NLO CORRECTIONS TO THE RELIC DENSITY OF DARK MATTER IN THE INERT HIGGS DOUBLET MODEL

Guillaume CHALONS
In collaboration with S. Banerjee, F. Boudjema, N. Chakrabarty

LPSC Grenoble

Dark Side of the Universe 2018, Annecy

MOTIVATIONS

- The Relic Density of DM (assuming ΛCDM) is measured with an impressive accuracy ($\simeq 2\%$ precision)

$$\boxed{\Omega_\chi h^2 = 0.1199 \pm 0.0027}$$

☞ Need for precise predictions from theory to compare with exp

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- If thermally produced (abundance obtained through solving the Boltzmann equation) a precise computation of DM annihilation channels should assess
  - ☞ higher order corrections
  - ☞ theoretical uncertainty
  - ☞ Sommerfeld enhancement
  - ☞ bound state formation

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- Assuming the WIMP paradigm, models with extended Higgs sector plus some ad hoc discrete symmetry can provide a good DM candidate
- Such models are interesting because they can be tested at the LHC

astrophysics/cosmology $\Longleftrightarrow$ colliders

☞ In the IDM, the SM is extended by the addition of a second scalar, Φ_2, transforming as a doublet under $SU(2)_L$. It is odd under a new discrete $\mathbb{Z}_2$ symmetry $\rightarrow$ does not get a vev

$$\mathcal{L}_{IDM} = \mathcal{L}_{SM} + \sum_{i=1}^{2} (D^\mu \Phi_i)^\dagger D_\mu \Phi_i + \mathcal{V}_{IDM}(\Phi_1, \Phi_2)$$

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$$\begin{aligned} \mathcal{V}_{IDM}(\Phi_1, \Phi_2) \quad = \quad & \mu_1^2 |\Phi_1|^2 + \mu_2^2 |\Phi_2|^2 + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 \\ & + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 (\Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \left[\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2) + \text{h.c} \right] \end{aligned}$$

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$$\Phi_1=\begin{pmatrix}G^+\\ \frac{1}{\sqrt{2}}(v+h+G)\end{pmatrix}\text{ and }\Phi_2=\begin{pmatrix}H^+\\ \frac{1}{\sqrt{2}}(H+iA)\end{pmatrix}$$

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- No mixing between Φ_1 and Φ_2
- lightest $\mathbb{Z}_2$-odd particle stable → H/A DM candidate
- All couplings of Φ_1 to fermions and gauge bosons are SM-like (Type-I 2HDM)
- Higgs automatically aligned
- $\lambda_{S/A} = (\lambda_3 + \lambda_4 + \lambda_5)/2$
- Only quartic couplings of inert scalars to gauge bosons.

☞ To compute observables at radiative corrections in the IDM, we have to *renormalise* the model

$$M_h^2 = \frac{T}{v} + v^2\lambda_1$$

$$M_{H^\pm}^2 = \mu_2^2 + \frac{v^2}{2}\lambda_3$$

$$M_H^2 = \mu_2^2 + \frac{v^2}{2}\lambda_S$$

$$M_A^2 = \mu_2^2 + \frac{v^2}{2}\lambda_A$$

COUNTING PARAMETERS

$$\mathcal{V}_{IDM}(\Phi_1,\Phi_2) = \underbrace{\mu_1^2|\Phi_1|^2+\mu_2^2|\Phi_2|^2+\frac{\lambda_1}{2}|\Phi_1|^4+\frac{\lambda_2}{2}|\Phi_2|^4 +\lambda_3|\Phi_1|^2|\Phi_2|^2+\lambda_4(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)+\left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)+\text{h.c}\right]}_{(\mu_1,\mu_2,\lambda_1,\lambda_2,\lambda_3,\lambda_4,\lambda_5)}$$

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- Minimisation conditions: $(\mu_1,\lambda_1) \rightarrow (T, M_h)$
- Spectrum:

$$\left.\begin{aligned} M_{H^\pm}^2 &= \mu_2^2 + \frac{v^2}{2}\lambda_3 \\ M_H^2 &= \mu_2^2 + \frac{v^2}{2}(\lambda_3+\lambda_4+\lambda_5) \\ M_A^2 &= \mu_2^2 + \frac{v^2}{2}(\lambda_3+\lambda_4-\lambda_5) \end{aligned}\right\} (\lambda_3,\lambda_4,\lambda_5) \rightarrow (M_H^\pm, M_H, M_A)$$

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- Finally

$$(\mu_1,\mu_2,\lambda_1,\lambda_2,\lambda_3,\lambda_4,\lambda_5) \to (T, M_h, M_H^\pm, M_H, M_A, \mu_2(\text{or } \lambda_{S/A}), \lambda_2)$$

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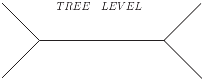
DIVERGENCES

- Due to perturbative development in the coupling constant.



RADIATIVE CORRECTIONS-RENORMALISATION

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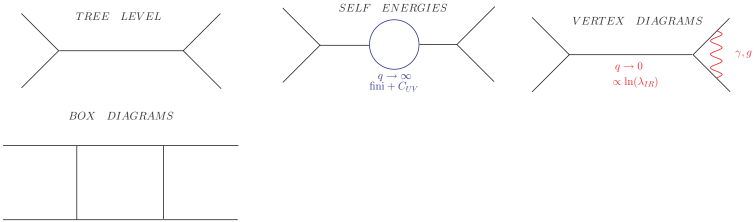

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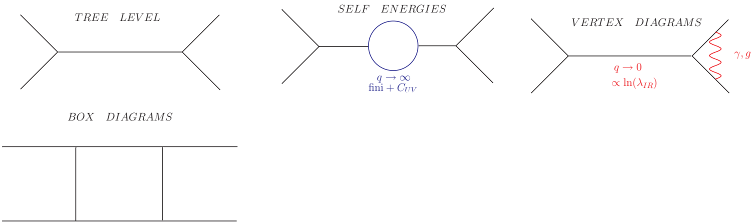

REGULARISATION

Isolate infinite parts in loops

- UV: $\ln \Lambda_{UV}$ with cut-off, $1/\epsilon_{UV}$ poles in DR.
- IR: $\ln \lambda_{IR}$ with cut-off, $1/\epsilon_{IR}$ poles in DR.

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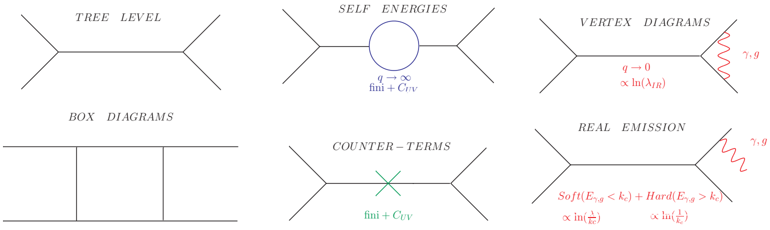

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- Reach the same accuracy for Higgs lineshapes as in the $\mathcal{SM}$: Full NLO EW corrections needed
- Full renormalisation needed for computing DM annihilation channels at NLO

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- Gauge $\longrightarrow$ as in the SM

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- Higgs

$$\mathcal{L}^0 = \mathcal{L}(\lambda_i, M_{ij}, \phi_i) + \delta\mathcal{L}(\lambda_i, M_{ij}, \phi_i, \delta\lambda_i, \delta M_{ij}, \delta Z_{ij}), \quad i = h, H$$

SHIFTS

- $\Phi_i^0 \longrightarrow (\delta_{ij} + \frac{1}{2}\delta Z_{ij})\Phi_j$
- $\lambda_2^0 \longrightarrow \lambda_2 + \delta\lambda_2,\ \mu_2^0 \longrightarrow \mu_2 + \delta\mu_2$
- $M_i^{0\,2} \longrightarrow M_i^2 + \delta M_i^2$
- $T^0 \longrightarrow T + \delta T$

ON-SHELL SCHEME

- $\widetilde{\mathcal{R}e}\hat{\Sigma}_{ii}(M_i^2) = 0 \longrightarrow \delta M_i^2$
- $\widetilde{\mathcal{R}e}\hat{\Sigma}'_{ii}(M_i^2) = 0 \longrightarrow \delta Z_{ii}$
- $\widetilde{\mathcal{R}e}\hat{T} = 0 \longrightarrow \delta T$

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SECTORS

- Fermion $\longrightarrow$ as in the SM
- Gauge $\longrightarrow$ as in the SM
- Higgs $\longrightarrow$ definition for $\Rightarrow$ $\boxed{\delta\lambda_2 \cdots \delta\lambda_5}$ $\Leftarrow$

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see also 1507.03630, 1605.08520...

RENORMALISATION OF INERT SCALAR PARAMETERS

- Renormalisation of λ_2: very difficult to access this parameter experimentally, $\overline{\text{MS}}$ definition

$$\delta\lambda_2 \equiv \delta\lambda_2^{\overline{\text{MS}}} = \frac{1}{32\pi^2}\left(\beta^S_{\lambda_2} + \beta^g_{\lambda_2}\right)\Delta, \quad \Delta = 2/(4-D) - \gamma_E + \ln 4\pi$$

with

$$\beta^S_{\lambda_2} = 24\lambda_2^2 + 2\lambda_3^2 + 2\lambda_3\lambda_4 + \lambda_4^2 + \lambda_5^2$$

$$\beta^g_{\lambda_2} = \frac{3}{8}\left[3g^4 + g'^4 + 2g^2g'^2 - 3\lambda_2\left(3g^2 + g'^2\right)\right]$$

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- Renormalisation of μ_2: extracted from HHh form factor (see 1612.01973)

$$\Gamma^{ren}_{HHh}(p_1^2, p_2^2, p) = \Gamma^0_{HHh}(p_1^2, p_2^2, p) + \Gamma^1_{HHh}(p_1^2, p_2^2, p) + \delta\Gamma_{HHh}(p_1^2, p_2^2, p)$$
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$$\boxed{\delta\mu_2^2 = -\left[\left(\frac{\Gamma^1_{HHh}(p_1^2, p_2^2, p)v}{2(M_H^2 - \mu_2^2)} + \frac{\delta v}{v} - \frac{1}{2}\delta Z_h - \delta Z_H\right)(M_H^2 - \mu_2^2) - \delta M_H^2\right]}$$

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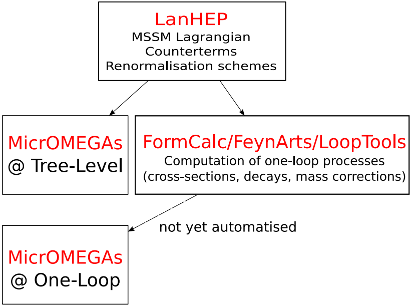
AUTOMATIC TOOL FOR ONE-LOOP CALCULATIONS: SLOOPS



SLOOPS

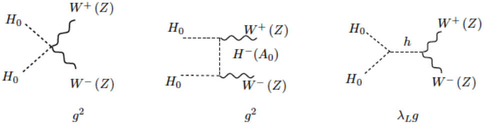
An automatic code for calculation of loops diagrams for $\mathcal{SM}$ and $\mathcal{BSM}$ processes with application to colliders, astrophysics and cosmology.

- Automatic derivation of the CT Feynman rules and computation of the CT's
- Models renormalized: SM, MSSM, NMSSM, Wino DM, **xSM** (w/ & w/o v_s),
- Modularity between different renormalisation schemes.
- Non-linear gauge fixing.
- Checks: results UV,IR finite and gauge independent.

http://code.sloops.free.fr/

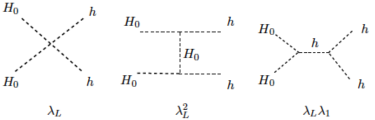
From S.Kraml SCALARS '15

see hep-ph/0612275, arXiv:1003.3125 [hep-ph]



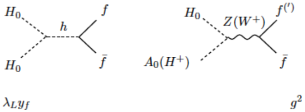
annihilation into gauge bosons

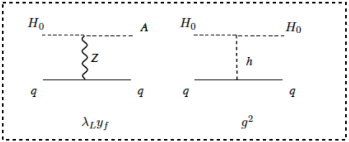
$$\lambda_L = \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)$$



annihilation into Higgs

Direct DM detection





DM BENCHMARKS IN THE IDM

- Many studies on the allowed parameter space (from LEP, EWPO, LHC, THEORY, COSMO/ASTRO) of the IDM: 1303.3010, 1310.0358, 1508.01671,1503.07367, 1612.00511...
- DM phenomenology for H or A as the candidate is very similar ($\lambda_5 \to -\lambda_5$)
- If IDM accounts for the whole $\Omega_\chi h^2$, two regimes survive:

HIGGS FUNNEL

- $M_H \simeq M_h/2$
- $HH \to WW*, b\bar{b}$ for RD
- $2 \to 3$ at 1L level for RD
- DD requires low $\lambda_{S/A}$ or $\mu_2 \simeq M_H$

$$\sigma_{HN} = \frac{m_r^2}{\pi}\left[\frac{M_H}{M_h^2 v^2}\left(1-\frac{\mu_2^2}{M_H^2}\right)\right]^2 f^2 m_N^2 = \frac{m_r^2}{\pi}\left[\frac{\lambda_L}{M_H M_h^2}\right]^2 f^2 m_N^2$$

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LARGE MASS

- $M_H \gtrsim 500$ GeV
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- Coannihilation $H^+H^-, AA, H^\pm H, H^\pm A \to VV'$
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$$\sigma_{HN} = \frac{m_r^2}{\pi}\left[\frac{M_H}{M_h^2 v^2}\left(1 - \frac{\mu_2^2}{M_H^2}\right)\right]^2 f^2 m_N^2 = \frac{m_r^2}{\pi}\left[\frac{\lambda_L}{M_H M_h^2}\right]^2 f^2 m_N^2$$

Side note: This precludes also large loop corrections to the hhh coupling, no non-decouping regime in the IDM if viable DM model

RESULTS FOR LARGE MASS REGIME

- Point satisfying tree level $\Omega_\chi h^2$ + Direct Detection with `micrOMEGAS`
- $(M_H, M_A, M_{H^\pm}) = (550, 551, 552)$ GeV
- $\mu_2 = 549.45$ GeV, $\lambda_2 = 0.01$

$$\boxed{\Omega_\chi h^2 = 0.118}$$

CHANNELS CONTRIBUTING MORE THAN 7%

- $HH \to W^+W^-$: 18%
- $HH \to ZZ$: 14%
- $H^+H^- \to W^+W^-$: 13%
- $AA \to W^+W^-$: 9%
- $H^\pm H \to \gamma W^\pm$: 8%
- $AA \to ZZ$: 7%
- $H^\pm A \to \gamma W^\pm$: 7%

LPSC Grenoble

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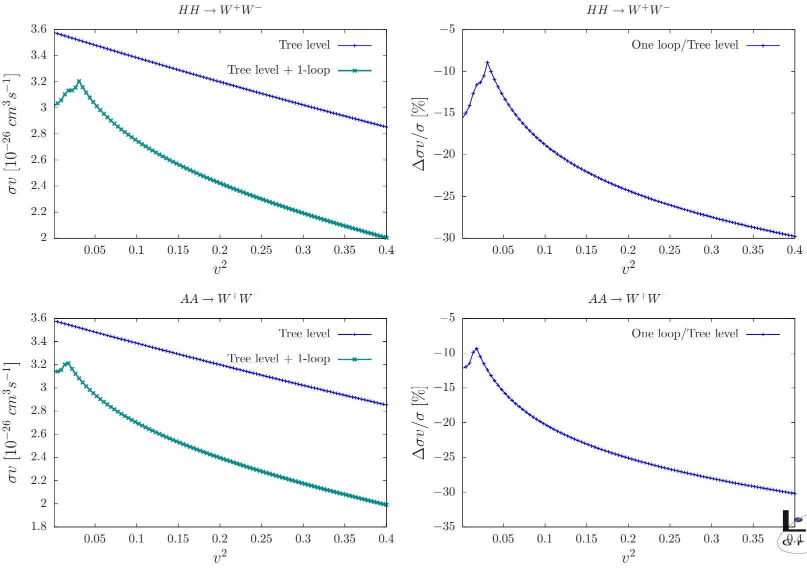
LPSC Grenoble

$\mu_R = M_H$


$HH \to W^+W^-$
Tree level
Tree level + 1-loop
$\sigma v\ [10^{-26}\ cm^3 s^{-1}]$
v^2
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One loop/Tree level
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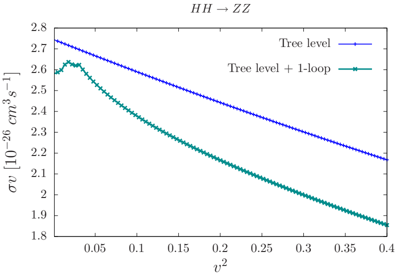
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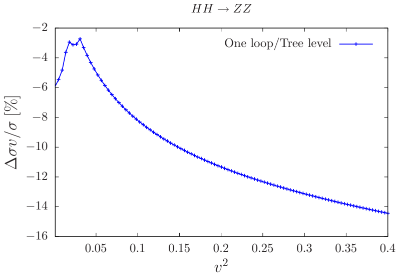
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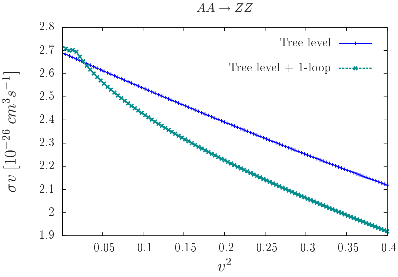
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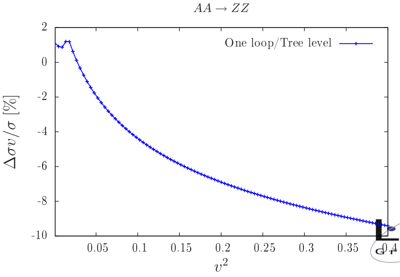
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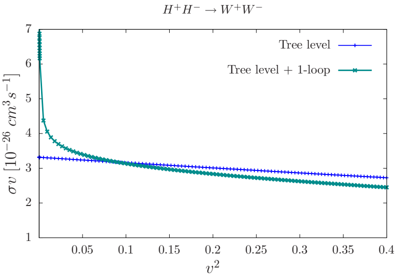

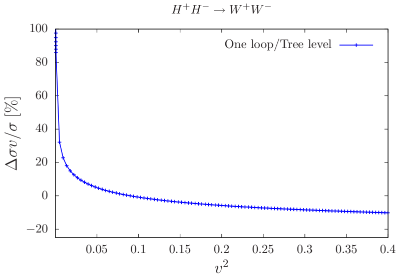

$$\sigma_1 v = a_1 + b_1 v^2 - \pi\alpha a_0 Q_i Q_j / v$$

$$S_{nr} = X_{nr}/(1 - e^{-X_{nr}}) \quad X_{nr} = -2\pi\alpha Q_i Q_j / v$$

- ☞ Given the exp. precision on $\Omega_\chi h^2$, precise theo predictions required
- ☞ Full renormalisation of the IDM achieved
- ☞ Two schemes available for μ_2: *OS* and $\overline{\mathrm{MS}}$
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- Comparison with built-in IDM model within `micrOMEGAs`
- Impact of rad. cor in the low mass regime ($2 \longrightarrow 3$ processes at 1L)

CONCLUSION AND OUTLOOK

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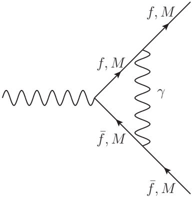
THANK YOU FOR YOUR ATTENTION

BACKUP

- Singularities arise in scalar triangle C_0 and box D_0 loop integrals when $\beta \to 0$.



$$C_0 \xrightarrow{\beta \to 0} -\frac{\pi^2}{Q^2 \beta}$$

$$\beta = v/2 = \sqrt{1 - 4M^2/Q^2}$$

- D_0 has the same infrared behavior because for $\beta = 0$ it can be split into a sum of triangle integrals.
- This effect can be resummed to all orders.
- $S_{1L} = \frac{\pi\alpha}{v} \times \sigma_0 Q_i Q_j$
- $S_{nr} = X_{nr}/(1 - e^{-X_{nr}}) \times \sigma_0 \quad X_{nr} = 2\pi\alpha Q_i Q_j / v$

Linear gauge fixing

$$\mathcal{L}_{GF} = -\frac{1}{\xi_W}|\partial_\mu W^{\mu\,+} + i\xi_W \frac{g}{2} v G^+ \,|^2 - \frac{1}{2\xi_Z}(\partial_\mu Z^\mu + \xi_Z \frac{g}{2c_w} v G^0)^2 - \frac{1}{2\xi_A}(\partial_\mu A^\mu)^2$$

$$\Gamma^{VV} = \frac{-i}{q^2 - M_V^2 + i\epsilon}\left[g_{\mu\nu} + (\xi_V - 1)\frac{q_\mu q_\nu}{q^2 - \xi_V M_V^2}\right]$$

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$\xi_{W,Z,A} = 1$ (Feynman gauge)

Non-Linear gauge fixing

$$
\begin{aligned}
\mathcal{L}_{GF} \quad = \quad & -\frac{1}{\xi_W}|(\partial_\mu - ie\tilde{\alpha}A_\mu - igc_w\tilde{\beta}Z_\mu)W^{\mu\,+} \\
& +i\xi_W\frac{g}{2}(v + \tilde{\delta}h^0 + \tilde{\omega}H^0 + i\tilde{\kappa}G^0 + i\tilde{\rho}A^0)G^+\,|^2 \\
& -\frac{1}{2\xi_Z}(\partial_\mu Z^\mu + \xi_Z\frac{g}{2c_w}(v + \tilde{\epsilon}h^0 + \tilde{\gamma}_H^0)G^0)^2 \\
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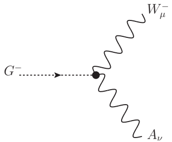

$$eM_W(1 + \tilde{\alpha}g_{\mu\nu})$$

$\xi_{W,Z,A} = 1$ (Feynman gauge)

→ Gauge parameter dependence in gauge/Goldstone/ghost vertices.

→ No "unphysical" threshold, no higher rank tensor.

More formal approach in Freitas, Stockinger, *PRD 66 (2002) 095014*

Remind that we can write the IDM scalar masses as

$$M_\Phi^2 = \mu_2^2 + \mathcal{O}(\lambda_i)v^2, \quad \Phi = [H, A, H^\pm]$$

Defining the deviation of the *hhh* coupling to the SM value as,

$$\Delta\kappa_h(q) = \frac{V_{hhh}(m_h^2, m_h^2, q)_{\rm IDM} - V_{hhh}(m_h^2, m_h^2, q)_{\rm SM}}{V_{hhh}(m_h^2, m_h^2, q)_{\rm SM}}$$

Then, assuming $M_\Phi \gg M_h$ and neglecting the SM loops and renormalisation effects, one finds

$$(4\pi)^2 \Delta\kappa_h(q) \backsimeq \sum_{\Phi = A^0, H, H^\pm} c_\Phi \frac{4}{3} \frac{M_\Phi^4}{m_h^2 v^2} \underbrace{\boxed{\left(1 - \frac{\mu_2^2}{M_\Phi^2}\right)^3}}_{\text{enters } \sigma_{HN}}$$