Electroweak Baryogenesis:

Beyond the Standard Model

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ICREA/IFAE

OUTLINE

- √ Introduction and SM results
- √ SM extensions with scalars: the MSSM
- √ SM extensions with fermions
- √ Towards split supersymmetry
- √ Conclusions

INTRODUCTION

Conditions for baryogenesis were stated by Sakharov in 1967[a]

✓ B-violation

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- √ B-violation
- √ C and CP violation
- √ Departure from thermal equilibrium
- √ Kuzmin, Rubakov and Shaposhnikov considered in 1985 the possibility of baryogenesis at the electroweak phase transition (EWPT)

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- √ Baryon number is non-perturbatively violated in the SM: sphalerons at finite temperature
- √ C and CP violating (CKM) phases are present in the SM
- √ The out-of-equilibrium conditions are present in the bubble wall in a FIRST ORDER PHASE TRANSITION

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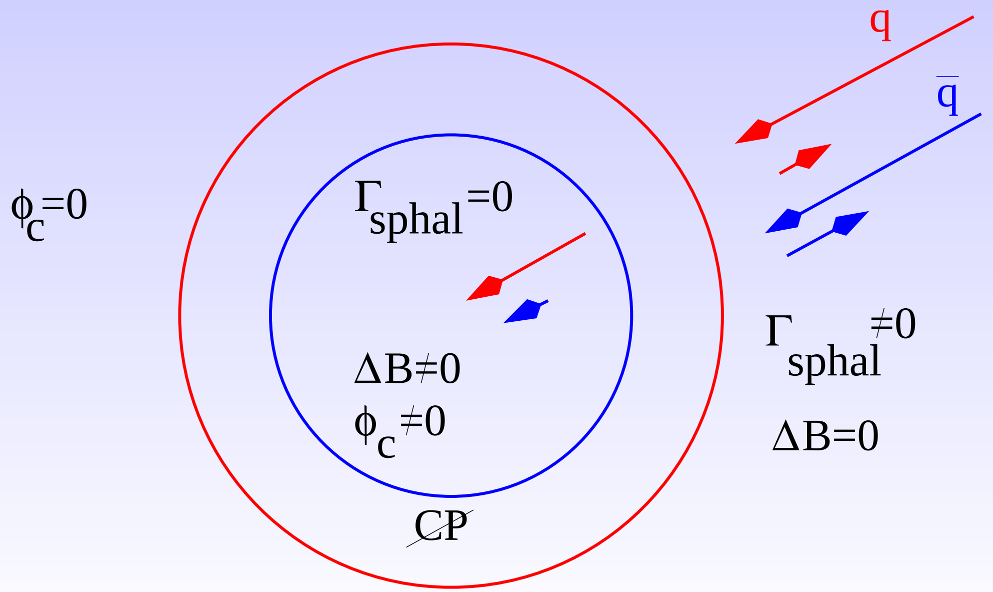

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If the phase transition is not strongly enough first order any previously generated BAU is erased by sphalerons in the symmetric phase $\Rightarrow \dfrac{\phi_c}{T_c} \geq 1$

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- The phase transition is not strong enough. Would a BAU be generated it would be erased by weak sphalerons in the broken phase. In fact the strength of the phase transition strongly depends on the Higgs mass and for present experimental limits it is extremely weak. A one-loop (improved by hard thermal loops) result is plotted

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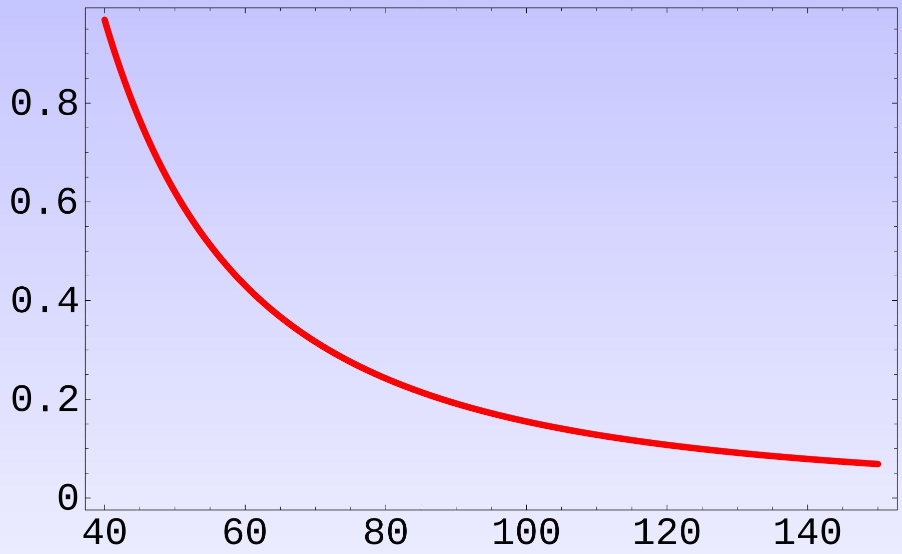

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- √ Bosons appear in supersymmetric extensions of the SM: in particular **STOPS**

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  - ⋆ Right-handed stop are light: $\sim m_t$ not to shield the phase transition
  - ⋆ The SM-like Higgs is light enough

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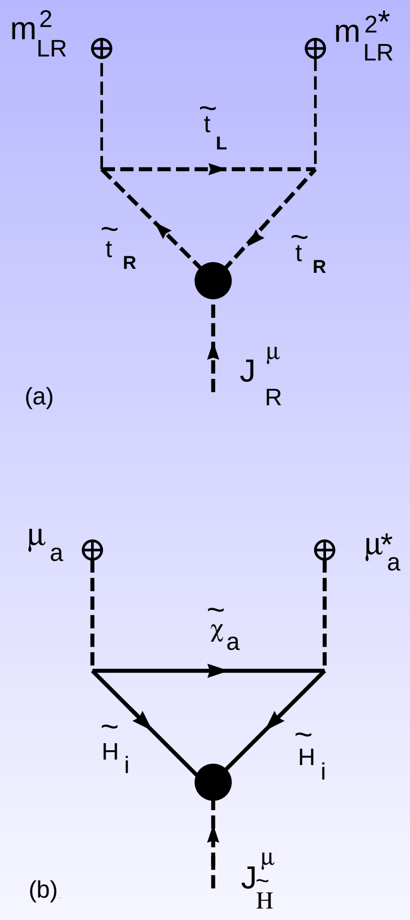


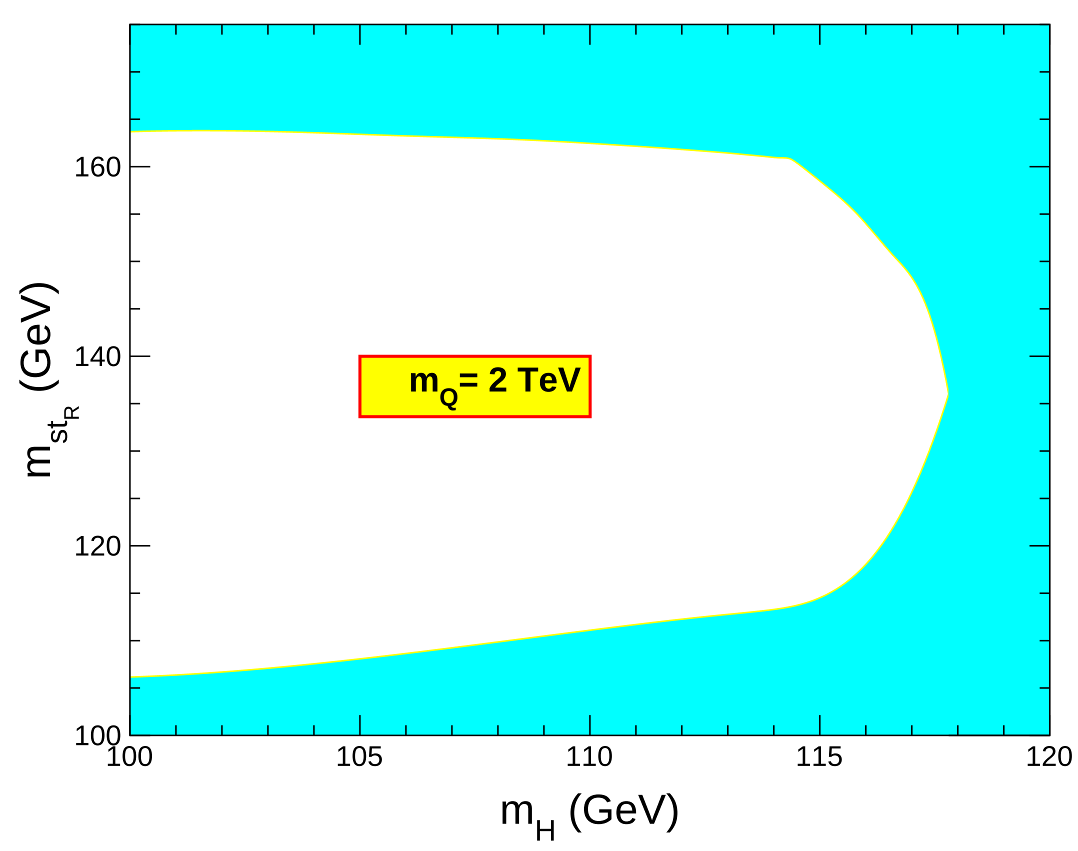
MSSM

BAU is barely consistent with WMAP results for $\mathcal{O}(1)$ phases and light charginos and neutralinos

The lightest neutralino is a candidate to Dark Matter

MSSM

The baryogenesis window for the MSSM is on the verge of experimental limits



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- √ Light Higgs boson, around its present experimental bounds $m_H > 115$ GeV

If the Higgs mass turns out to be (much) larger an economical solution requires that supersymmetry is broken (sfermions masses are) at a much larger scale: SPLIT SUPERSYMMETRY

Conclusion

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- If $\tilde{t}_R$ is heavy ($\sim m_{susy}$) charginos and neutralinos should be strongly coupled and responsible for both the strong phase transition and EWBG [M. Carena, A. Megevand, M.Q. and C.E.M. Wagner, NPB716 (2005) 319]

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- If $\tilde{t}_R$ is light ($\sim m_t$) charginos and neutralinos can be weakly coupled and only responsible for the EWBG [M. Carena, G. Nardini, M.Q. and C.E,M. Wagner, in preparation]: A special version of split supersymmetry.

SM EXTENSION WITH FERMIONS

We will consider the SM + Higgsinos ($\tilde{H}_{1,2}$), Winos and Binos ($\tilde{W}^a$, $\tilde{B}$) coupled to the SM Higgs doublet H with the Lagrangian [M. Carena, A. Megevand, M.Q. and C.E.M. Wagner, NPB716 (2005) 319]

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$$\mathcal{L} = H^\dagger \left(h_2\, \sigma_a \tilde{W}^a + h_2'\, \tilde{B} \right) \tilde{H}_2$$

$$+ H^T \epsilon \left(-h_1\, \sigma_a \tilde{W}^a + h_1'\, \tilde{B} \right) \tilde{H}_1 + \frac{M_2}{2}\, \tilde{W}^a \tilde{W}^a$$

$$+ \frac{M_1}{2}\, \tilde{B}\tilde{B} + \mu\, \tilde{H}_2^T \epsilon \tilde{H}_1 + h.c.$$

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The matching with the MSSM couplings and Higgs fields would be

$$h_2 = g \sin\beta/\sqrt{2}, \quad h_1 = g \cos\beta/\sqrt{2}$$
$$h_2' = g' \sin\beta/\sqrt{2}, \quad h_1' = g' \cos\beta/\sqrt{2}$$
$$H = \sin\beta H_2 - \cos\beta \epsilon H_1^*$$

However we will not match them with the MSSM but instead will consider h_i, h_i' as INDEPENDENT PARAMETERS

The phase transition

- The phase transition is much stronger than in the SM depending on the values of the Yukawa coupling $h_1 \simeq h_2 = h$ and the masses $M_1 = M_2 = M, \mu$

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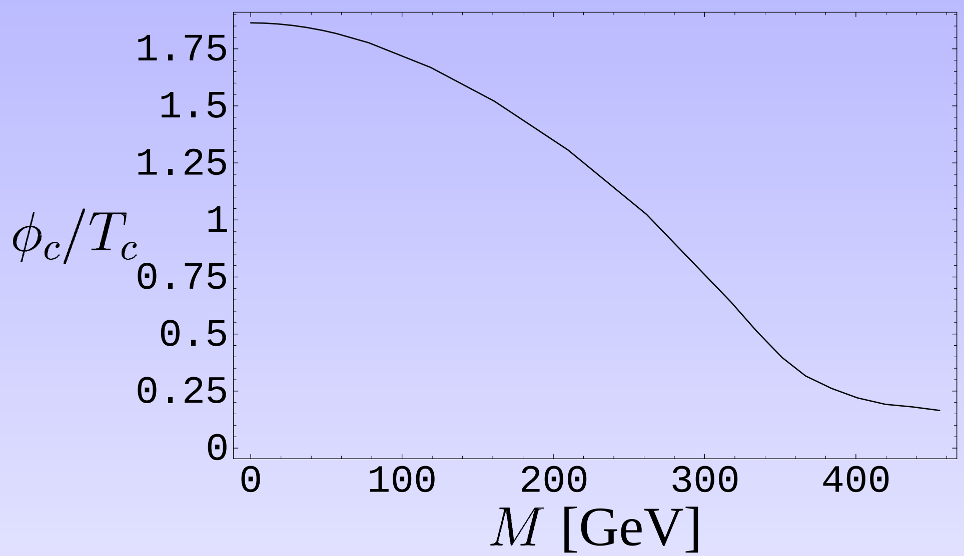

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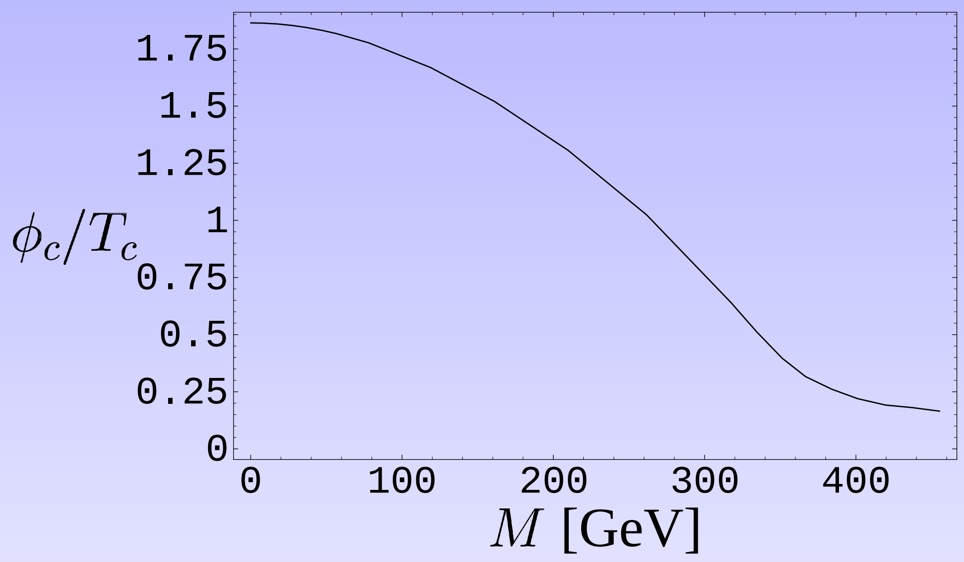

Figure 1: $m_H = 120\ GeV,\ h = 2\ and\ M = -\mu$

- In the $M \to \infty$ limit the phase transition goes to the Standard Model one

The Higgs mass

Up to now we have fixed it to a “minimal” value
$m_H = 120$ GeV

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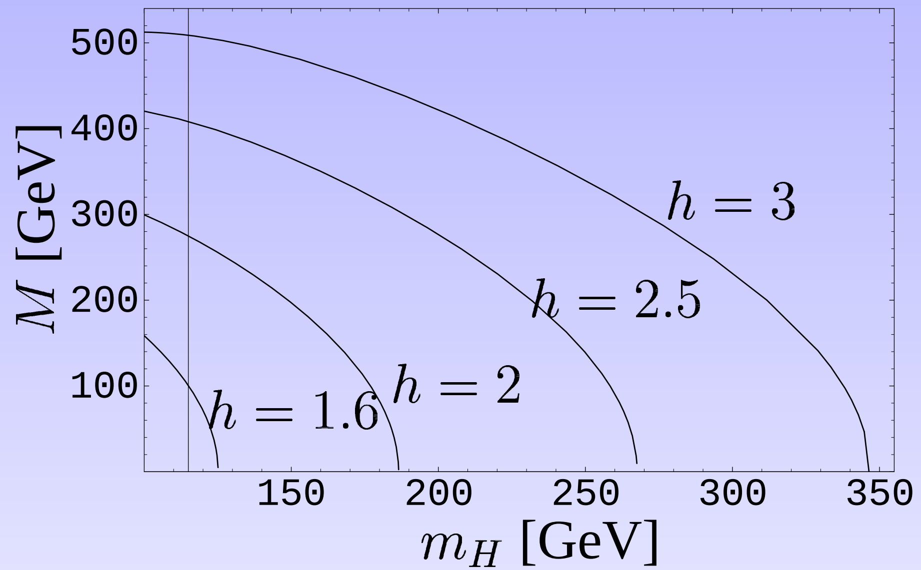
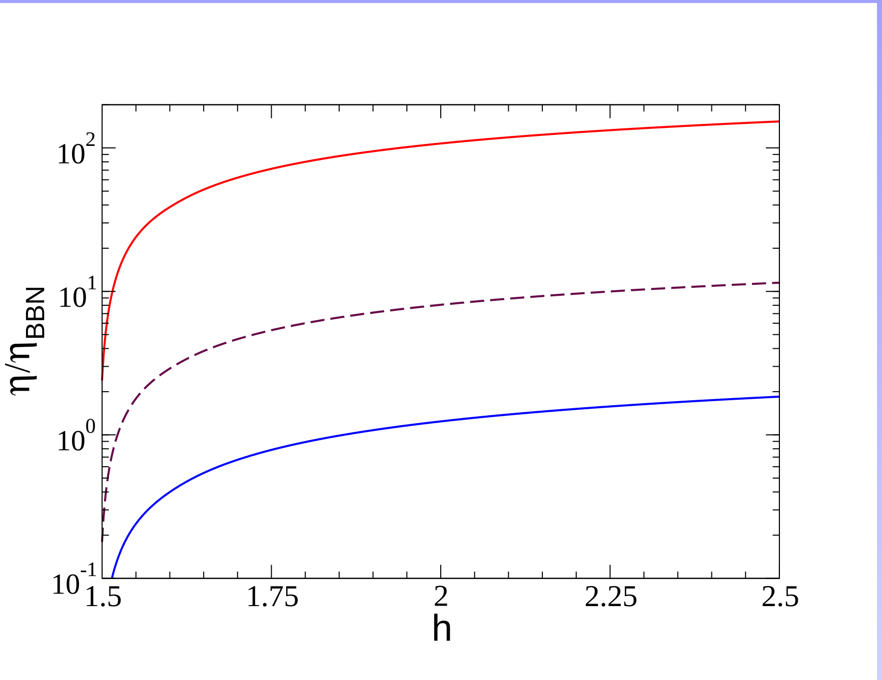


Figure 2: *Contours of* $\phi_c/T_c = 1$ *in the* (M, m_H)*-plane for* $h = 1.6, 2, 2.5, 3$ *and* $M = -\mu$

Baryon asymmetry



$\eta/\eta_{\rm BBN}$ for $\mu = -M_2 \exp(i\varphi)$, $M_2 = 50$ GeV, $\sin\varphi = 1$, and bubble parameters $L_\omega = 10/T_c$, $v_\omega = 0.1$. The lower (upper) solid line corresponds to heavy (light) right-handed stops, $m_T > 1$ TeV ($m_T \simeq 100$ GeV). Dashed line corresponds to right-handed stops with $m_T \simeq 500$ GeV. WMAP $\eta_{\rm BBN} = (8.7 \pm 0.3) \times 10^{-11}$

Dark Matter

The charginos and two of the neutralinos acquire masses of about $h_+ v$. The mass of the lightest neutralino is close to $|\mu|$ and the lightest neutralino (Dark Matter candidate) is therefore an almost pure Higgsino state

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The annihilation cross section is governed by the coupling of the lightest neutralino to the Z-gauge boson

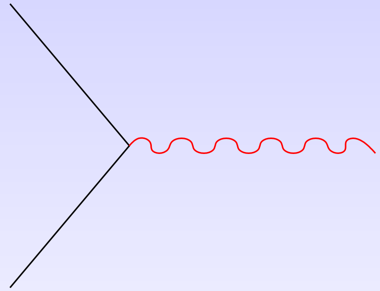

Figure 2: Annihilation $\chi\bar{\chi} \to Z$

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The coupling of a neutralino state to the Z-gauge boson is proportional to the difference of the square of the components $N_{\tilde{\chi}\tilde{H}_i}$ of the neutralino into the two weak Higgsino states $\tilde{H}_i$

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$$\boxed{g_{\tilde{\chi}Z} \propto \frac{h_2^2 - h_1^2}{h_2^2 + h_1^2}}$$

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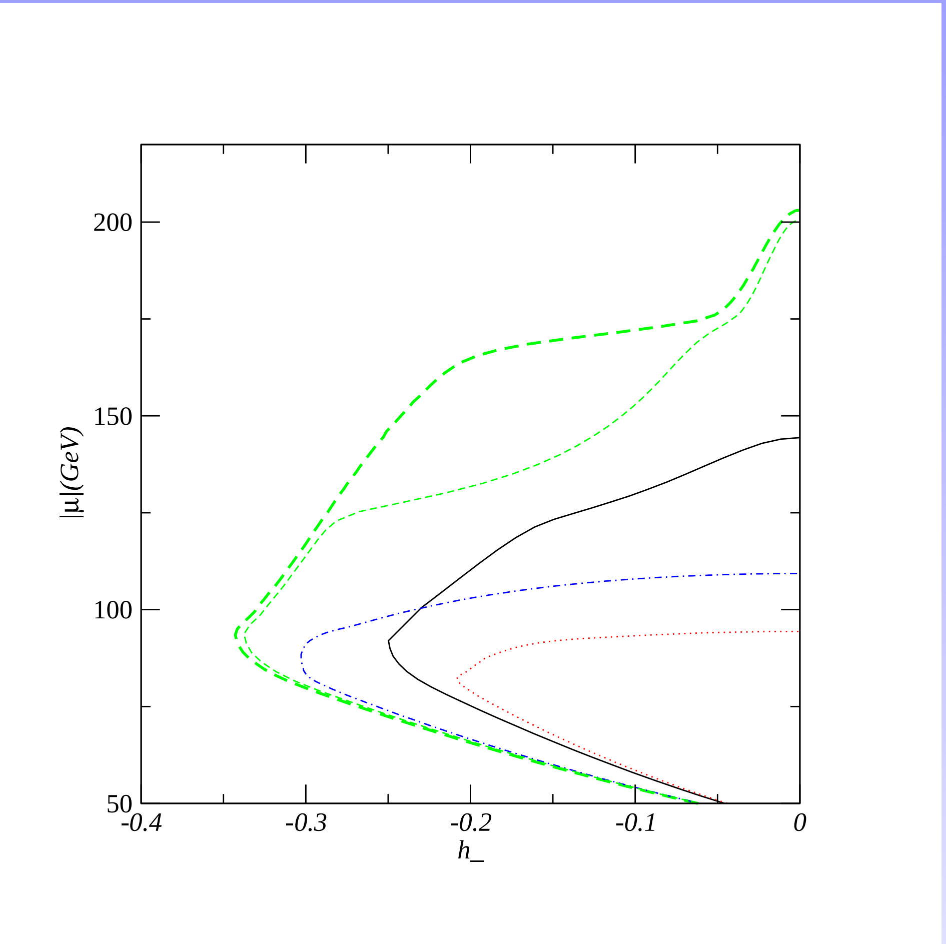

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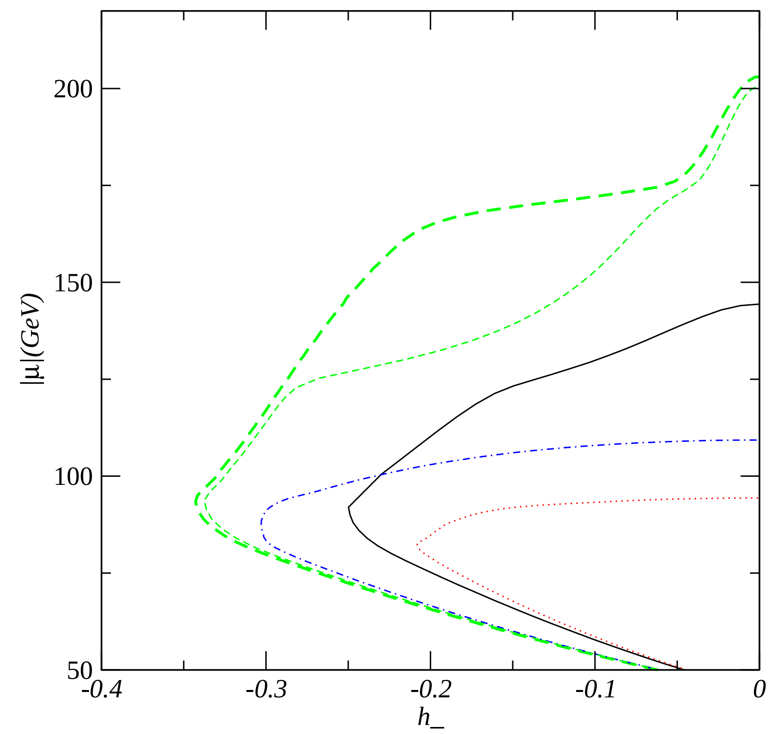
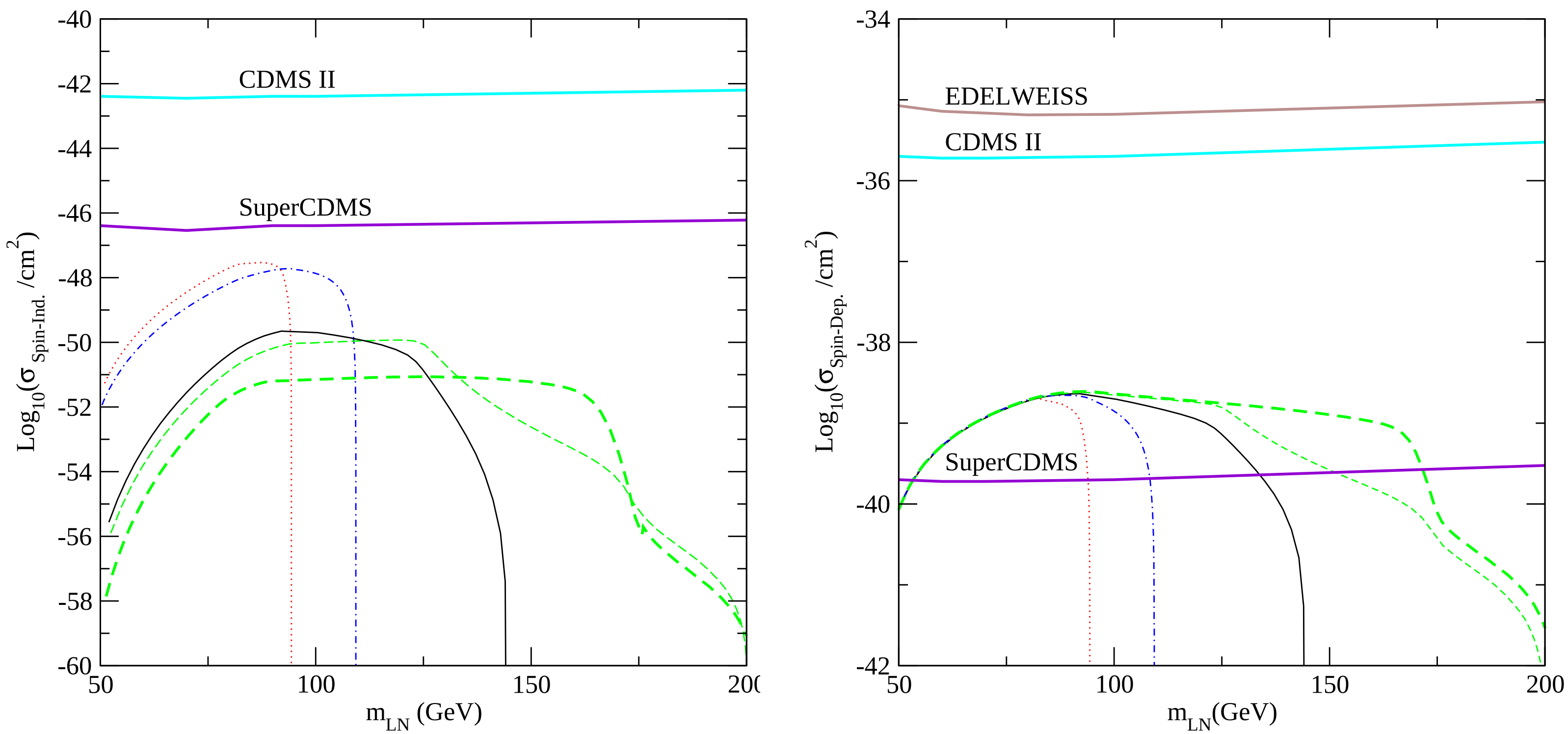


$\Omega_{LN}h^2 = 0.113$ for h, φ and m_H/ GeV = (2,0,300) [green dashed], (2,0,150) [green dotted], (1.5,0,150) [black], (2,$\pi/2$,150) [blue], (1.5,$\pi/2$,150) [red]

Dark Matter detection



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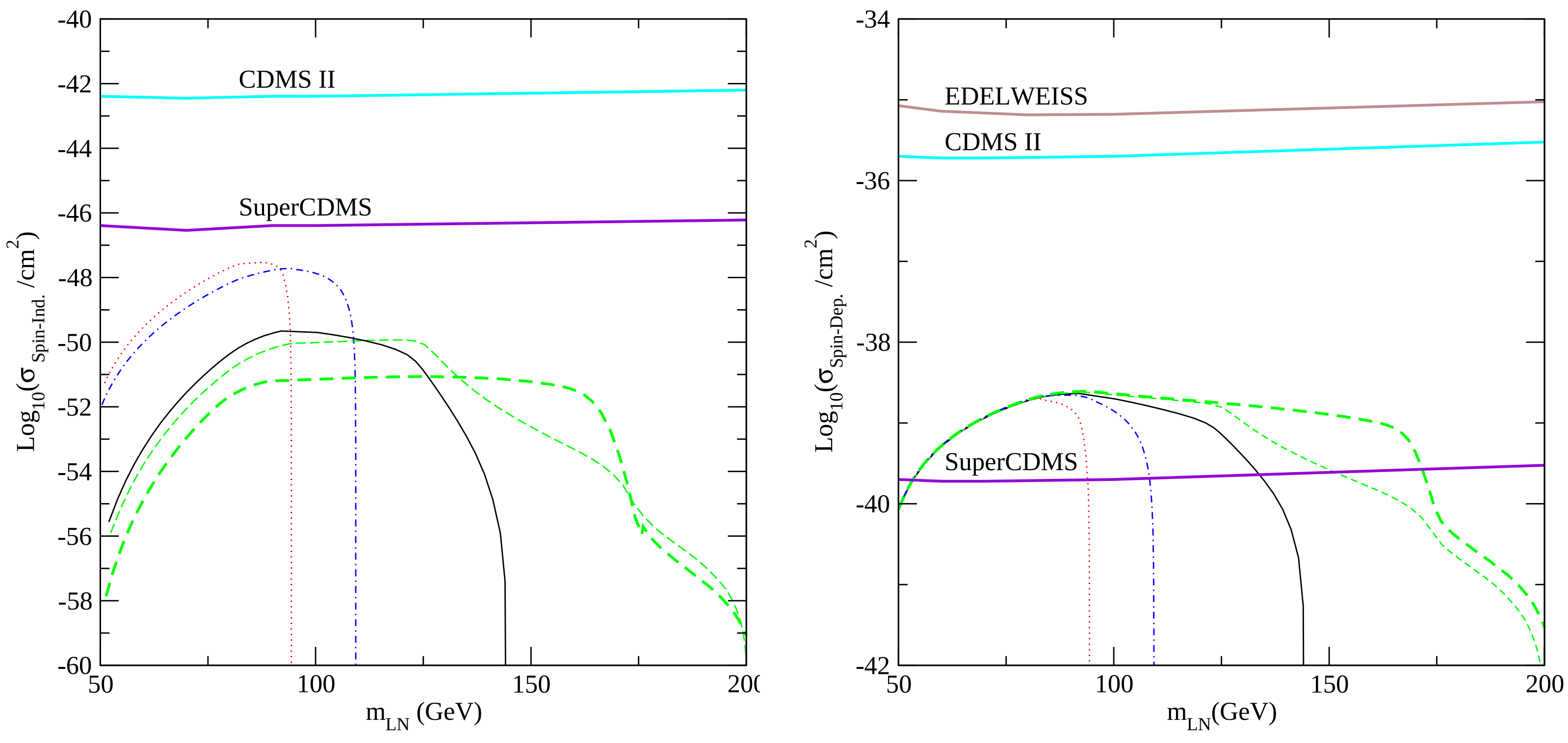
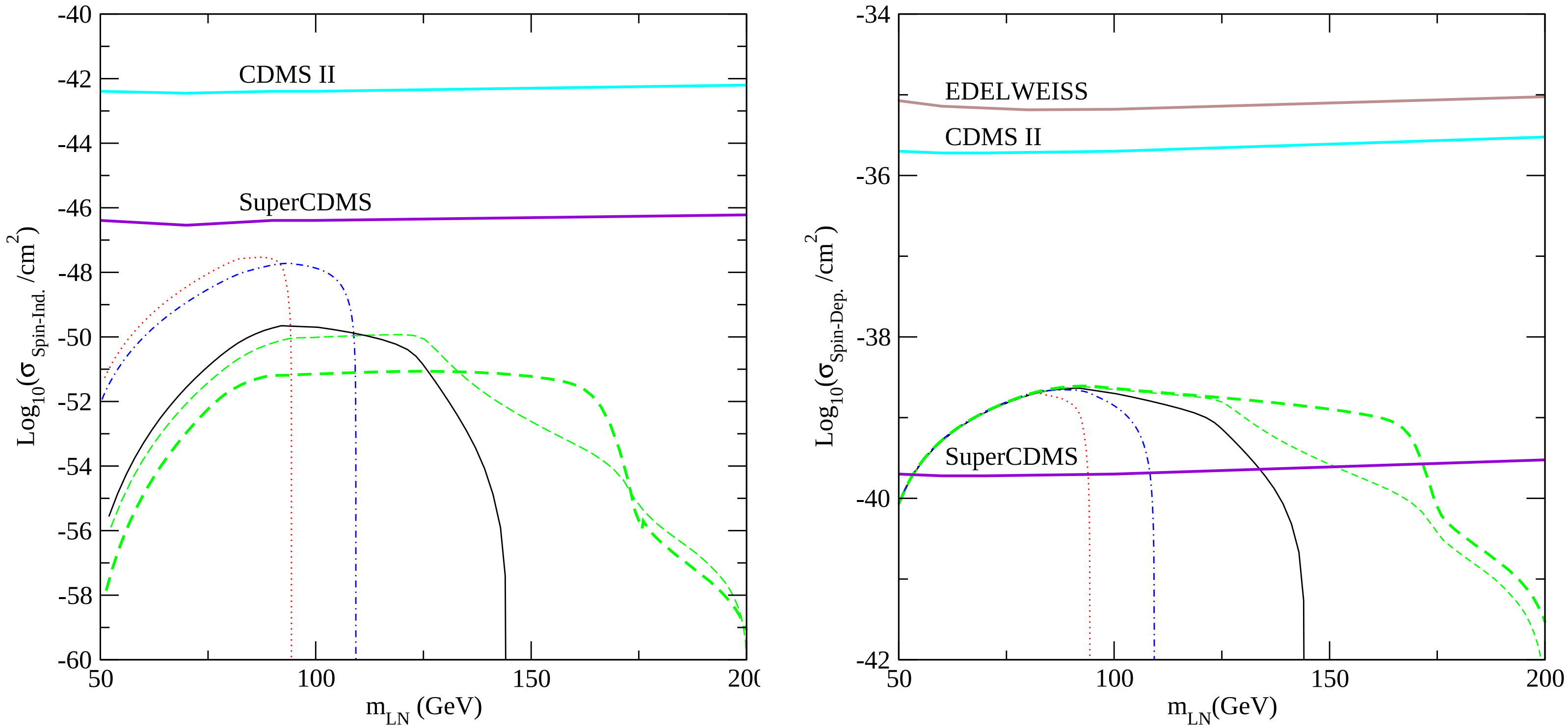


Proton spin-independent (left panel) and neutron spin-dependent (right panel) cross-sections Vs. current (CDMS II) and projected (SuperCDMS) bounds

Dark Matter detection



A. Provenza, P. Ullio, M.Q., arXiv:hep-ph/0507325

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  - ⋆ The right-handed stop
- √ This theory requires two fine tunings (unlike split supersymmetry)

Split supersymmetry

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- ⋆ Be consistent with unification
- ⋆ Have a Dark Matter candidate
- ⋆ Describe EWBG

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Unification is consistent with scale of supersymmetry breaking around $10 - 100$ TeV. [Including two-loop corrections amounts to $\Delta_{2-loop}\alpha_3(M_Z) \sim 0.01$.] The one-loop prediction is

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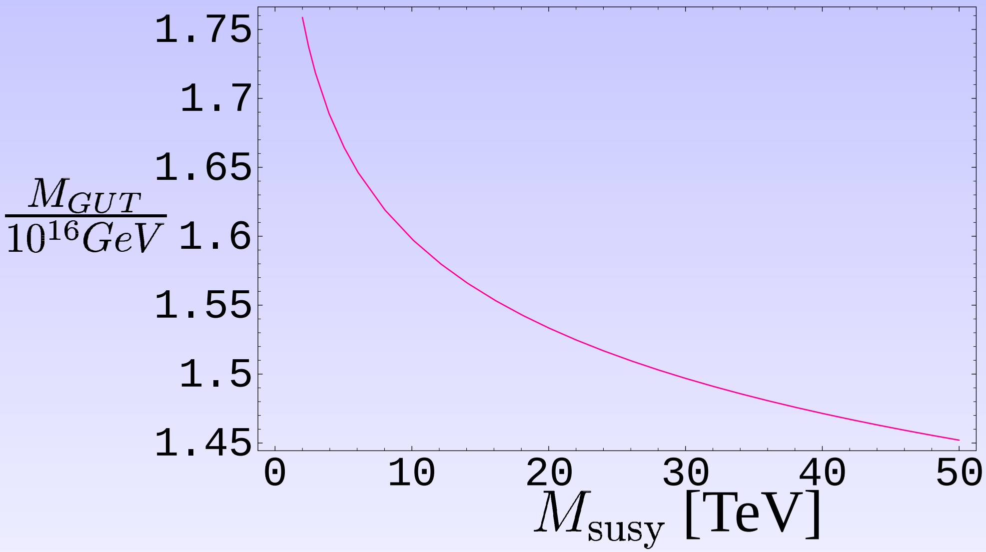

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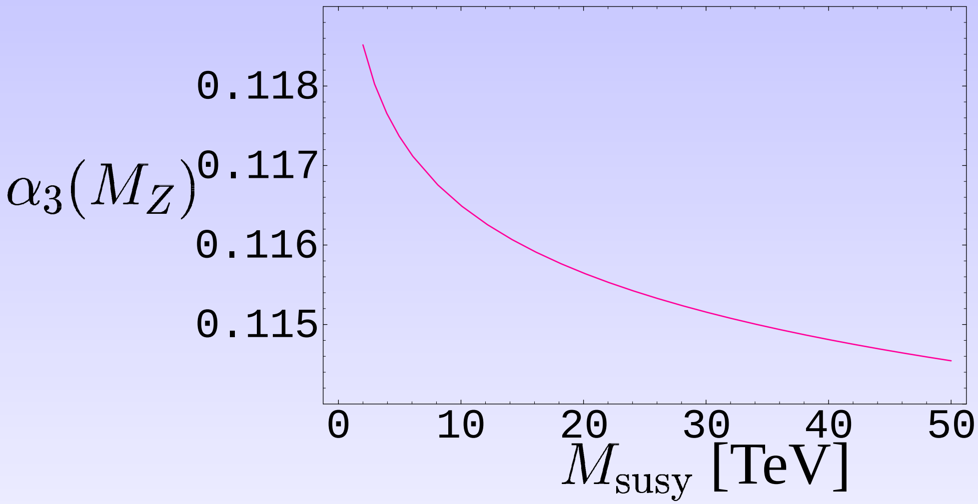
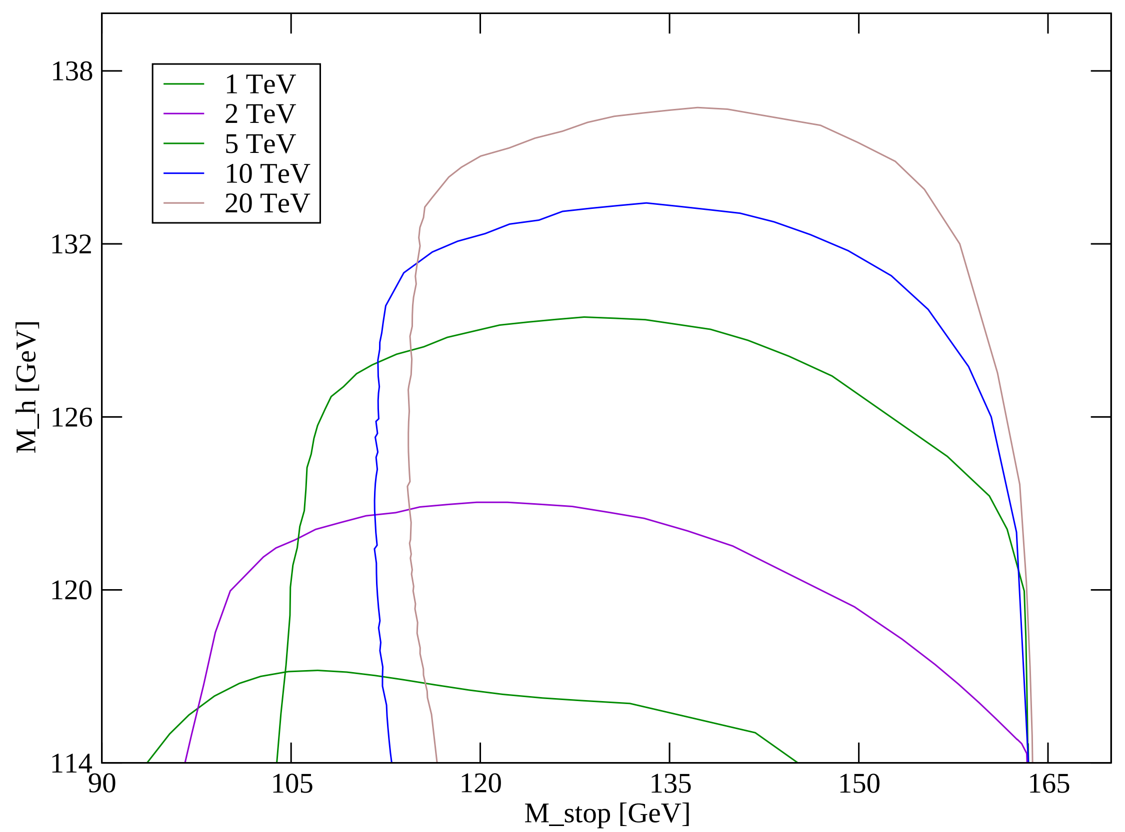


Phase transition



Level contours of $\frac{\phi_c}{T_c} \simeq 1$ for different values of M_{susy}

CONCLUSION

EWBG can be tested at present and future accelerators that are useful to probe models

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- √ If the Higgs mass turns out to be below ~ 200 GeV then probably some sort of split supersymmetry can do the job
- √ If the Higgs mass is much heavier ($\gg 300$ GeV) then we should (most probably) abandon the idea of SUPERSYMMETRY