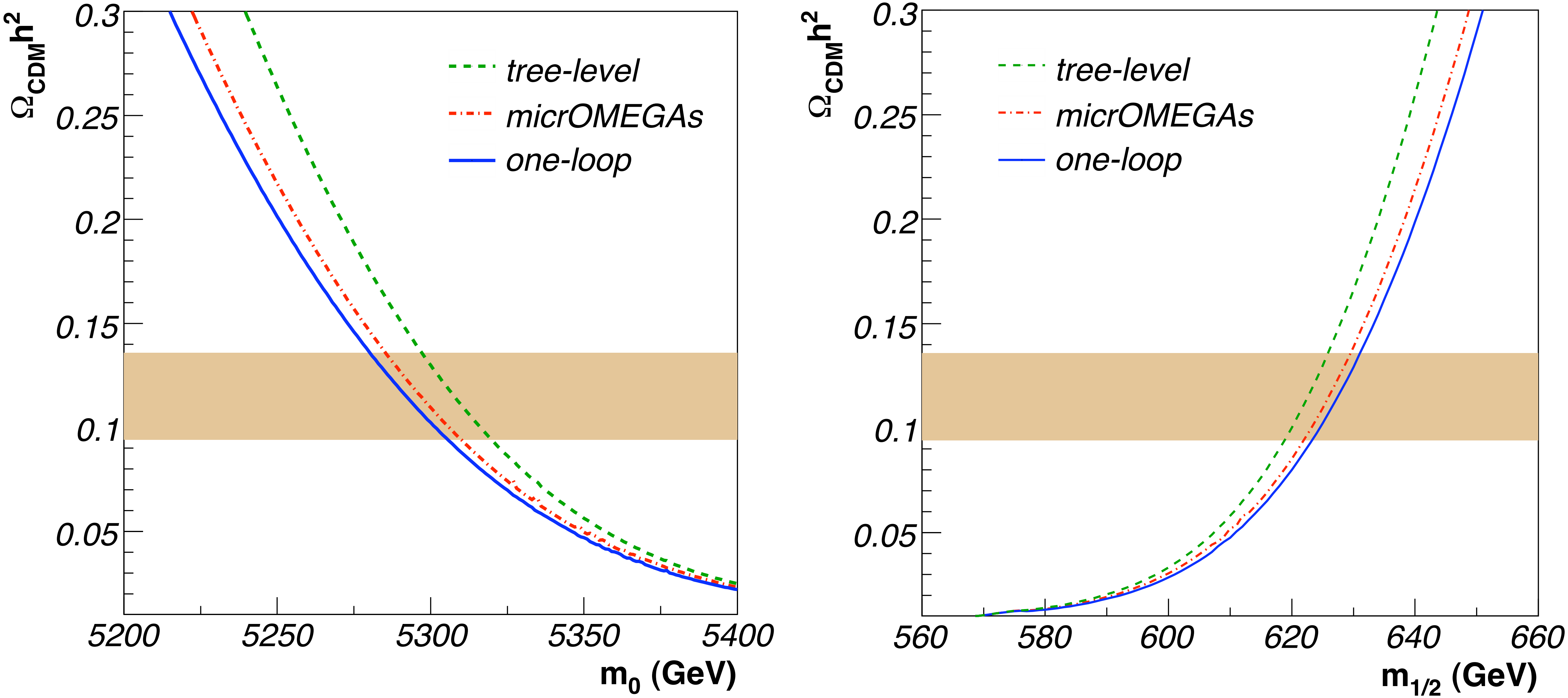

Prediction of neutralino relic density receives sizeable corrections

Numerical results: Focus point region *(preliminary)*

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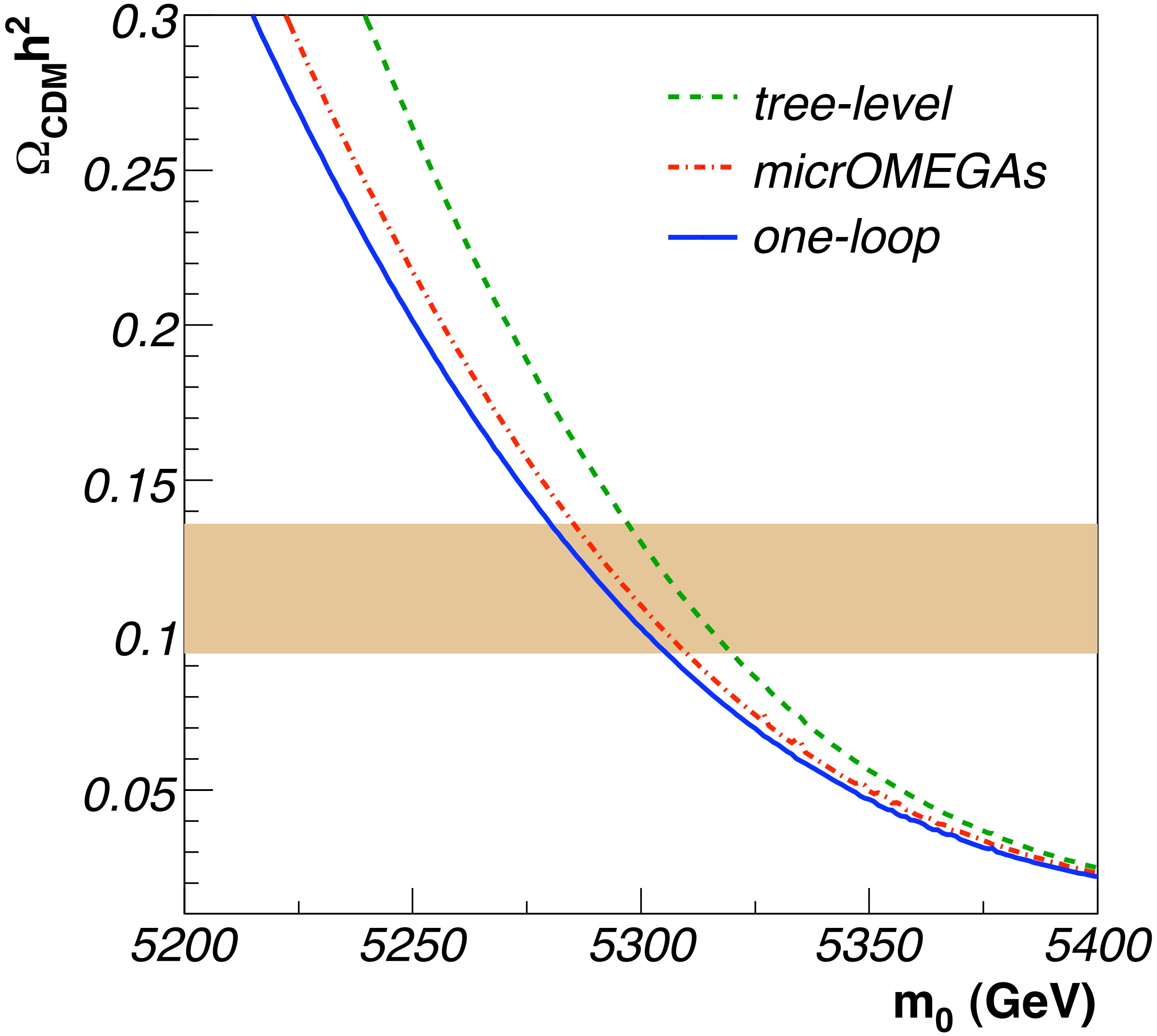
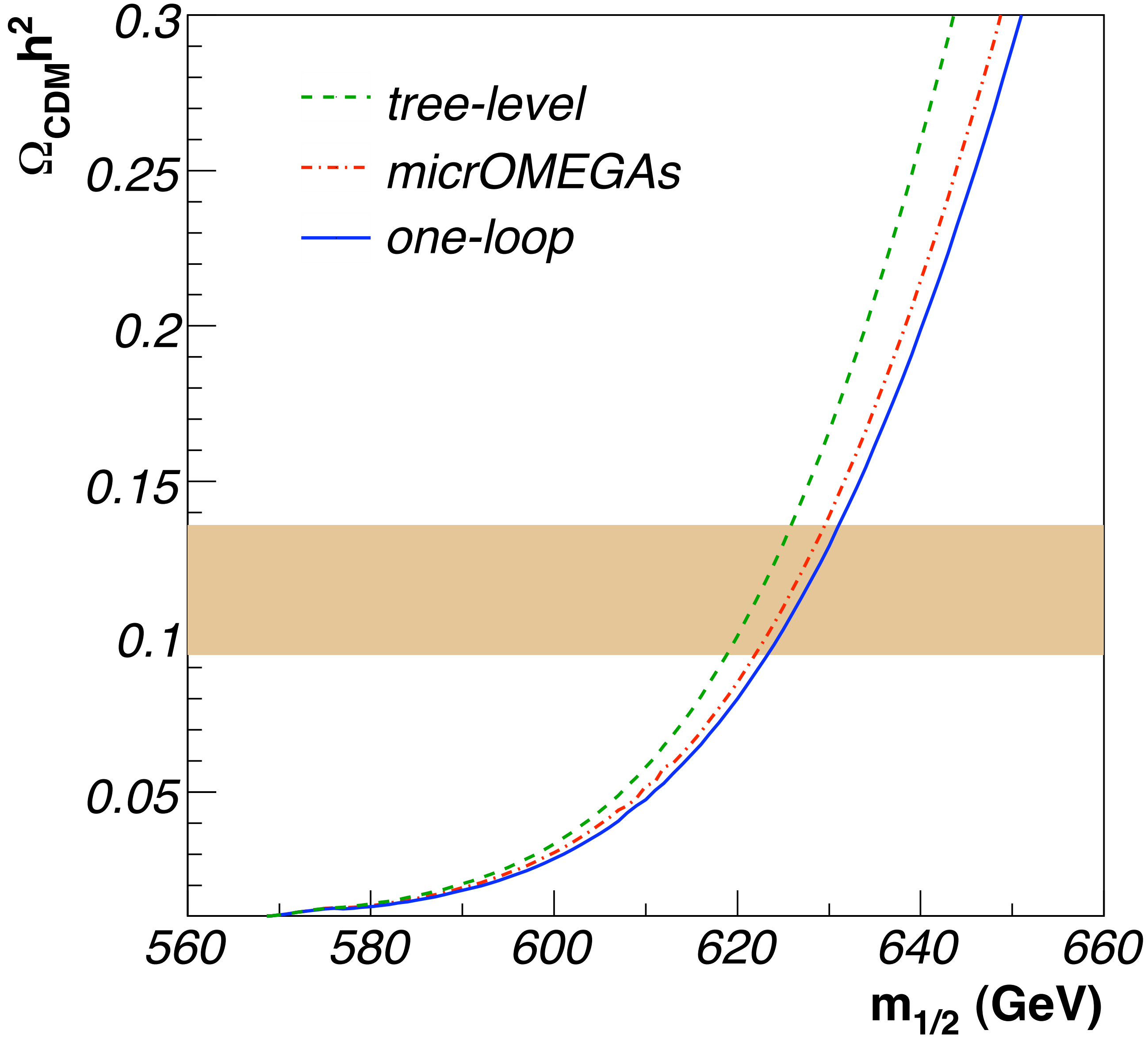


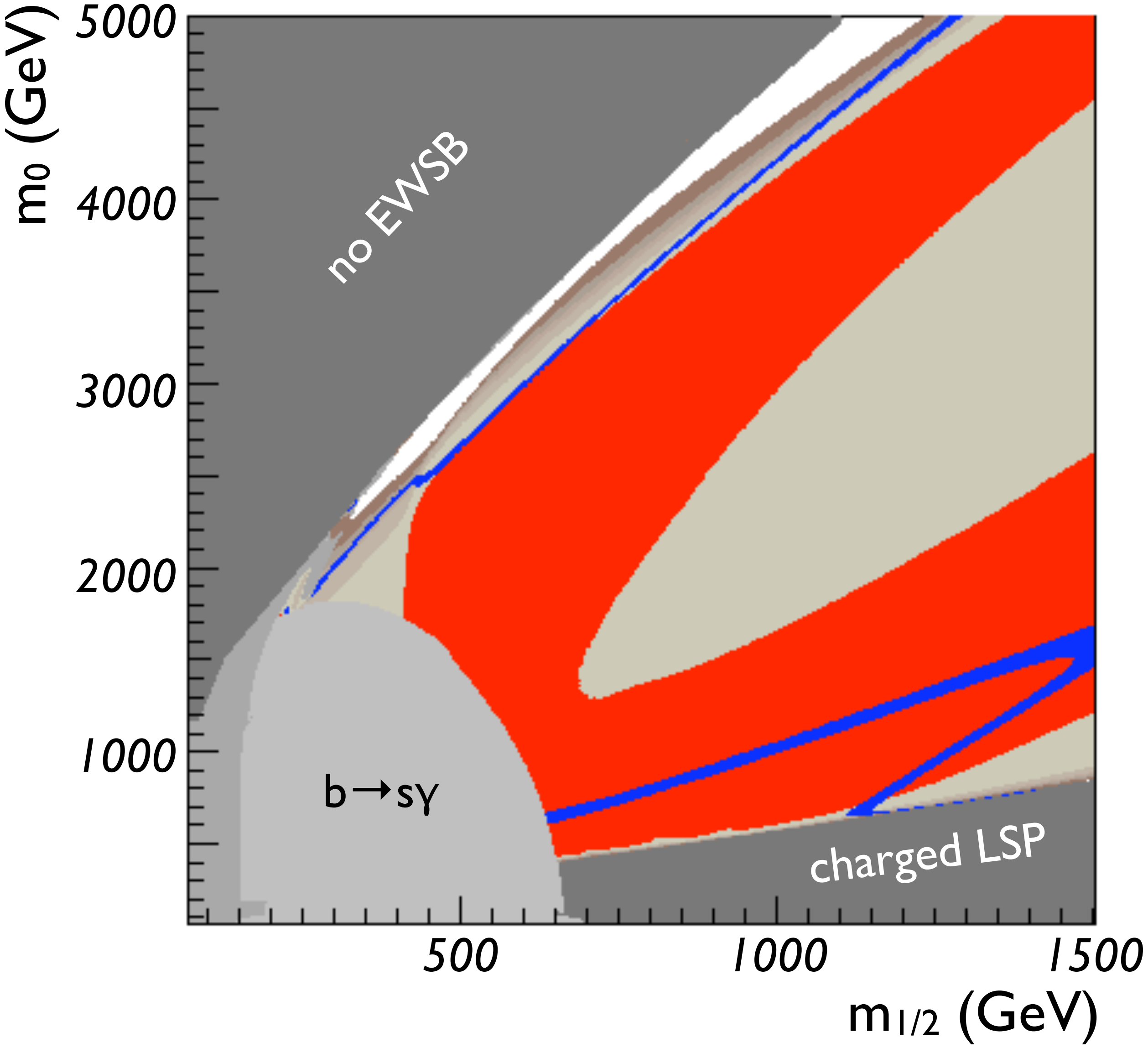


Prediction of neutralino relic density receives sizeable corrections

Favoured region shifted to higher scalar masses m_0 and smaller gaugino masses $m_{1/2}$

Numerical results: Focus point region *(preliminary)*

mSUGRA parameters: m_0=3000 GeV, $m_{1/2}$=600 GeV, A_0=0, tanβ=50, μ>0



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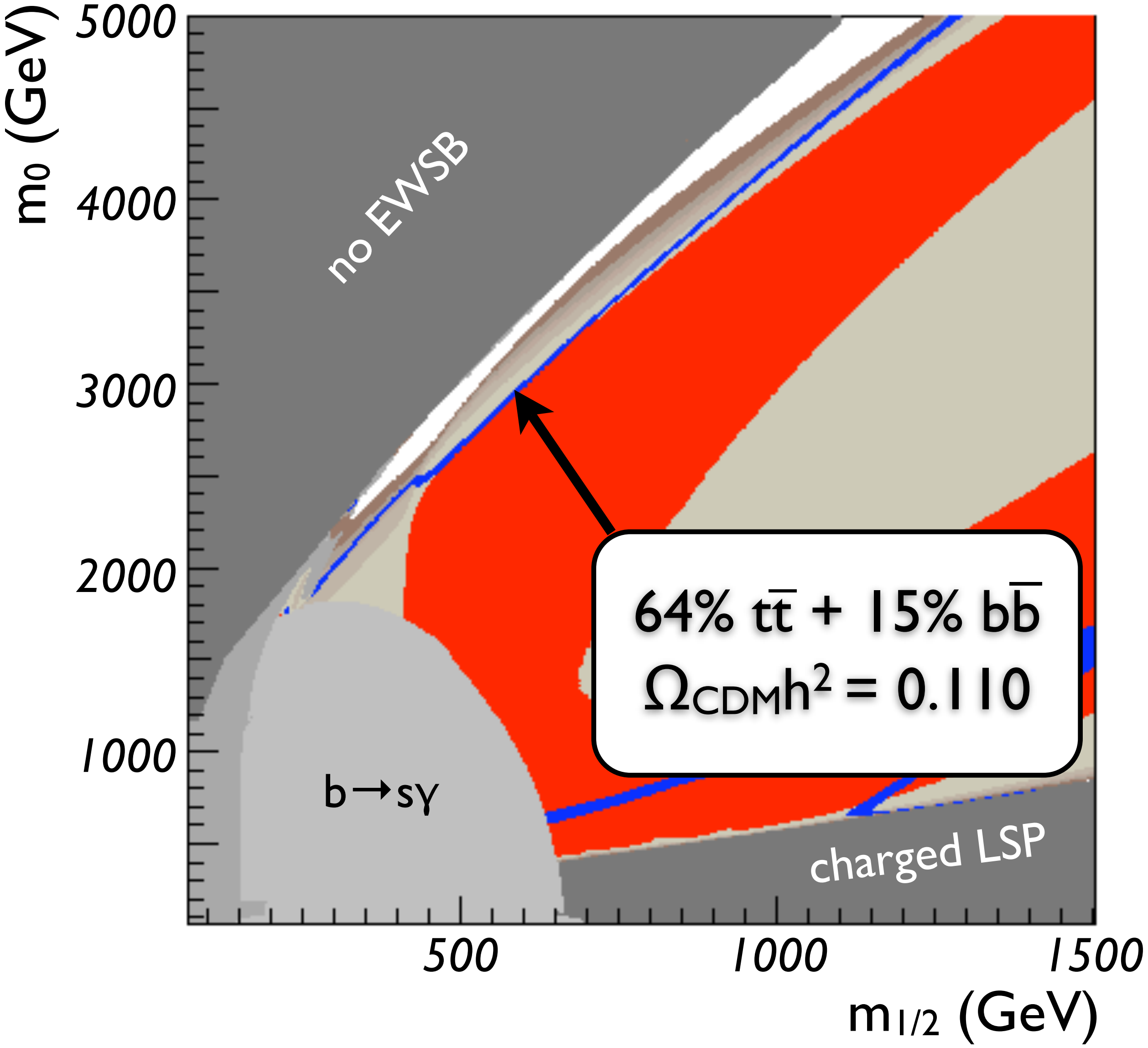

Important top and bottom quark contributions due to large top mass and large tanβ

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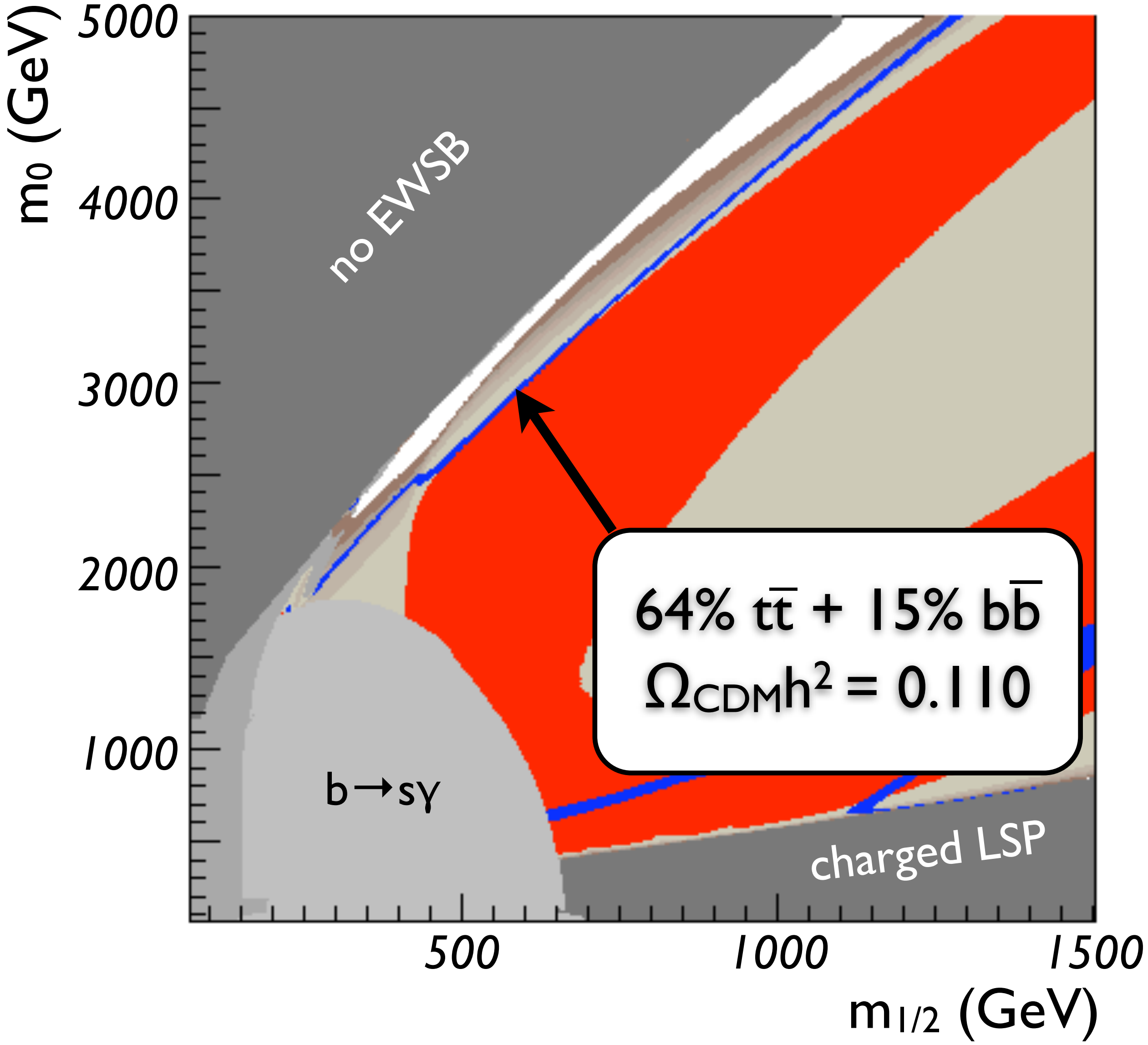

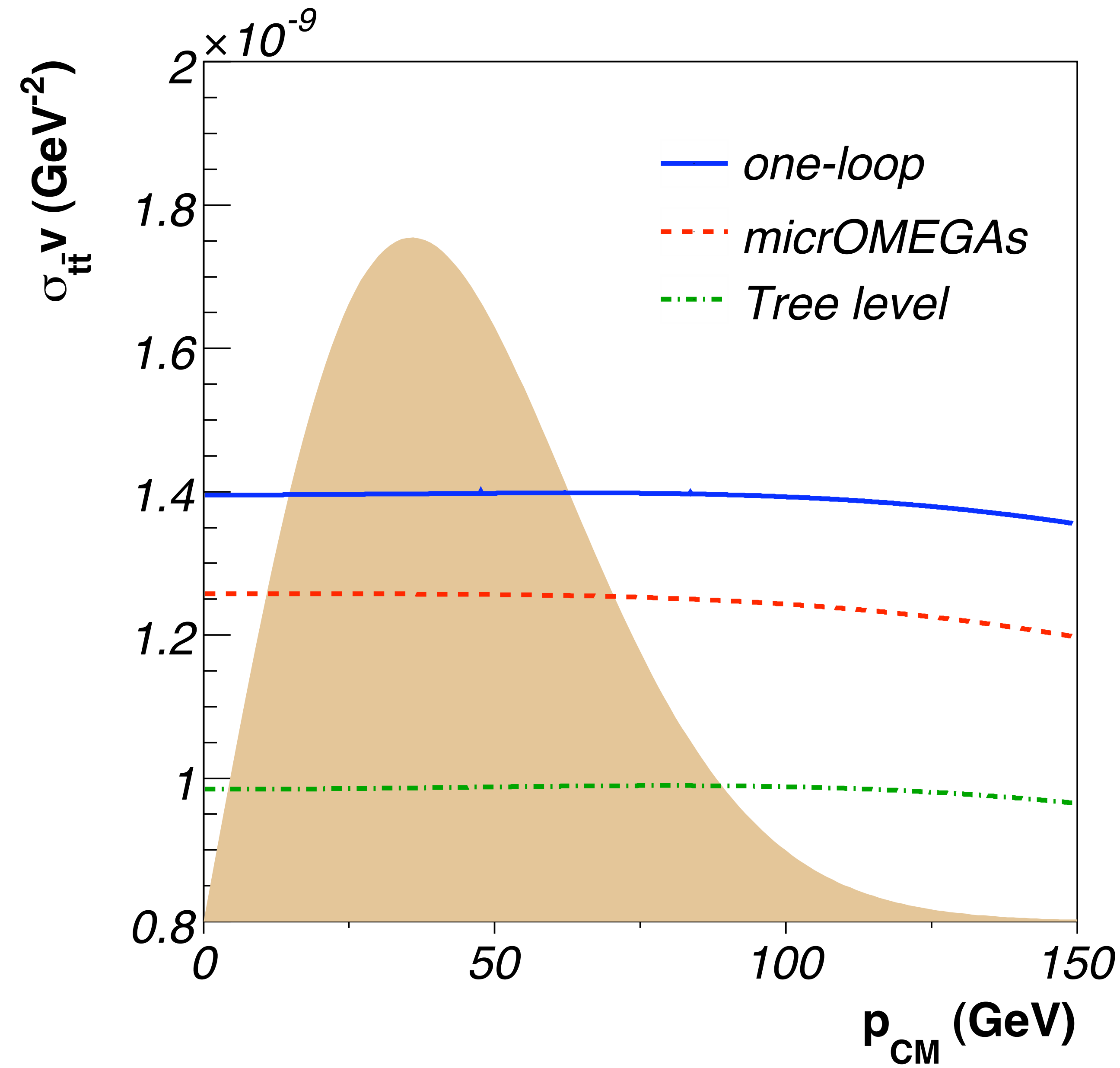

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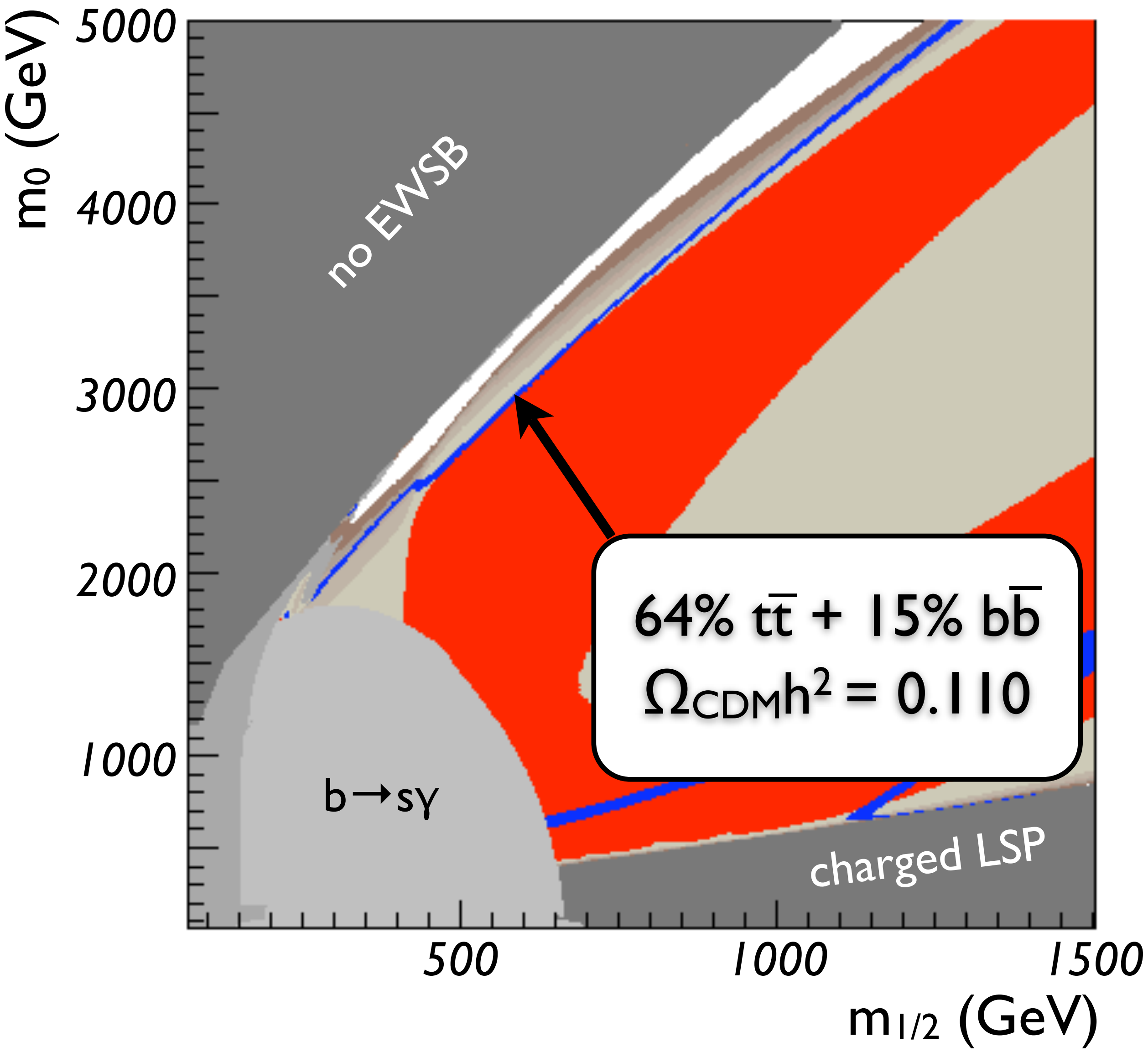

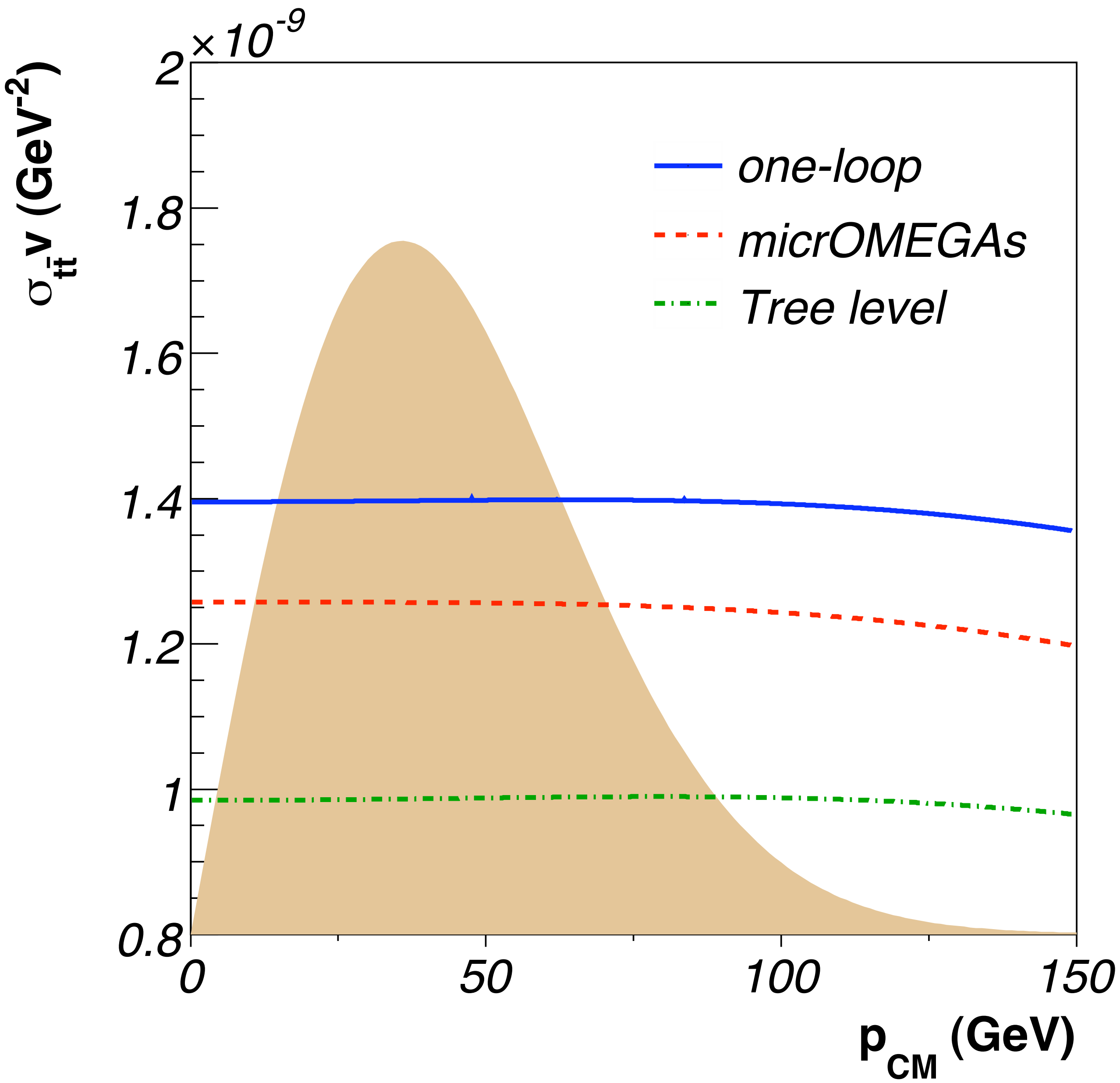

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Each cross section enhanced significantly by one-loop QCD and SUSY-QCD corrections

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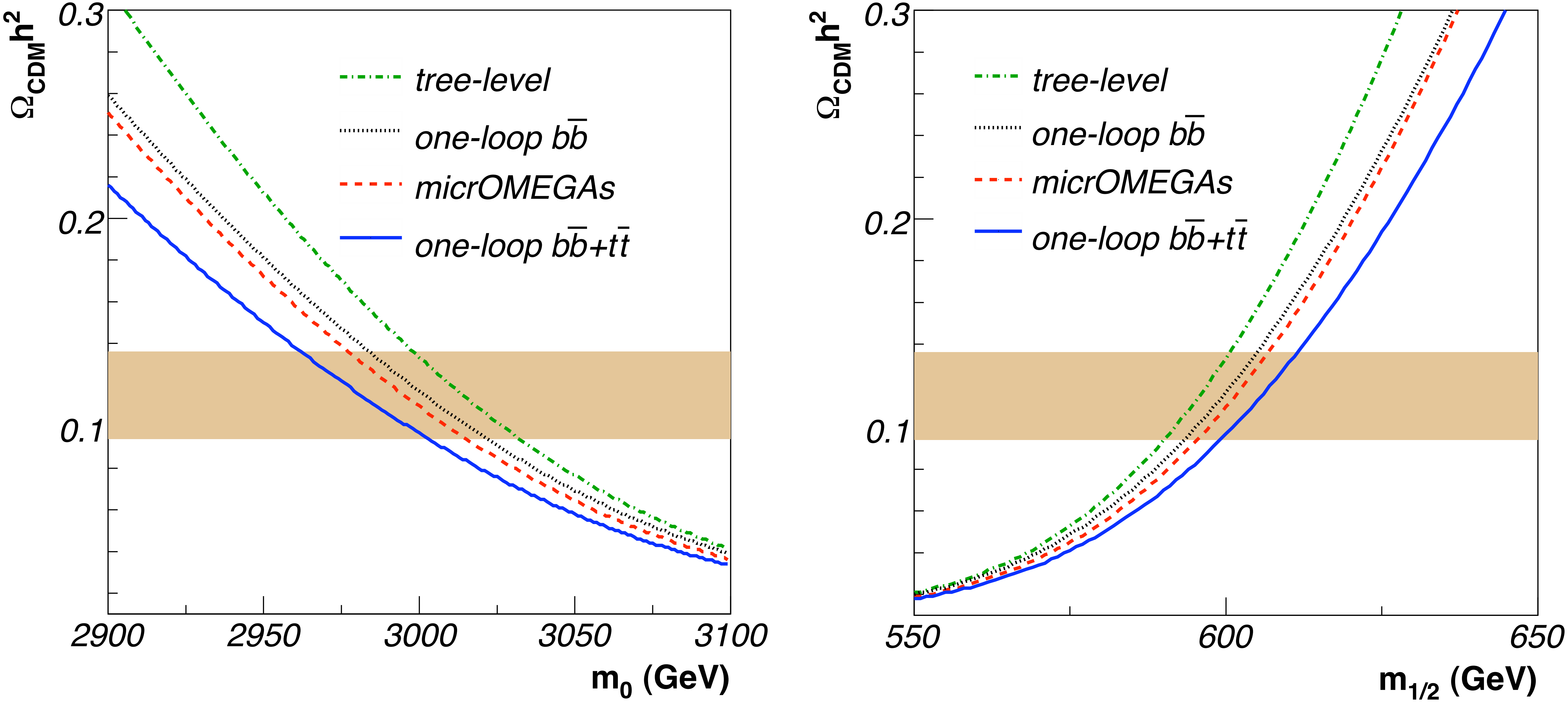

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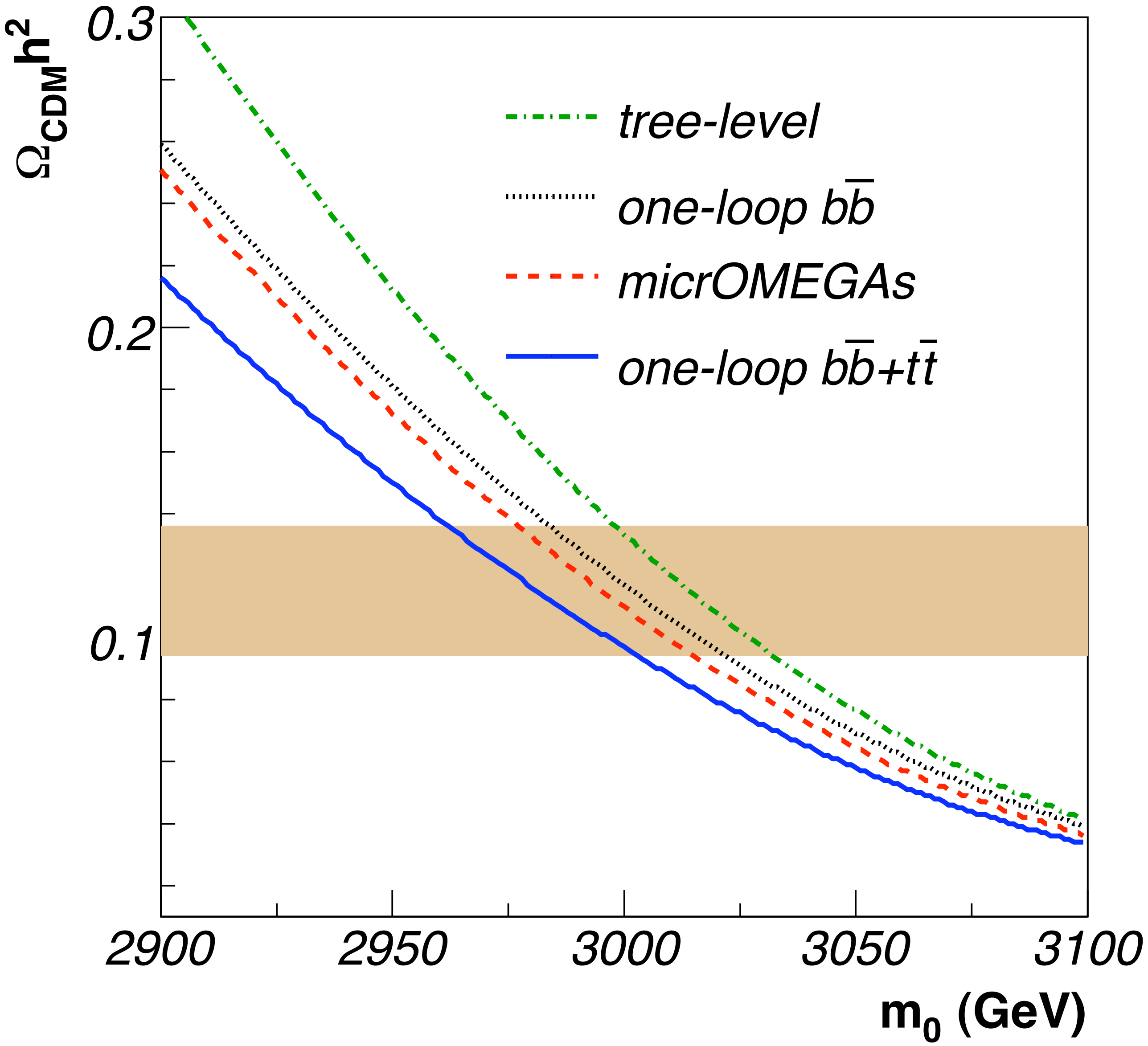

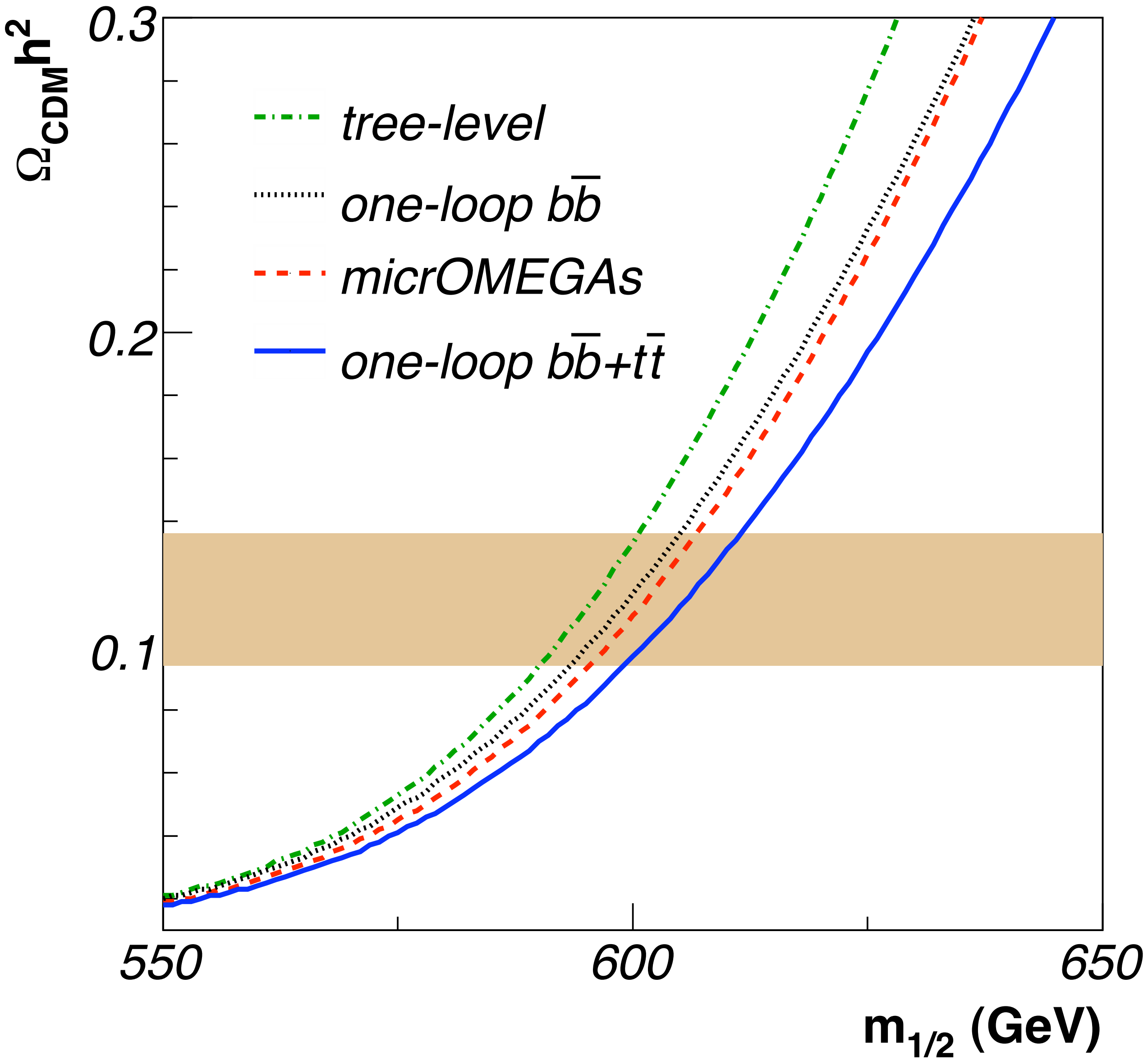

Bottom quark correction very important due to large tanβ

Top and bottom corrections shift relic density in the same direction

Numerical results: Focus point region *(preliminary)*

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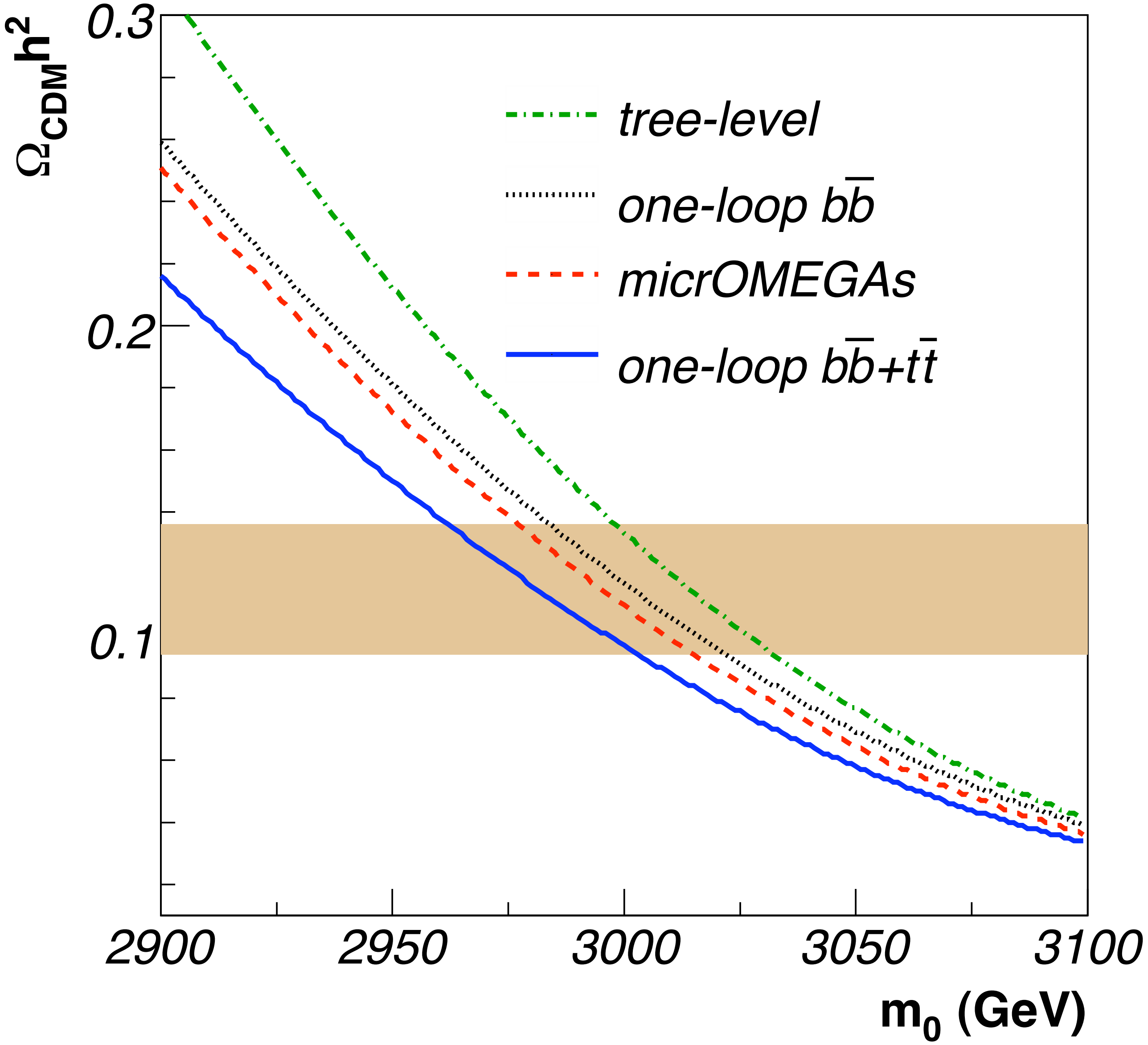

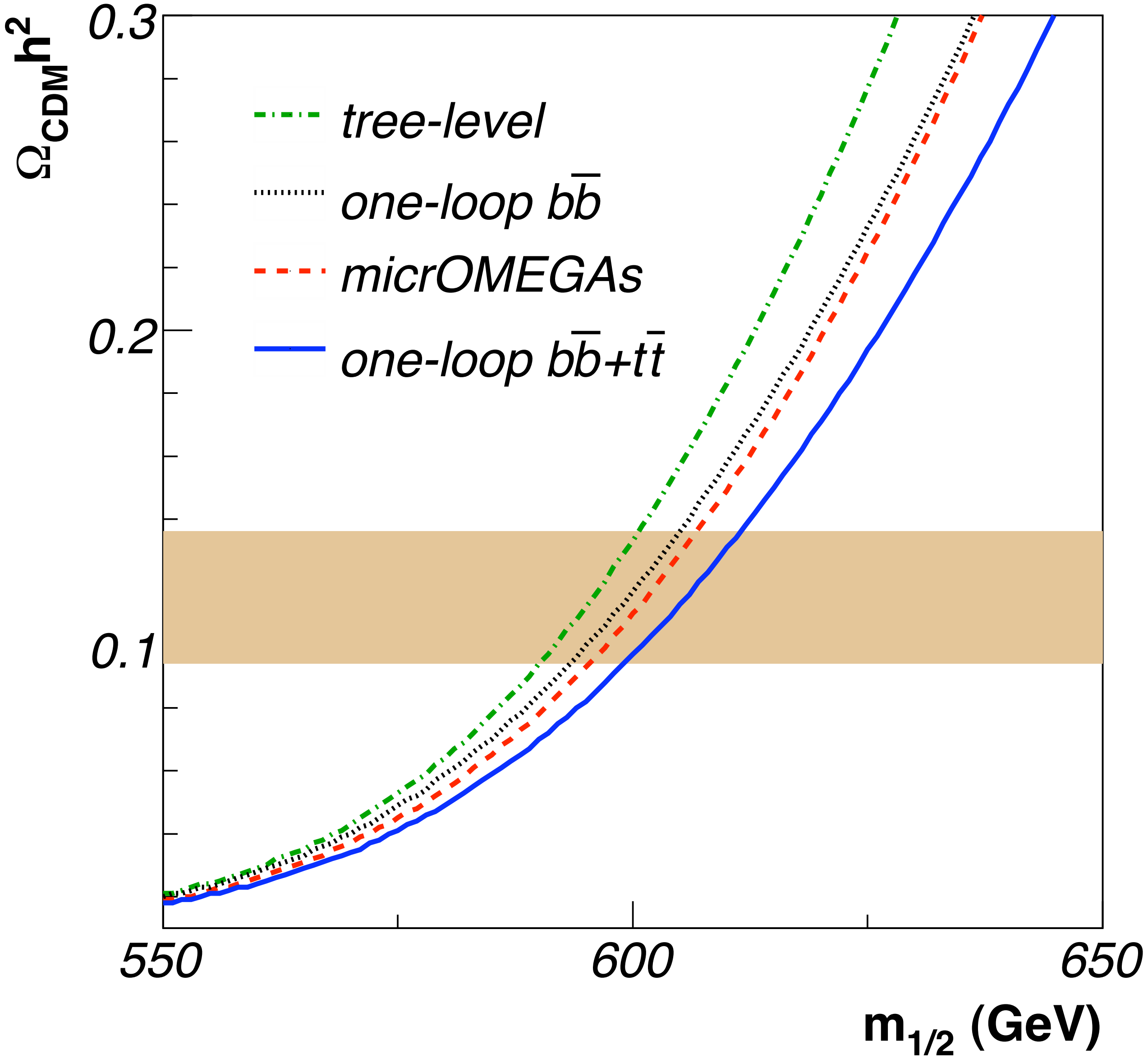

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→ Complementary information with respect to collider and low-energy data

→ Neutralino annihilation into "heavy" quark-antiquark pairs

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Outlook / Perspectives:

→ Study scenarios with important contributions from light quark final states

→ Include corrected cross section also in DarkSUSY and compare...

→ Application to indirect dark matter detection...

→ Implementation of electroweak corrections...