Electroweak symmetry breaking induced by dark matter

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In collaboration with Michel Tytgat: arXiv:0707.0633 (hep-ph)

Motivation

What kind of new physics can we expect at 100 GeV - 1 TeV ?

- Origin of electroweak symmetry breaking,

  unitarity bound, triviality bound, electroweak precision constraints,...

- the Dark Matter particle

  from galaxy rotation curves, missing mass in clusters, lensing, CMB and LSS, bullet clusters... $\Longrightarrow$ $\Omega_{DM} \simeq 0.23$

  If $\sigma_{annihil.} \sim g^4/m_{DM}^2$, $\Omega_{DM} \sim 0.23$ requires $m_{DM} \sim 100\,\mathrm{GeV}$ (WIMP mechanism)

- Hierarchy problem(s): suggest new low scale physics, SUSY,...

$\Longrightarrow$ Could these issues be related???

Relation between EWSB and DM?

This talk: these 2 issues could be deeply related

A model where EWSB is due to the existence of DM, a la Coleman-Weinberg

The model

very minimal assumptions:

- 2 Higgs doublets: $H_1,\ H_2$
- a Z_2 symmetry: all particles even, except H_2 which is odd

$\Longrightarrow$ the lightest H_2 component is stable, i.e. a DM candidate

"Inert Higgs doublet model": H_2 has no vev, no mixing with H_1 and no couplings to SM fermions

Deshpande, Ma 78'; Ma 06'; Barbieri, Hall, Rychkov 06',...

Dark Matter

- $H_2 = \begin{pmatrix} H^+ \\ \frac{H_0 + i A_0}{\sqrt{2}} \end{pmatrix}$ → 4 components: $H^\pm, H_0, A_0$

  → if H_0 or A_0 is the lightest state: good DM candidate

- Most general scalar potential:

$$
\begin{aligned}
V &= \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 \\
&\quad + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2} \left[(H_1^\dagger H_2)^2 + h.c. \right]
\end{aligned}
$$

Dark Matter: tree level mass spectrum

$$m^2_{H^+} = \mu_2^2 + \lambda_3 \frac{v^2}{2}$$

$$m^2_{H_0} = \mu_2^2 + \lambda_L \frac{v^2}{2} \qquad (\lambda_L = \lambda_3 + \lambda_4 + \lambda_5)$$

$$m^2_{A_0} = \mu_2^2 + \lambda_S \frac{v^2}{2} \qquad (\lambda_S = \lambda_3 + \lambda_4 - \lambda_5)$$

→ To have H_0 or A_0 the lightest: $\lambda_L < \lambda_3$ or $\lambda_S < \lambda_3$

Relic DM density: annihilation freeze out mechanism

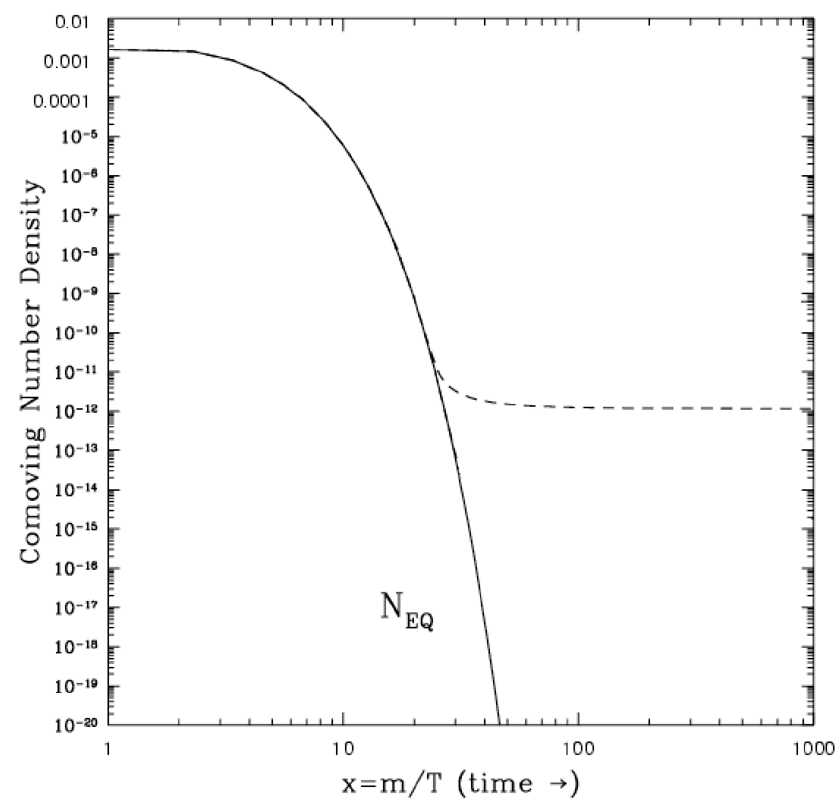
- Down to $T \sim m_{DM}$, DM is in thermal equilibrium: $n_{DM} \simeq n_{DM}^{Eq}$

- For $T < m_{DM}$: $n_{DM} \propto e^{-m_{DM}/T}$ ← Boltzmann suppression

→ freeze out of the annihilation at $T = T_f$

↓

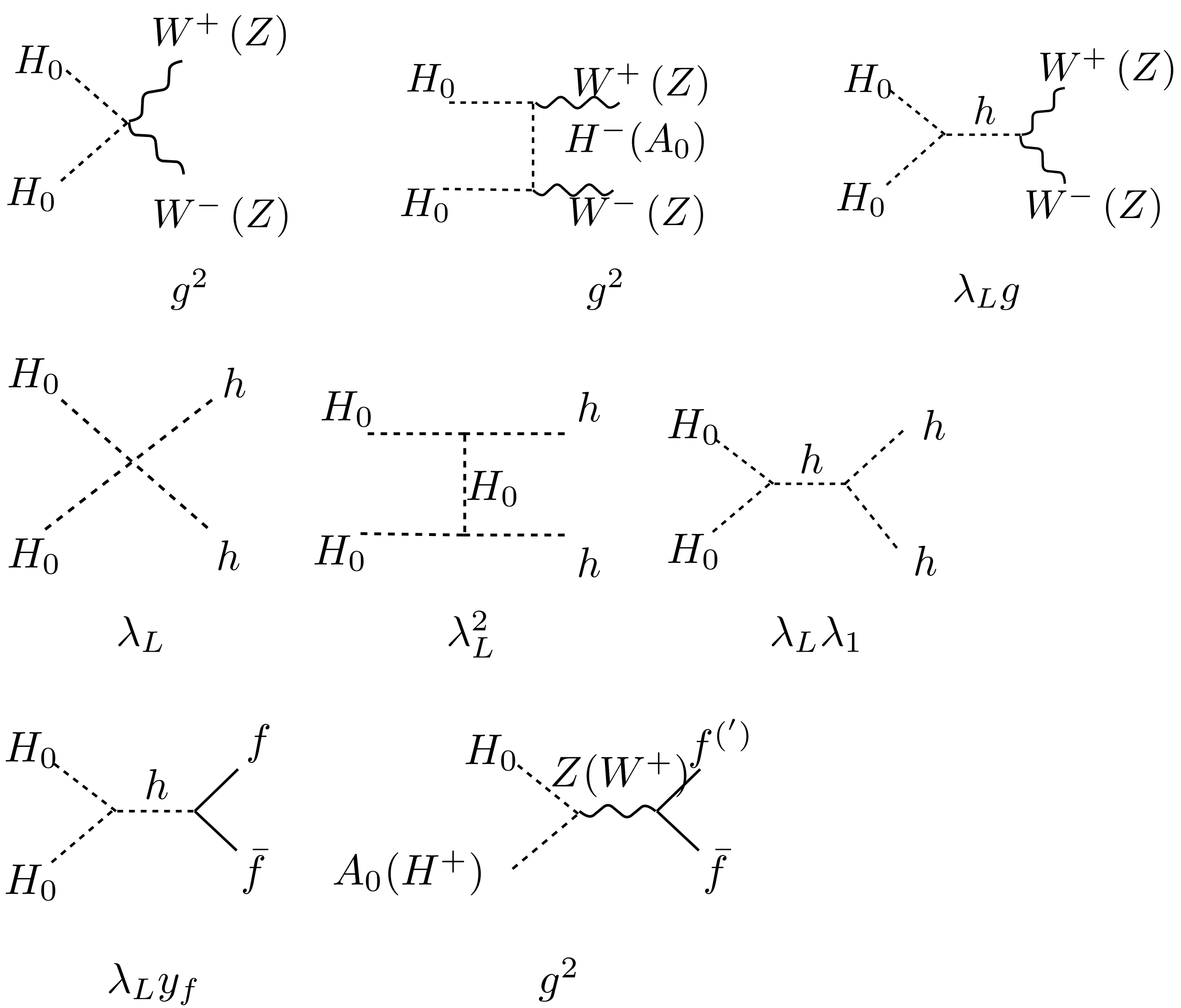
$$n_{DM}(T < T_f) = n_{DM}^{Eq}(T = T_f)$$



⟹ If $\sigma_{annihil.} \sim g^4/m_{DM}^2$, $\Omega_{DM} \sim 0.23$ requires $m_{DM} \sim 100\,\mathrm{GeV}$ (WIMP mechanism)

Relic DM density: annihilation processes

If H_0 is the DM:



Two possible DM mass regimes

- Low DM mass regime: $m_{DM} < m_W$ $\qquad (DM = H_0 \text{ or } A_0)$

To avoid too fast $DM\,DM \to W\,W, Z\,Z$ annihilation

$$40\,\text{GeV} < m_{DM} < 75\,\text{GeV}$$

Detailed analysis: Lopez-Honorez, Nezri, Oliver, Tytgat '06;
see also Barbieri, Hall, Rychkov '06;
Bergstrom et al '07

In agreement with direct and indirect
gamma detection constraints

Two possible DM mass regimes

- High DM mass regime: $m_{DM} > 400\,\mathrm{GeV}$

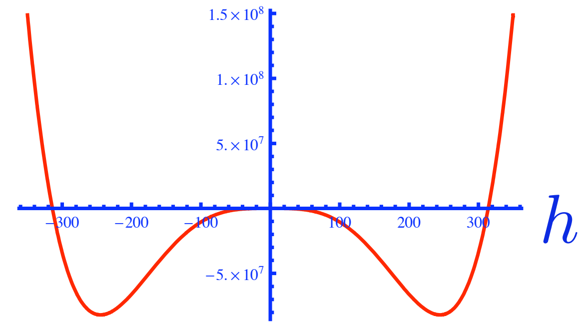
→ Not relevant for EWSB a la Coleman-Weinberg

↑

DM couplings too large

EWSB: Coleman-Weinberg mechanism in the SM

- Standard Model: $V = \mu^2 H^2 + \lambda H^4$



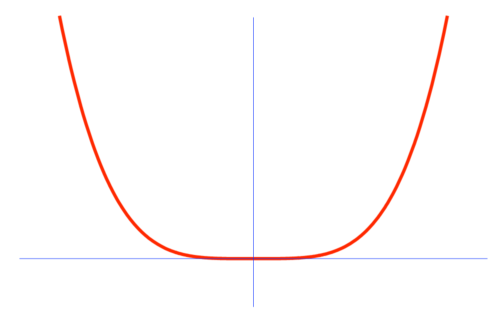
$\Longrightarrow$ only one scale: μ^2

$\langle h \rangle = v = 246\,\mathrm{GeV}$

- Coleman-Weinberg: could we start with no scale at all or at least no large scale at all? $\leftarrow$ $\mu^2 \simeq 0$

$\downarrow$

$V \simeq \lambda H^4$



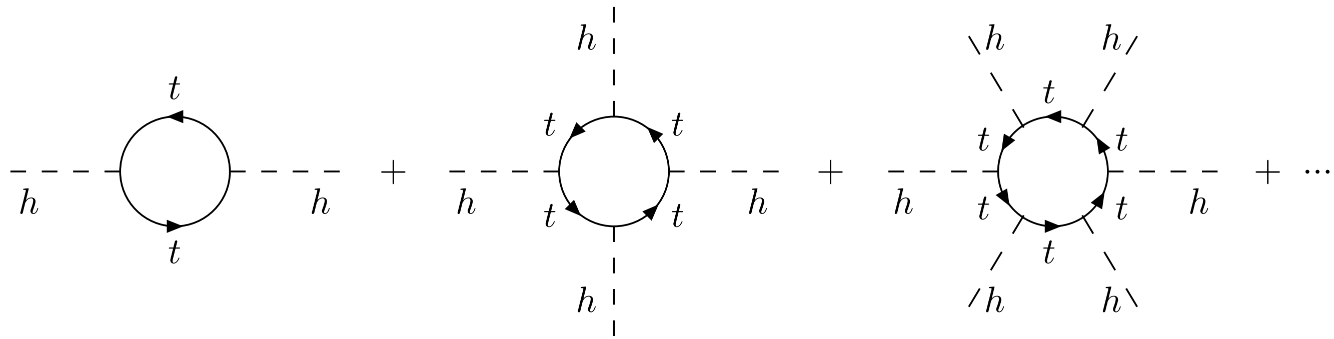
$\downarrow$

no EWSB at tree level

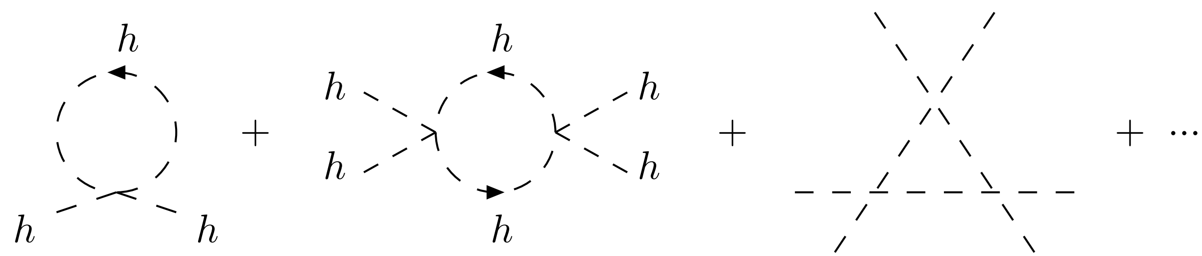
Coleman-Weinberg in the SM: one loop diagrams

S. Coleman, E. Weinberg '73

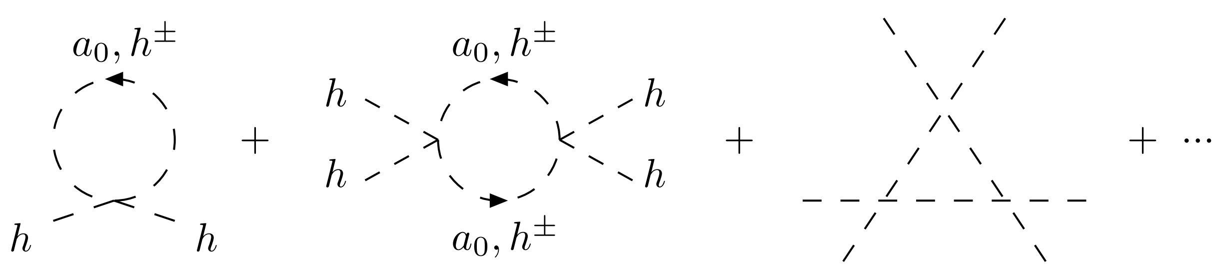
Top loops:



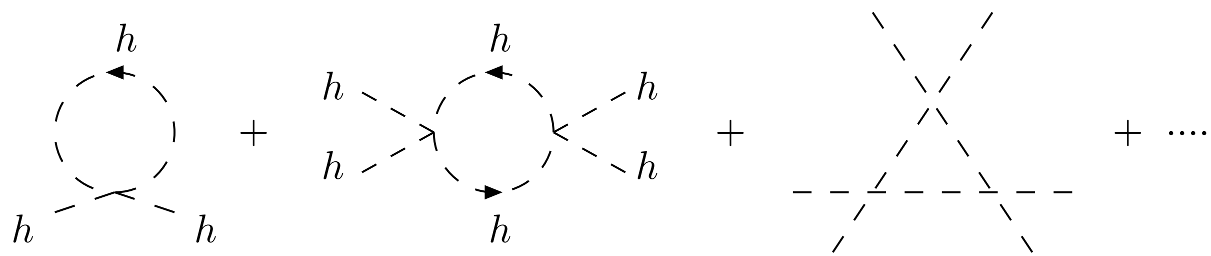
Higgs loops:



Goldstone loops:



Coleman-Weinberg in the SM: summation of diagrams



$$V_{eff}(h) \ni i \int \frac{d^4k}{(2\pi)^4} \frac{1}{2} \left(3 \frac{\lambda h^2}{k^2 + i\varepsilon} + \frac{3^2}{2} \frac{\lambda^2 h^4}{(k^2 + i\varepsilon)^2} + \frac{3^3}{3} \frac{\lambda^3 h^6}{(k^2 + i\varepsilon)^3} + \ldots \right)$$

$$= \frac{1}{2} \int \frac{d^4k}{(2\pi)^4} \log \left(1 + \frac{\lambda h^2}{2k^2} \right)$$

$$= \frac{9}{64\pi^2} \lambda^2 h^4 \left(\log \frac{3\lambda h^2}{\mu^2} - \frac{3}{2} \right)$$

← $\overline{MS}$ scheme

↑ renormalization scale

Full effective potential in the SM

$$V_{\rm eff}(h) = \lambda_1 \frac{h^4}{4}$$ ← Tree level

$$+ \frac{1}{64\pi^2} 9\lambda_1^2 h^4 (ln \frac{3\lambda_1 h^2}{\mu^2} - \frac{3}{2})$$ ← Higgs loops

$$+ \frac{3}{64\pi^2} \lambda_1^2 h^4 (ln \frac{\lambda_1 h^2}{\mu^2} - \frac{3}{2})$$ ← Goldstone loops

$$- \frac{12}{64\pi^2} \frac{g_t^4}{4} h^4 (ln \frac{g_t^2 h^2}{2\mu^2} - \frac{3}{2})$$ ← top loops

⇒ Imposing $\left.\frac{dV_{eff}}{dh}\right|_{h=246\,GeV} = 0$ determines $\lambda = \mathrm{fct}(g_t)$

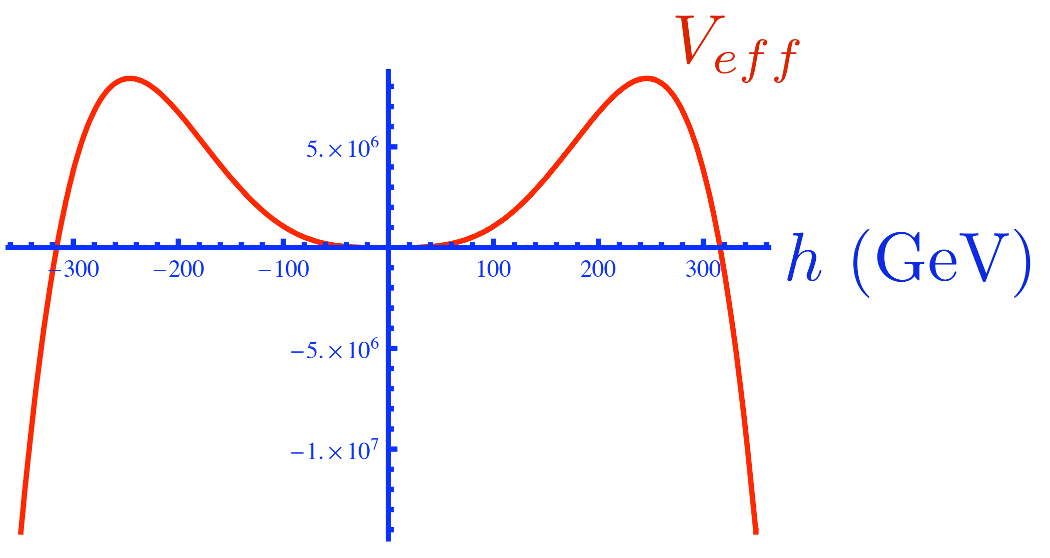
⇒ No free parameter: potential known

Coleman-Weinberg in the SM: final result

dominated by the top loop contribution

⇓

has the wrong sign

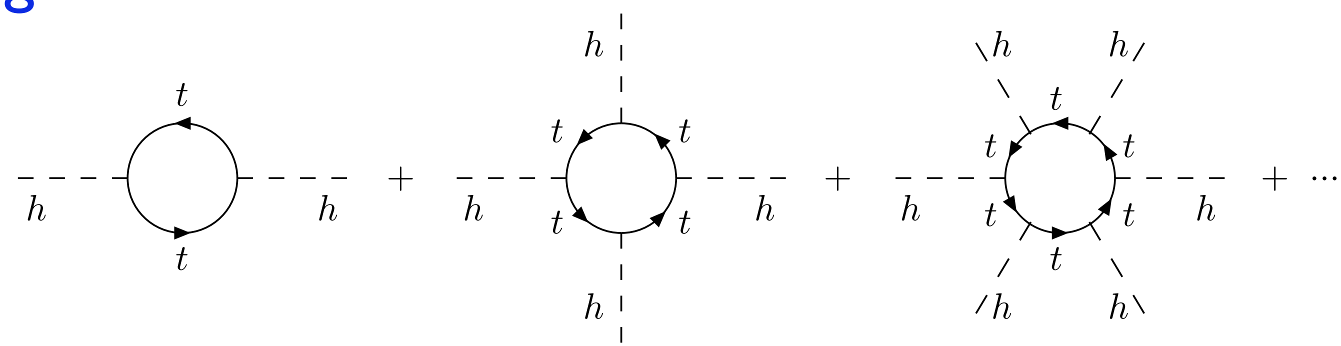


⟹ Coleman-Weinberg doesn't work in the Standard Model

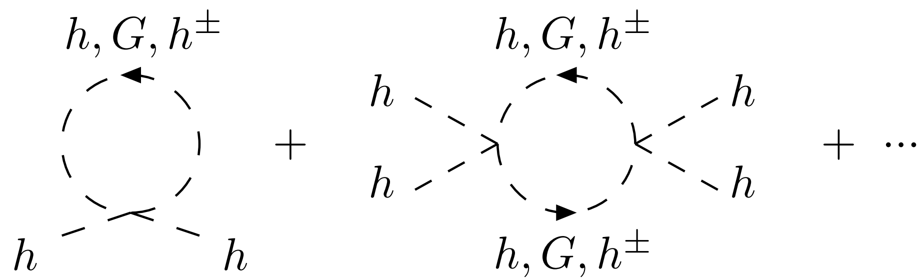
Coleman-Weinberg with an additional inert Higgs doublet: one loop diagrams

- Tree level: no scale: $\mu_1 \simeq \mu_2 \simeq 0$ (no EWSB)
- One loop diagrams:

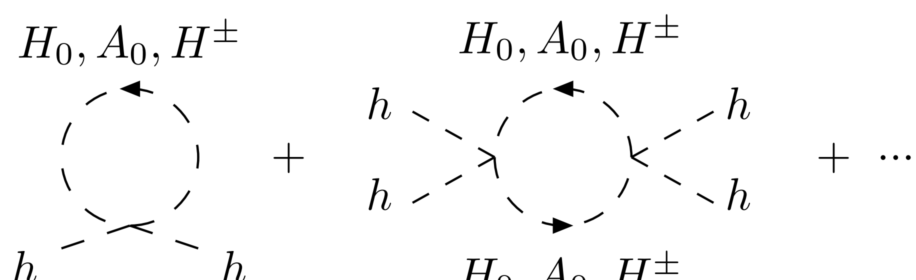
Top loops:



Higgs loops:



Inert Higgs loops:



Effective potential with a inert Higgs

- Total one loop effective potential:

$$
\begin{aligned}
V_{\text{eff}}(h) &= \lambda_1 \frac{h^4}{4} && \leftarrow \text{Tree level} \\
&+ \frac{1}{64\pi^2} 9\lambda_1^2 h^4 (ln \frac{3\lambda_1 h^2}{\mu^2} - \frac{3}{2}) && \leftarrow \text{Higgs loops} \\
&+ \frac{3}{64\pi^2} \lambda_1^2 h^4 (ln \frac{\lambda_1 h^2}{\mu^2} - \frac{3}{2}) && \leftarrow \text{Goldstone loops} \\
&- \frac{12}{64\pi^2} \frac{g_t^4}{4} h^4 (ln \frac{g_t^2 h^2}{2\mu^2} - \frac{3}{2}) && \leftarrow \text{top loops} \\
&+ \frac{2}{64\pi^2} \frac{\lambda_3^2}{4} h^4 (ln \frac{\lambda_3 h^2}{2\mu^2} - \frac{3}{2}) && \leftarrow H^{\pm} \text{ loops} \\
&+ \frac{1}{64\pi^2} \frac{\lambda_L^2}{4} h^4 (ln \frac{\lambda_L h^2}{2\mu^2} - \frac{3}{2}) && \leftarrow H_0 \text{ loops} \\
&+ \frac{1}{64\pi^2} \frac{\lambda_S^2}{4} h^4 (ln \frac{\lambda_S h^2}{2\mu^2} - \frac{3}{2}) && \leftarrow A_0 \text{ loops}
\end{aligned}
$$

SM contri-bution (Tree level, Higgs loops, Goldstone loops, top loops)

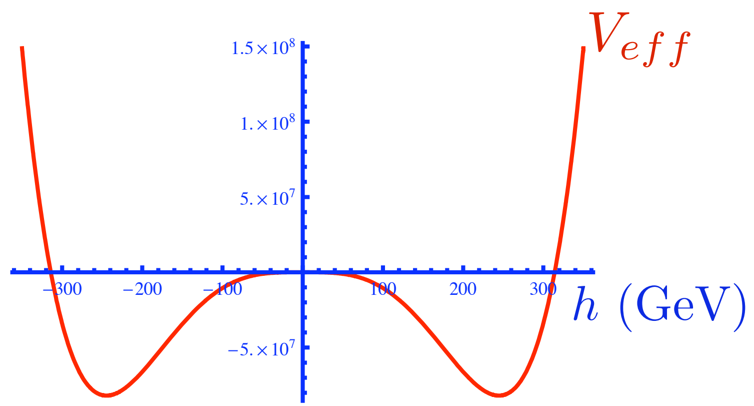
new inert Higgs contribut. ($H^{\pm}$ loops, H_0 loops, A_0 loops)

EWSB: Inert Higgs contribution

Coleman, Weinberg '73; Gildener, Weinberg '76; Meissner, Nicolai '07; Espinosa, Quiros '07; Foot at al. '07

→ a scalar contribution: has the right sign

⇒ all we need is the inert Higgs contribution larger than the top one (λ_3 and/or λ_L and/or λ_S large)



- to have a maximum we need one quartic coupling to be larger than $\sim 3g_t^2$
- to have $m_H > 114.4\ \mathrm{GeV}$ we need one quartic coupling to be larger than $\sim 6g_t^2$

⇒ requires fairly large quartic coupling(s) (still perturbative)

EWSB vs DM constraints

- EWSB: at least one among $\lambda_{3,L,S}$ must be large (i.e. at least one H^+, H_0, A_0 must be heavy, above $\sim 350\,\mathrm{GeV}$)

- DM: H_0 or A_0 must be below the W (i.e. λ_L or λ_S smaller)

$\Rightarrow$ Large mass splittings are required inside the inert Higgs

↪ Electroweak precision measurement??

$\Downarrow$

T parameter constraint

T parameter constraint

$$T = \frac{\Pi_{WW}(0)}{M_W^2 \alpha} - \frac{\Pi_{ZZ}(0)}{M_Z^2 \alpha}$$

Sensitive to mass splittings between members of a SU(2) multiplet

However: vanishes if $m_{H^+} - m_{A_0}$ or $m_{H^+} - m_{H_0}$ vanishes

custodial symmetry — twisted custodial symmetry

$\Longrightarrow$ to get $|\Delta T| < 0.2$ we need: $|m_{H^+} - m_{A_0}| <\sim 40\text{GeV}$

or $|m_{H^+} - m_{H_0}| <\sim 40\text{GeV}$

for example: $m_{H_0} = 70\,\text{GeV},\ m_{H^+} = 110\,\text{GeV},\ m_{A_0} = 350\,\text{GeV}$

Custodial symmetry

SO(3) symmetry: nice way to justify:

- necessary mass spectrum
- T parameter constraint
- no CP violation (i.e. no phase in λ_5, otherwise bad for DM)

Either with normal custodial symmetry $(m_{A_0} \sim m_{H^+})$ or with twisted custodial symmetry $(m_{H_0} \sim m_{H^+})$

Gerard, Herquet '07

Examples of sets of parameters

$\Omega_{DM} h^2 = 0.11$

λ_1	λ_2	λ_3	λ_4	λ_5	M_h	M_{H_0}	M_{A_0}	$M_{H^\pm}$	h_{BR}	W_{BR}
-0.11	0	5.4	-2.8	-2.8	120	12	405	405	100%	0%
-0.11	-2	5.4	-2.7	-2.7	120	43	395	395	100%	0%
-0.11	-3	5.4	-2.6	-2.6	120	72	390	390	94%	6 %
-0.30	0	7.6	-4.1	-4.1	180	12	495	495	100%	0 %
-0.30	-2.5	7.6	-3.8	-3.8	180	64	470	470	100%	0 %
-0.18	-3	-0.003	4.6	-4.7	120	39	500	55	100%	0 %
-0.29	-5	-0.07	5.5	-5.53	150	54	535	63	0%	100 %

$\Longrightarrow$ possible range of m_{DM} extended: $10\,\mathrm{GeV} < m_{DM} < 75\,\mathrm{GeV}$

More general situation: large μ^2

- In this model the DM Higgs doublet can have dramatic effect on EWSB parameters even for large μ^2 as soon as some of the quartic couplings are sizeable

- Might be generic for other models

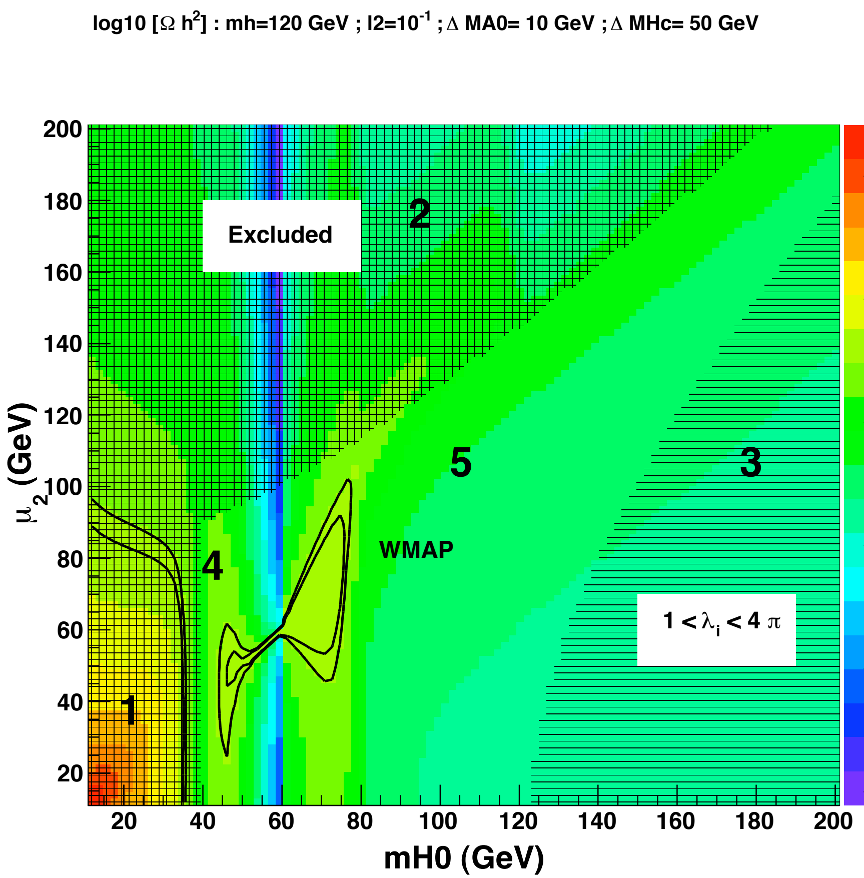
Summary

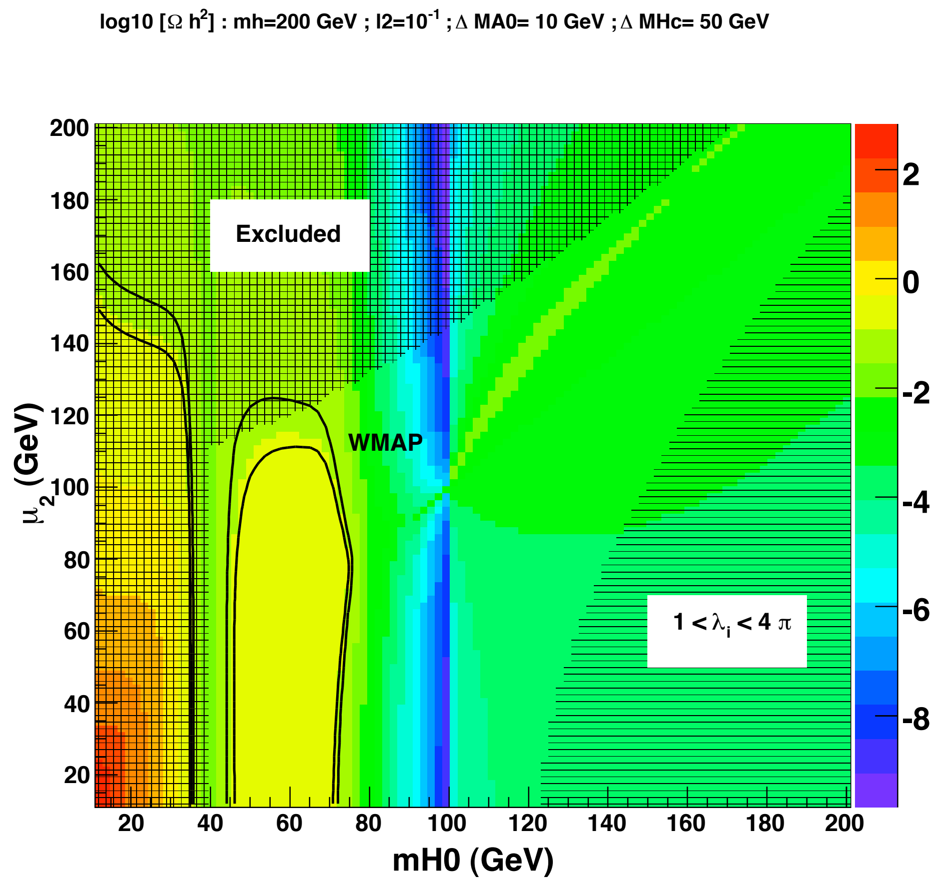
- EWSB and WIMP DM: similar scales $\Longrightarrow$ possible link???

- DM could be crucial for EWSB: explicit minimal example where a single additional Higgs doublet with Z_2 parity provides a good DM candidate and allows EWSB a la Coleman-Weinberg

- In this framework the DM mass is proportional to the EW scale $\Longrightarrow$ provides a possible hint for why DM would be at the EW scale as required by the WIMP mechanism

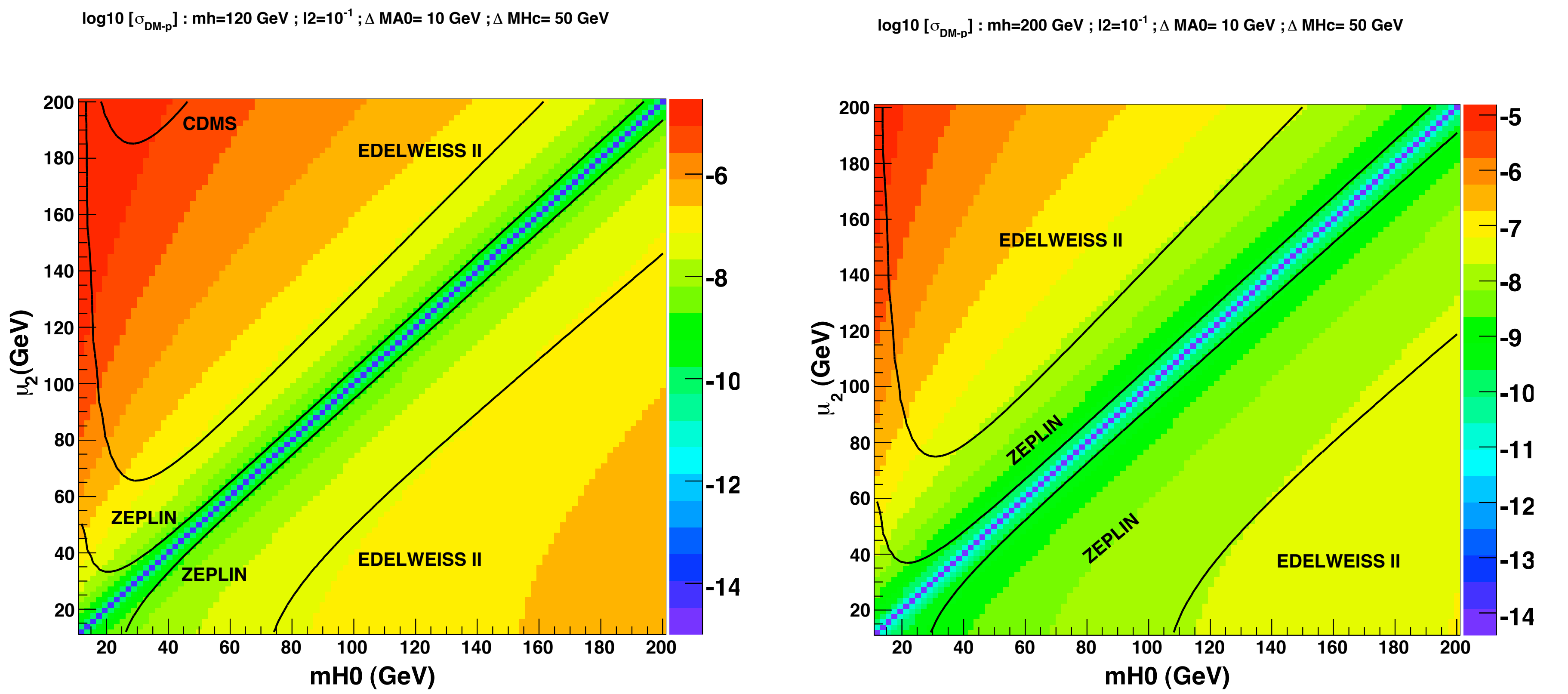
Relic density





Lopez-Honorez, Nezri, Oliver, Tytgat '06

Direct detection



Indirect detection