Edinburgh HEP Seminar

Higgs Portal to New Physics

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Overview

1. Motivation
2. Model building based on classical scale invariance
3. Higgs-sector phenomenology
4. Stabilisation of the Higgs potential
5. Matter-anti-matter asymmetry
6. Inflation
7. Dark Matter

1. Motivation

The discovery of the 125 GeV Higgs boson and no sign of low-energy supersymmetry (or any other 'mainstream' new physics) is an invitation to go back to the drawing board.

I will advocate a possibility of a very different BSM model building paradigm based on:

- a *minimally extended* Standard Model
- with classical scale-invariance (for 'effective' naturalness)

Beyond the Standard Model - in a minimal way

The LHC Higgs discovery is the crowning achievement of the SM. At a more fundamental level it leaves key questions unanswered:

- It accommodates $v = 246\ \mathrm{GeV}$ and $m_h \simeq 125\ \mathrm{GeV}$ essentially as input parameters, but the SM does not explain the origin and smallness of the EWSB scale $\{v\,,\ m_h\} \ll M_{\rm Pl}$
- The SM Higgs potential is unstable
- The Generation of the matter-anti-matter asymmetry of the Universe (BAU) is impossible within the SM
- There is no Dark Matter in the SM
- Particle physics implementation of Cosmological Inflation?
- Strong CP, etc...?

2. The rational for a 'heretical' approach to model building based on classical scale invariance

1. There is just a single occurrence of a non-dynamical scale in the Standard Model – the negative-valued $\mu^2_{\rm SM}$ parameter in:

$$V^{\rm SM}_{\rm cl}(H) = \mu^2_{\rm SM}\, H^\dagger H + \frac{\lambda_{\rm H}}{2}\left(H^\dagger H\right)^2$$

Remove $\mu^2_{\rm SM}$ by introducing a Higgs portal interaction with new ϕ:

$$V_{\rm cl}(H,\phi) = -\lambda_{\rm P}(H^\dagger H)|\phi|^2 + \frac{\lambda_{\rm H}}{2}(H^\dagger H)^2 + \frac{\lambda_\phi}{4!}|\phi|^4$$

$V_{\rm cl}$ is now scale-invariant. If the right value for $\langle\phi\rangle \ll M_{UV}$ can be generated quantum mechanically, it will trigger the EWSB:

$$\mu^2_{\rm SM} = -\lambda_{\rm P}|\langle\phi\rangle|^2 \quad = -\frac{1}{2}\, m_h^2 = -\frac{1}{2}\,\lambda_{\rm H}\, v^2$$

2. The rational for classical scale invariance -continued-

2. Coleman-Weinberg mechanism 40 years ago: a massless scalar field ϕ coupled to a gauge field dynamically generates a non-trivial $\langle\phi\rangle$ via dimensional transmutation of the log-running couplings

$$\langle\phi\rangle \sim M_{UV} \times \exp\left[-\frac{\mathrm{const}}{g_{CW}^2}\right] \ll M_{UV}$$

g_{CW} is the gauge coupling of ϕ.

SM$\times$U(1)$_{CW}$ BSM theory

Classically scale-invariant with the Higgs portal $-\lambda_{\rm P}|H|^2|\phi|^2$

$\langle\phi\rangle$ is non-vanishing, calculable in a weakly-coupled theory, and is naturally small (exp. suppressed) relative to the UV cut-off. Then:

$$\mathrm{EWSB}: \quad v = \sqrt{\frac{2\lambda_{\rm P}}{\lambda_{\rm H}}}\,\langle\phi\rangle\,, \quad m_h = \sqrt{2\lambda_{\rm P}}\,\langle\phi\rangle$$

2. The rational for classical scale invariance -continued-

SM$\times$U(1)$_{CW}$ BSM theory

Classically scale-invariant: No input mass terms are allowed!

In the course of UV renormalisation, the subtraction scheme is chosen to set the *renormalised masses* at the origin of the field space to zero

$$m^2|_{\phi=0} := V''(\phi)\Big|_{\phi=0} = 0$$

In *dimensional regularisation* this masslessness eqn is automatic:

- No power-like dependences on the cutoff scale can appear;
- Since there are no explicit mass scales at the outset, no finite corrections to mass terms at the origin are genereated.

Dim reg preserves classical scale invariance, the theory as it stands is not fine-tuned.

Comments on classical scale-invariance:

- Classical scale invariance is not an exact symmetry. It is broken anomalously by logarithmically running couplings.
- This is precisely what generates dynamical scales $\langle\phi\rangle \ll M_{UV}$ and feeds to EWSB and other features.
- The scale invariance is broken by the anomaly in a controlled way – the order parameter is $\langle|\phi|^2\rangle$.
  Generic UV regularisation instead would introduce *large* effects $\sim \alpha\, M_{UV}^2$
  $$\alpha\, M_{UV}^2 \gg \langle|\phi|^2\rangle$$
  To maintain the anomalously broken scale invariance, one must choose a scale-invariance-preserving regularisation scheme – dimensional regularisation – Bardeen 1995.

2. The rational for classical scale invariance -continued-

SM$\times$U(1)$_{CW}$ BSM theory

Classically scale-invariant: No input mass terms are allowed!

Summary: within scale-inv.-preserving dimensional regularisation, the masslessness conditions

$$\left.\frac{\partial^2 V(H,\phi)}{\partial\phi^\dagger\partial\phi}\right|_{H=\phi=0} = 0\,, \quad \left.\frac{\partial^2 V(H,\phi)}{\partial H^\dagger\partial H}\right|_{H=\phi=0} = 0$$

are self-consistent and contain no fine-tuning in the theory at hand. And, once enforced at one scale, they hold at all RG scales.

SM$\times$U(1)$_{CW}$ classically scale-invariant BSM

All mass scales in the theory must be generated dynamically

2. The rational for classical scale invariance -continued-

3. A powerful principle for the BSM model building. No vastly different scales can co-exist in such a theory:

1. Hard to generate a large hierarchy of scales from one $\langle\phi\rangle$
2. Large new mass scales would ultimately couple to the Higgs and destabilise it mass.

The BSM theory is a minimal extension of the SM which should address all the sub-Planckian shortcomings of the SM without introducing scales higher than $\langle\phi\rangle$ which itself is not much higher the electroweak scale.

Some references:

Coleman-Weinberg mechanism:

S. R. Coleman and E. J. Weinberg, Phys. Rev. D **7** (1973) 1888

SM$\times$U(1)$_{CW}$ model first appears in:

R. Hempfling, Phys. Lett. B **379** (1996) 153

The special role of dimensional regularisation:

W. A. Bardeen, FERMILAB-CONF-95-391-T

Classical scale invariance introduced in:

K. A. Meissner and H. Nicolai, Phys. Lett. B **648** (2007) 312

Our approach and presentation follows:

C. Englert, J. Jaeckel, V. V. Khoze and M. Spannowsky, 1301.4224

V. V. Khoze and G. Ro, 1307.3764

V. V. Khoze, 1308.6338

3. Higgs phenomenology

- The $\mathrm{U}(1)_{CW}$ sector gives two new d.o.f's: the scalar ϕ and the Z' boson

$$m_\varphi^2 = \frac{3g_{CW}^4}{8\pi^2}|\langle\phi\rangle|^2 \quad \ll \quad m_{Z'}^2 = g_{CW}^2|\langle\phi\rangle|^2$$

- The SM Higgs $H^T(x) = \frac{1}{\sqrt{2}}(0, v + h(x))$ and the hidden Higgs $\phi = \langle\phi\rangle + \varphi$ mix with each other via the portal interaction $-\lambda_{\mathrm{P}}(H^\dagger H)|\phi|^2$ thanks to their vevs v and $\langle\phi\rangle$. The mass matrix is

$$m^2 = \begin{pmatrix} m_h^2 + \Delta m_{h,\mathrm{SM}}^2 & -\kappa\, m_h^2 \\ -\kappa\, m_h^2 & m_\varphi^2 + \kappa^2 m_h^2 \end{pmatrix}, \quad \kappa = \sqrt{\frac{2\lambda_{\mathrm{P}}}{\lambda_H}}$$

$$m_h^2 = \lambda_{\mathrm{H}} v^2, \quad \Delta m_{h,\mathrm{SM}}^2 = \frac{1}{16\pi^2}\frac{1}{v^2}\left(6m_W^4 + 3m_Z^4 + m_h^2 - 24m_t^4\right) \approx -2200\,\mathrm{GeV}^2$$

Diagonalise via

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} h \\ \varphi \end{pmatrix}, \quad \vartheta \approx \kappa \frac{m_h^2}{m_\varphi^2 - m_h^2 - \Delta m_{h,\mathrm{SM}}^2} \ll 1\,.$$

C. Englert, J. Jaeckel, V. V. Khoze and M. Spannowsky, 1301.4224

3. Higgs phenomenology -continued-

• If $m_{h_1} > 2m_{h_2}$ the SM Higgs can decay into two hidden Higgses

$$\Gamma_{h_1 \to h_2 h_2} = \frac{4\lambda_{\rm P}^2 v^2}{16\pi} \frac{[m_{h_1}^2 - 4m_{h_2}^2]^{1/2}}{m_{h_1}^2}$$

• A similar equation holds for $m_{h_2} > 2m_{h_1}$ with $v \to \sqrt{2}\,\langle|\phi|\rangle$ and $m_{h_1} \leftrightarrow m_{h_2}$.

• In the simplest SM$\times$U(1)$_{CW}$ setup there are no light hidden sector particles into which the hidden Higgs can decay. The h_2 therefore decays back into SM particles via the mixing with the Higgs and its couplings to light particles,

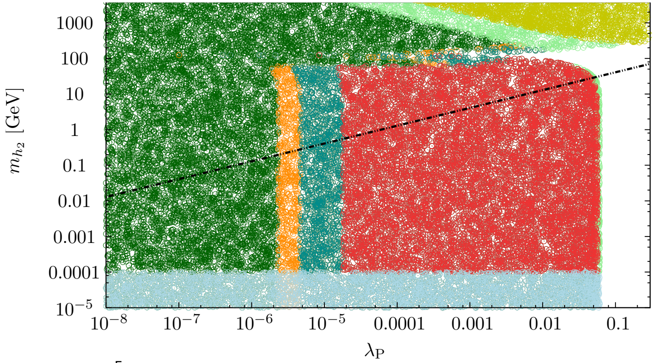
$$\Gamma_{h_2 \to X X^c} = \sin^2\vartheta\, \Gamma^{\rm SM}_{h \to X X^c}(m_h = m_{h_2})\,,$$

$$\sigma(XY \to h_2) = \sin^2\vartheta\, \sigma^{\rm SM}_{XY \to h}(m_h = m_{h_2})$$

• Combining already quite small SM Higgs decay width, e.g. at $m_h \simeq 125\ \mathrm{GeV}$, $\Gamma_{\rm SM} \simeq 4\ \mathrm{MeV}$ with a small mixing angle, h_2 becomes an extremely narrow resonance.

3. Higgs phenomenology -continued-

C. Englert, J. Jaeckel, V. V. Khoze and M. Spannowsky, 1301.4224



Scatter plot for 10^5 randomly generated parameter choices in the (λ_P, m_{h_2}) plane. Red region is excluded by current LHC measurements. The cyan region can be probed by HL LHC and orange region is a projection for a combination of a HL LHC with an LC. The allowed parameter points are depicted in green. Points below the black dash-dotted line require some fine-tuning.

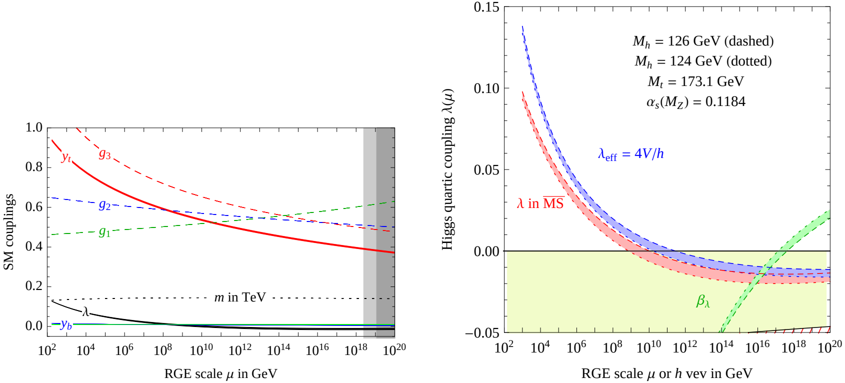
3. Higgs phenomenology -summary-

- The minimal SM$\times$U$(1)_{CW}$ model has only two free remaining parameters, the portal coupling, $\lambda_{\rm P}$ and the mass of the 2nd scalar eigenstate m_{h_2} (can be traded for a much heavier Z').
- We can see that the model is perfectly viable in the light of present and future experimental data:
- In particular, the presently available Higgs data constrains the portal coupling to be $\lambda_{\rm P} \lesssim 10^{-5}$ on the part of the parameter space where $10^{-4}\,{\rm GeV} < m_{h_2} < m_{h_1}/2$.
- For $m_{h_2} > m_{h_1}/2$ the coupling $\lambda_{\rm P}$ is much less constrained experimentally, but has a theoretical upper limit $\lambda_{\rm P} \lesssim 10^{-2}$.

C. Englert, J. Jaeckel, V. V. Khoze and M. Spannowsky, 1301.4224

4. Stabilisation of the Higgs potential

The SM Higgs potential is unstable as the Higgs self-coupling λ turns < 0.



D. Buttazzo, G. Degrassi, P. P. Giardino, G. F. Giudice, F. Sala, A. Salvio and A. Strumia, 1307.3536

4. Stabilisation of the Higgs potential -continued-

A minimal and robust way to repair the EW vacuum stability is provided by the Higgs portal extension of the SM – just what we have in our theory.

Two effects to stabilise the vacuum:

1. The portal coupling gives a positive contribution to the beta function of the Higgs quartic coupling, $\Delta\beta_\lambda \sim +\lambda_{\rm P}^2$
2. The vev of the second scalar, $\langle\phi\rangle > v$, leading to mixing between ϕ and the Higgs and resulting in a threshold correction lifting the SM Higgs self-coupling

- O. Lebedev, 1203.0156 [hep-ph]
- J. Elias-Miro, J. R. Espinosa, G. F. Giudice, H. M. Lee and A. Strumia, 1203.0237
- T. Hambye and A. Strumia, 1306.2329
- C. D. Carone and R. Ramos, 1307.8428

5. Leptogenesis

- With no signs of supersymmetry and no anomalies in the quark flavour sector, the most attractive scenario for generating BAU is Leptogenesis:
- Standard approach: Lepton asymmetry is generated by out-of-equilibrium decays of heavy sterile Majorana neutrinos into SM leptons at T much above the electroweak scale. The lepton asymmetry is then reprocessed into the baryon asymmetry by electroweak sphalerons.
- Requires extremely heavy masses for sterile neutrinos, $M_N \gtrsim 10^9$ GeV. Inconsistent with the classical scale-invariance.
- We adopt an *alternative* approach to leptogenesis: the lepton flavour asymmetry is produced during oscillations of Majorana neutrinos with masses $200\,\mathrm{MeV} \lesssim M_N \lesssim 500\,\mathrm{GeV}$.
- Use the B-L model where Majorana masses of sterile neutrinos arise from the Coleman-Weinberg $\langle\phi\rangle$.
- Perfectly fits with the classical scale-invariance settings.

V. V. Khoze and G. Ro, 1307.3764

5. Leptogenesis -continued-

- Identify the CW $U(1)$ factor with the gauged $B-L$ flavour-subgroup of the Standard Model.

  S. Iso, N. Okada and Y. Orikasa, arXiv:0902.4050

- The Z' massive ($\gtrsim$ few TeV) vector boson now couples to quarks and leptons of the Standard Model proportionally to their $B-L$ charge.

- Cancellation of $U(1)_{B-L}$ gauge anomalies requires an automatic inclusion of three generations of Majorana neutrinos, $\nu_{R\,i}$. They have $B-L=1$, but are sterile under the SM gauge groups.

$$\mathcal{L}_{\rm int}^{\nu_R} = -\frac{1}{2}\left(Y_{ij}^{\rm M}\phi\,\overline{\nu^c_{R}}_i\nu_{R\,j} + Y_{ij}^{\rm M\,\dagger}\phi^\dagger\,\overline{\nu_R}_i\nu^c_{R\,j}\right) - Y_{ia}^{\rm D}\overline{\nu_R}_i(\epsilon H)\,l_{L\,a} - Y_{ai}^{\rm D\,\dagger}\,\overline{l_L}_a(\epsilon H)^\dagger\,\nu_{R\,i}$$

$Y_{ij}^{\rm M}$ and $Y_{ia}^{\rm D}$ are 3×3 complex matrices of the Majorana and Dirac Yukawas.

The CW scalar ϕ is assigned the $B-L$ charge $=2$. Spontaneous breaking of the $B-L$ symmetry by the vev $\langle|\phi|\rangle \neq 0$ generates Majorana masses of ν_R

$$M_{ij} = Y_{ij}^{\rm M}\,\langle|\phi|\rangle$$

5. Leptogenesis via neutrino oscillations -continued-

- The right-handed neutrinos are produced thermally in the early Universe.
- After being produced, they begin to oscillate, $\nu_{Ri} \leftrightarrow \nu_{Rj}$, between the three different flavour states $i, j = 1, 2, 3$ in the expanding Universe.
- The lepton number of individual flavours is not conserved: complex non-diagonal Majorana matrices induce CP-violating flavour oscillations followed by out-of-equilibrium – due to small of Yukawas – decays

$$\nu_{Ri} \leftrightarrow \nu_{Rj} \rightarrow l_{Lj} H$$

- Require that by the time the temperature cools down to T_{EW}, where electroweak sphaleron processes freeze out, only two out of three neutrino flavours equilibrate with their Standard Model counterparts

$$\Gamma_2(T_{EW}) > H(T_{EW}) \ , \quad \Gamma_3(T_{EW}) > H(T_{EW}) \ , \quad \Gamma_1(T_{EW}) < H(T_{EW})$$

E. K. Akhmedov, V. A. Rubakov and A. Y. .Smirnov, hep-ph/9803255

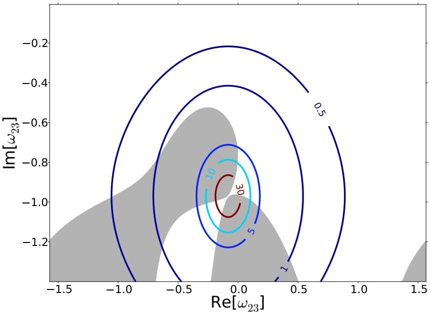
T. Asaka and M. Shaposhnikov, hep-ph/0505013

M. Drewes and B. Garbrecht, 1206.5537

5. Leptogenesis via neutrino oscillations -conclusion-

2-dimensional slice of the parameter space from

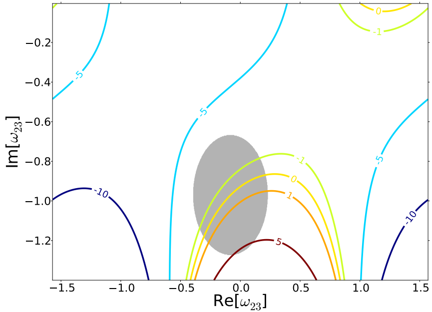
V. V. Khoze and G. Ro, 1307.3764



Superposition of the Majorana mass contours in GeV satisfying the wash-out bound, with the baryon asymmetry produced. Shaded regions denote the required baryon asymmetry.

2-dimensional slice of the parameter space from

V. V. Khoze and G. Ro, 1307.3764



Shaded region has the required wash-out rate $\Gamma_1(T_{EW}) < H(T_{EW})$. The contours show the normalised baryon asymmetry produced $n_B/n_B^{\rm obs}$.

The observed value of the asymmetry is $n_B^{\rm obs}/s = (8.75 \pm 0.23) \times 10^{-11}$ and we require $|n_B/n_B^{\rm obs}| \geq 1$.

	Scenario 5	Scenario 6	Scenario 7
$\langle\phi\rangle$	10^5 GeV	2.5×10^4 GeV	3.4×10^3 GeV
M_1	3.6 GeV	3.6 GeV	3.96 GeV
M_2	4.0 GeV	4.0 GeV	4.0 GeV
M_3	4.4 GeV	4.4 GeV	4.04 GeV
m_1	0.0 meV	0.0 meV	0.0 meV
m_2	8.7 meV	8.7 meV	8.7 meV
m_3	49.0 meV	49.0 meV	49.0 meV
s_{12}	0.55	0.55	0.55
s_{23}	0.63	0.63	0.63
s_{13}	0.16	0.16	0.16
δ	$-\pi/4$	$-\pi/4$	$-\pi/4$
α_1	0	0	0
α_2	$-\pi/2$	$-\pi/2$	$-\pi/2$
ω_{12}	1+2.6i	1+2.6i	1+2.6i
ω_{13}	0.9+2.7i	0.9+2.7i	0.9+2.7i
ω_{23}	0.3-1.5i	-1.2i	-0.04-0.976i
$n_{Le}/(s\times2.5\times10^{-10})$	-18	-5	-6.6
$n_{L\mu}/(s\times2.5\times10^{-10})$	99	27	41
$n_{L\tau}/(s\times2.5\times10^{-10})$	-81	-22	-34
$\Gamma_e/H(T_{EW})$	0.64	0.64	0.67
$\Gamma_\mu/H(T_{EW})$	290	290	304
$\Gamma_\tau/H(T_{EW})$	920	920	960
T_{osc}	10^6 GeV	7.5×10^7 GeV	9.8×10^7 GeV

5. Leptogenesis via neutrino oscillations -conclusion-

V. V. Khoze and G. Ro, 1307.3764

	Scenario 5	Scenario 6	Scenario 7
$\langle\phi\rangle$	$10^5\,\mathrm{GeV}$	$2.5\times10^4\,\mathrm{GeV}$	$3.4\times10^3\,\mathrm{GeV}$
λ_p	8×10^{-7}	10^{-5}	0.7×10^{-3}
Y_1^{M}	3.6×10^{-5}	1.4×10^{-4}	1.2×10^{-3}
Y_2^{M}	4×10^{-5}	1.6×10^{-4}	1.2×10^{-3}
Y_3^{M}	4×10^{-5}	1.8×10^{-4}	1.2×10^{-3}
$\langle Y^{\mathrm{D}}\rangle$	4×10^{-8}	4×10^{-8}	4×10^{-8}
$M_{Z'}$	$3.5\,\mathrm{TeV} < M_{Z'} < 220\,\mathrm{TeV}$	$3.5\,\mathrm{TeV} < M_{Z'} < 56$	$3.5\,\mathrm{TeV} < M_{Z'} < 7.4$
g_{B-L}	$0.0175 < g_{B-L} < 1.1$	$0.15 < g_{B-L} < 1.1$	$0.5 < g_{B-L} < 1.1$
λ_ϕ	$5\times10^{-4} < \lambda_\phi$	$0.04 < \lambda_\phi$	$0.4 < \lambda_\phi$

6. Single-field slow-roll Inflation in the Higgs portal

- Inflation is the leading theory of the early universe.
- Was proposed in the 80s to solve the flatness, isotropy, homogeneity, horizon and relic problems in cosmology.
- Confirmed by observations, including the recent data from Planck satellite, which favour a simple inflationary scenario with one slow rolling scalar field.
- Relevant energy scales are far higher than can be probed at colliders, the underlying particle physics implementation of inflation is still unknown.

6. Inflation in the Higgs portal -continued-

- We will focus on the approach based on renormalisable QFT Lagrangians
- Include a non-minimal coupling of a scalar field to gravity, in addition to the usual Einstein-Hilbert term
- By taking the non-minimal coupling ξ to be (moderately) large $\sim 10^4$, a slow-roll potential for the scalar is generated and inflation takes place

Original approach based on non-minimal scalar-to-gravity coupling:

D. S. Salopek, J. R. Bond and J. M. Bardeen, Phys. Rev. D **40** (1989)

Higgs inflation proposal:

F. L. Bezrukov and M. Shaposhnikov, Phys. Lett. B **659** (2008) 703

6. Inflation in the Higgs portal -continued-

V. V. Khoze, 1308.6338

- Start with the class. scalar potential of the SM coupled to the CW sector

$$V_{\rm cl}(H,\phi) = \frac{\lambda_{\rm H}}{2}\left(|H|^2 - \frac{\lambda_{\rm P}}{\lambda_{\rm H}}|\phi|^2\right)^2 + \frac{\tilde{\lambda}_\phi}{4!}|\phi|^4$$

- *Extend* this model by adding a real scalar field $s(x)$ – a gauge singlet coupled only via the scalar portal interactions with the Higgs and ϕ,

$$V_{\rm cl}(H,\phi,s) = \frac{\lambda_{hs}}{2}|H|^2 s^2 + \frac{\lambda_{\phi s}}{4}|\phi|^2 s^2 + \frac{\lambda_s}{4}s^4 + V_{\rm cl}(H,\phi)$$

  which is the general renormalisable gauge-invariant scalar potential for the three massless scalars. – Classically scale-invariant theory.

- $\lambda_{hs} \geq 0$ and $\lambda_{\phi s} \geq 0$ ensure that $\langle s \rangle = 0$. No mixing with ϕ and the Higgs, instead the CW vev $\langle \phi \rangle$ generates the mass for the singlet $s(x)$

$$m_s^2 = \frac{\lambda_{hs}}{2}\, v^2 + \frac{\lambda_{\phi ss}}{2}\, |\langle \phi \rangle|^2$$

6. Inflation in the Higgs portal -continued-

Couple the theory to gravity

$$\mathcal{L}_J = \sqrt{-g_J}\Big(-\frac{M^2}{2}R - \frac{\xi_s}{2}s^2R + \frac{1}{2}g_J^{\mu\nu}\,\partial_\mu s\,\partial_\nu s + g_J^{\mu\nu}\,(D_\mu H)^\dagger D_\nu H + \frac{1}{2}g_J^{\mu\nu}\,(D_\mu\phi)^\dagger D_\nu\phi$$
$$-\frac{\lambda_s}{4}s^4 - \frac{\lambda_{hs}}{2}|H|^2s^2 - \frac{\lambda_{\phi s}}{4}|\phi|^2s^2 - V(H,\phi) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \text{Fermions} + \text{Yukawas}\Big)$$

- $M \sim 10^{18}$ GeV denotes the reduced Planck mass; it appears only in the Einstein-Hilbert term and does not couple directly to non-gravitational d.o.f's.
- $(\xi_s/2)\,s^2R$ is the non-minimal coupling of the singlet $s(x)$ to gravity, R is the scalar curvature. For successful inflation ξ_s should be relatively large, $\xi_s \sim 10^4$.
- Hence we will treat ξ_s and $\sqrt{\xi_s}$ as large parameters $\gg 1$. In this sense, $s(x)$ is distinguished from the two other scalars, H and ϕ, which in our case have either vanishing or small loop-induced non-minimal gravitational couplings

6. Inflation in the Higgs portal -continued-

- *Remove* the non-minimal scalar to gravity interaction with a metric transformation to the Einstein frame:

$$g_{\mu\nu} \to \Omega^{-2} g_{\mu\nu}\,, \qquad \Omega^2 := 1 + \frac{\xi_s s^2}{M^2}$$

$$\mathcal{L}_E = \sqrt{-g_E}\left(-\frac{1}{2} M^2 R + \left(\frac{\Omega^2 + \frac{6\xi_s^2 s^2}{M^2}}{\Omega^4} \right) \frac{g_E^{\mu\nu}\,\partial_\mu s\,\partial_\nu s}{2} + \frac{g_E^{\mu\nu}\,(D_\mu H)^\dagger D_\nu H}{\Omega^2} + \ldots \right.$$
$$\left. - \frac{1}{\Omega^4}\left(\frac{\lambda_s}{4} s^4 + \frac{\lambda_{hs}}{2} |H|^2 s^2 + \frac{\lambda_{\phi s}}{4} |\phi|^2 s^2 + V(H,\phi) \right) + \frac{\text{Yukawas}}{\Omega^4} \right)$$

- Now the kinetic term for $s(x)$ is no longer normalised canonically; it includes a dimension-6 interaction (coming from the transformation of R):

$$\frac{6\,\xi_s^2\, s^2}{M^2} \times \frac{g_E^{\mu\nu}}{2\,\Omega^2}\, \partial_\mu s\, \partial_\nu s$$

- M/ξ_s is the scale at which this non-renormalisable interaction becomes strong. Does the theory break down here *before* it reaches the inflation scale $M/\sqrt{\xi_s}$?

6. Inflation in the Higgs portal -continued-

- Fortunately, the appearance of the scale M/ξ_s is not problematic for the case of a *single* real scalar $s(x)$ with ξ_s:

R. N. Lerner and J. McDonald, 0912.5463; M. P. Hertzberg, 1002.2995

- The simplest way to see this is to perform a field redefinition $s(x) \to \sigma(x)$

$$\sigma = \int_0^s ds \sqrt{\frac{1}{\Omega^2} + \frac{6\xi_s s^2}{M^2\Omega^4}}$$

so that

$$\frac{d\sigma}{ds} = \sqrt{\frac{1}{\Omega^2} + \frac{6\xi_s s^2}{M^2\Omega^4}} = \sqrt{\frac{\Omega^2 + \frac{3}{2}M^2(\partial_s\Omega^2)^2}{\Omega^4}}$$

- which gives the canonically normalised kinetic term:

$$\left(\frac{1}{\Omega^2} + \frac{6\xi_s s^2}{M^2\Omega^4}\right) \frac{g_E^{\mu\nu}\, \partial_\mu s\, \partial_\nu s}{2} = \frac{1}{2}\, g_E^{\mu\nu}\, \partial_\mu \sigma\, \partial_\nu \sigma\,.$$

F. L. Bezrukov and M. Shaposhnikov, Phys. Lett. B **659** (2008) 703

6. Inflation in the Higgs portal -continued-

- At small field values, e.g. at the EW scale and up to $s \lesssim 10^{14}$ GeV the field redefinition is trivial

$$s(x) = \sigma(x)\,, \quad \text{for} \;\; s \ll M/\xi_s$$

- At higher values of s, the solution for s in terms of σ is

$$s(x) = \frac{M}{\sqrt{\xi_s}} \sqrt{\exp\left(\frac{2\sigma(x)}{\sqrt{6}M}\right) - 1}\,, \quad \text{for} \;\; s \gg \frac{M}{\xi_s}$$

- At an even higher scale $s \gg M/\sqrt{\xi_s}$ this gives

$$s(x) = \frac{M}{\sqrt{\xi_s}} \times \exp\left(\frac{\sigma(x)}{\sqrt{6}M}\right)\,, \quad \text{for} \;\; s \gg \frac{M}{\sqrt{\xi_s}}$$

- The Einstein frame potential for the canonically normalised singlet $\sigma(x)$ is now exponentially flat and well-suited for the slow-roll inflation:

$$V_E(s[\sigma]) = \frac{\lambda_s}{4}\frac{s^4(x)}{\Omega^4} = \frac{\lambda_s M^4}{4\,\xi_s^2}\left(1 - \exp\left[-\frac{2\sigma(x)}{\sqrt{6}M}\right]\right)^2\,, \quad \text{for} \;\; s \gg \frac{M}{\xi_s}$$

Inflation in the Higgs portal

Potential $V(\sigma)$ for the canonically normalised singlet $\sigma(x)$ is exponentially flat at large σ and provides the slow-roll inflation

- Everything follows from this $V(\sigma)$. The slow-roll inflation parameter is

$$\epsilon := \frac{M^2}{2}\left(\frac{V(\sigma)/d\sigma}{V(\sigma)}\right)^2 = \frac{4\,M^4}{3\,\xi_s^2\,s^2}$$

- Inflation ends when $\epsilon = 1$ which corresponds to $s_{\rm end} = (4/3)^{1/4} M/\sqrt{\xi_s}$ or $\sigma_{\rm end} \simeq 0.94M$.
- Inflation starts at $s_0 \simeq 9.14\,M/\sqrt{\xi_s}$. The CMB normalisation condition

$$\frac{V}{\epsilon}(s = s_o) \simeq (0.0276\,M)^4$$

  determines the value of the non-minimal singlet coupling to gravity

$$\xi_s \simeq 4.7 \times 10^4\,\sqrt{\lambda_s}$$

- The spectral index and the tensor-to-scalar perturbation ratios in this model are the same as computed in the Bezrukov-Shaposhnikov Higgs-inflation. They are in agreement with the Planck measurements.

6. Inflation in the Higgs portal -conclusions-

Our realisation is a one-field slow-roll inflation model. The singlet field σ plays the role of the inflaton, while the other scalars decouple during inflation as they are much heavier than the Hubble H during inflation:

$$m_h = \sqrt{\frac{\lambda_{hs}}{2}}\frac{M}{\sqrt{\xi_s}} \quad \text{and} \quad m_\phi = \sqrt{\frac{\lambda_{\phi s}}{2}}\frac{M}{\sqrt{\xi_s}} \quad \gg \quad H = \sqrt{\frac{\lambda_s}{12}}\frac{M}{\xi_s}$$

- Our model of inflation does not require inclusion of new physics d.o.f's at the the 'low' M/ξ_s and 'intermediate' scale $M/\sqrt{\xi_s}$.
- H and ϕ, are already canonically normalised and there are no non-renormalisable interactions involving sub-Planckian scales.
- If new physics was required to be included below the UV cutoff M, this would have destroyed the classical scale invariance of the theory and induced large threshold contributions to the masses of the Higgs and the CW scalar, reintroducing the fine-tinning problem into the SM.

7. Dark Matter = Inflaton

- In our classically scale-invariant SM$\times$U(1)$_{CW}$ theory with the singlet $s(x)$

$$V_{\rm cl}(H,\phi,s) \,=\, \frac{\lambda_{hs}}{2}|H|^2 s^2 \,+\, \frac{\lambda_{\phi s}}{4}|\phi|^2 s^2 \,+\, \frac{\lambda_s}{4} s^4 \,+\, V_{\rm cl}(H,\phi)$$

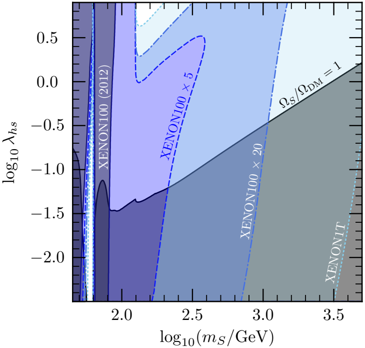
  the stability of the singlet is protected by a Z_2 symmetry, $s \to -s$, giving a natural dark matter candidate.

- The Z_2 symmetry of the potential is an automatic consequence of the renormalisability (dimension 4), scale-invariance and gauge invariance.
- At large field values, $s(x) > M/\sqrt{\xi_s}$, the singlet plays the role of the inflaton field which slowly rolls in an exponentially flat potential.
- After inflation is completed, the singlet enters the regime $s(x) \ll M/\xi_s$ where it is canonically normalised, its potential is no longer flat. The singlet assumes the role of the dark matter with the mass

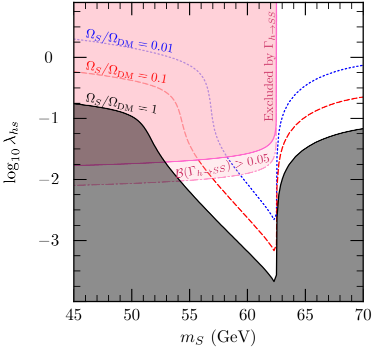
$$m_s^2 \,=\, \frac{\lambda_{hs}}{2}\, v^2 \,+\, \frac{\lambda_{\phi ss}}{2}\, |\langle\phi\rangle|^2$$

Dark Matter exclusion contours on the λ_{hs}, m_s plane

J. M. Cline, K. Kainulainen, P. Scott and C. Weniger, 1306.4710



Plot is over a wide mass range
45 GeV $\leq m_s \leq 5$ TeV.



Close-up on the region $m_s \lesssim m_h/2$.

The dark-shaded lower region is ruled out by the upper bound on the singlet DM relic density, $\Omega_S/\Omega_{\rm DM} \leq 1$. The region in the upper-left corner is ruled out by constraints on invisible Higgs decays.

Summary

1. Motivation
2. Model building based on classical scale invariance
3. Higgs-sector phenomenology
4. Stabilisation of the Higgs potential
5. Matter-anti-matter asymmetry
6. Inflation
7. Dark Matter

The End