# Elementary Goldstone Higgs and Dark Matter

Tommi Alanne

University of Jyväskylä

November 25, 2014

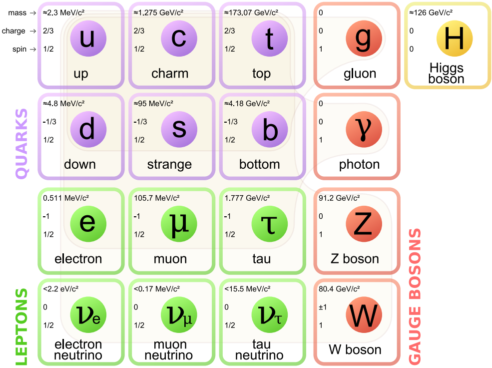
In collaboration with H. Gertov, F. Sannino, and K. Tuominen
[arXiv: 1411.6132]

# Outline

# I

# Introduction

# The Standard Model




[Figure from Wikipedia]

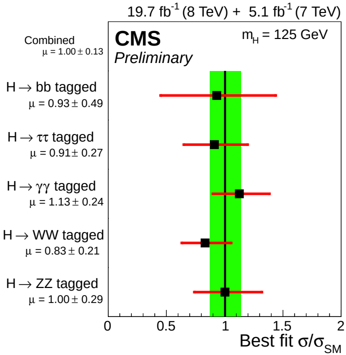
- The Standard Model is a huge success story
- Describes three of the four known forces
- Includes the observed matter particles
- The discovery of the Higgs completed the picture

# Symmetries

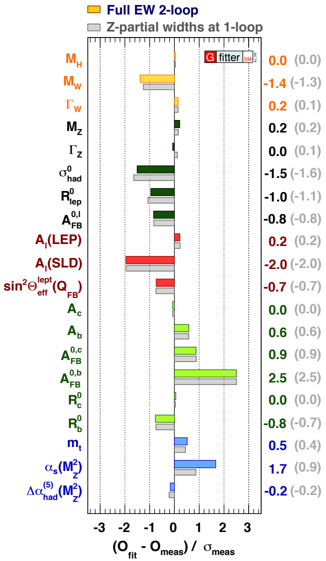
- The SM is based on different local symmetries
  - The forces are described by underlying gauge symmetries
  - The gauge group group is the semi-simple $\mathrm{SU}(3)_\mathrm{c} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y$
- The Higgs sector exhibits even a larger global symmetry
  - The custodial chiral symmetry $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R}$
  - This ensures $\rho \approx 1$ in the SM
  - At tree level in the SM $\quad \rho = \dfrac{m_W^2}{m_Z^2 \cos^2 \theta_\mathrm{W}} = 1$

# Experimental verifications

- The SM is in excellent agreement with collider experiments

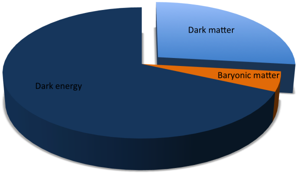



[Figure from CMS-PAS-HIG-14-009]




[Figure from Gfitter]

# Need to go beyond: Observations




- The SM only explains about 5% of the energy budget of the Universe (*Planck Collaboration 2013*)
- About 27% is dark matter (DM)
- The rest is dark energy

- We observe almost only matter and not antimatter
- Neutrino oscillations ⇒ At least two of them must be massive

# Hints beyond: Theory

- Hierarchy and naturalness problems
  - If the SM is the full story, it should be valid up to the Planck scale, $1.22 \cdot 10^{19}$ GeV
  - Why is the electroweak symmetry breaking happening so much below, at $v_w = 246$ GeV
  - If Higgs is an elementary scalar, why is it so light?
- Fermion masses and their hierarchy are only modelled, not explained

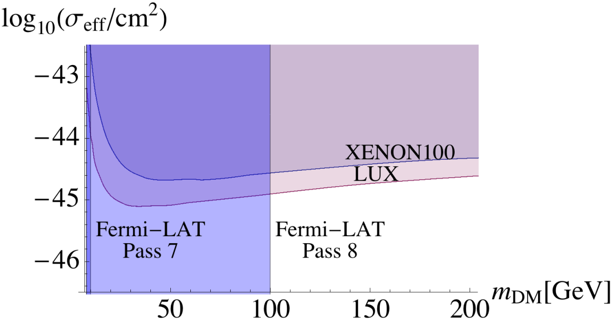
# Unbearable lightness of being

- Hierarchy problem could be solved by introducing new sector of strong dynamics
  - Perfect example: QCD
  - The Higgs mass is light compared to the natural scale $4\pi v_w$
  - Cannot produce fermion masses without further extensions
- Invoke some new symmetry protecting Higgs mass
  - SUSY is the time-honored example along this line
  - Requires a large amount of new, still unobserved, particles
  - A low-scale SUSY breaking would introduce a new hierarchy problem

# DM and baryogenesis

- One possibility to include DM is to extend the SM with a hidden sector that communicates with the SM only via the Higgs
- The simplest scenario: one additional singlet scalar
  - If stable, this additional scalar can produce the observed dark matter relic abundance
  - Baryogenesis can be obtained from this kind of singlet sector as well
  - Both DM and baryogenesis cannot have the same origin in the simplest singlet extensions (*Alanne et al. 2014*, [1407.0688])

# DM observation bounds




- The experiments set tight limits on the DM scenarios

- **Direct observations:** The most stringent bounds from the LUX
  - Try to observe the scattering of DM on SM nuclei
- **Indirect observations:** Fermi-LAT satellite studies $\gamma$-ray spectrum of dwarf satellite galaxies of the Milky Way for DM annihilations
  - The preliminary results push the exclusion limit of the traditional DM scenarios (model dependent) to almost 100 GeV (*Anderson* 2014)

# II

# The Model

# Extended global symmetry

- The observed Higgs is light
  - Some symmetry protecting the scalar mass?
  - Higgs a Goldstone boson of a larger global symmetry?
- Minimal breaking pattern $\mathrm{SO}(5) \to \mathrm{SO}(4)$
- If want to explain also DM, then minimal is $\mathrm{SU}(4) \to \mathrm{Sp}(4)$
  - $\mathrm{SO}(n)$ generators satisfy $TE + ET^T = 0$, where $E$ symmetric
  - $\mathrm{Sp}(n)$ generators satisfy $TE + ET^T = 0$, where $E$ antisymmetric

# Scalar sector

- Composite-Higgs scenario of $SU(4) \to Sp(4)$ breaking already studied (*Cacciapaglia & Sannino 2014*)
- Here, we treat the degrees of freedom as **elementary** scalars and study a linearly realized Lagrangian
  - The renormalizability has new phenomenological consequences compared to the composite-Higgs case
- The DoF's of the linear realization can be assembled into a $4 \times 4$ matrix $M$
  - $M = \left[ \frac{\sigma + \mathrm{i}\Theta}{2} + \sqrt{2}(\mathrm{i}\Pi_i + \tilde{\Pi}_i)X^i \right] E$
  - $M$ transforms as a six-dimensional antisymmetric representation of $SU(4)$
  - $\Pi$'s are the Goldstone bosons
  - Breaking occurs when $\langle M \rangle = \frac{v}{2} E$.

# The SU(4)-symmetric potential

- We write the most general *renormalizable* SU(4)-symmetric potential for $M$

$$
\begin{aligned}
V_M = & \frac{1}{2} m_M^2 \mathrm{Tr}[M^\dagger M] + (c_M \mathrm{Pf}(M) + \mathrm{h.c.}) \\
& + \frac{\lambda}{4} \mathrm{Tr}[M^\dagger M]^2 + \lambda_1 \mathrm{Tr}[M^\dagger M M^\dagger M] - 2 \left( \lambda_2 \mathrm{Pf}(M)^2 + \mathrm{h.c.} \right) \\
& + 4\lambda_3 \mathrm{Pf}(M)\mathrm{Pf}(M^\dagger) + \left( \frac{\lambda_4}{2} \mathrm{Tr}[M^\dagger M] \mathrm{Pf}(M) + \mathrm{h.c.} \right)
\end{aligned}
$$

  - For antisymmetric matrix $\mathrm{Pf}(M)^2 = \det(M)$
- Choose the couplings such that the tree-level potential is stable

# Tree-level ground state and spectrum

- We find a minimum

$$\langle \sigma^2 + \Pi^2 \rangle = \frac{c_M - m_M^2}{\lambda + \lambda_1 - \lambda_2 + \lambda_3 - \lambda_4}, \quad \langle \Theta^2 \rangle = \langle \tilde{\Pi}^2 \rangle = 0,$$

  and choose the parameters such that this is a global one

- Due to the SU(4) symmetry, we can choose that only $\sigma$ gets a vev
  - The vacuum is then aligned in the $E$ direction and the $\Pi$ fields are really the Goldstone bosons
- For simplicity, set the tree-level masses of all the massive scalars equal to $M_S$
  - In this limit the relevant effective quartic scalar coupling is $\tilde{\lambda} = \lambda + 4\lambda_1 - 2\lambda_3$

# Electroweak gauge sector

- Embed the custodial symmetry group of the SM $\mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}}$ into $\mathrm{SU}(4)$
  - Gauge the EW symmetry by introducing covariant derivative to $M$
- There are vacua that leave EW intact ($E_{\mathrm{GB}}$) and those that break EW completely ($E_H$)
- We study a superposition of these vacua $E = \cos\theta E_{\mathrm{GB}} + \sin\theta E_H$ where the vacuum angle $\theta$ is *a priori* a free parameter
- As $M$ acquires vev, the EW bosons get masses

$$m_{\mathrm{W}}^2 = \frac{1}{4} g^2 v^2 \sin^2\theta, \text{ and } m_{\mathrm{Z}}^2 = \frac{1}{4}(g^2 + g'^2) v^2 \sin^2\theta$$

# Standard Model fermions

- Since we have elementary scalars, we can give the Standard Model fermions masses without invoking further dynamics
- For the quantum vacuum analysis, the top quark is the dominant
- We add Yukawa term

$$\mathcal{L}_{\text{Yuk}} = y_t (Q t^c)^\dagger_\alpha \text{Tr}[P_\alpha M] + \text{h.c.}$$

  - The projectors $P_\alpha$ pick the components of $M$ transforming as $\text{SU}(2)_\text{L}$ doublet
  - Similarly, we add interactions for other SM fermions
- The top gets mass as $M$ acquires vev, $m_t = \frac{y_t}{\sqrt{2}} v \sin\theta$

# Explicit SU(4) breaking

- There are several renormalizable terms that break the SU(4) symmetry
- We want the remaining GB $\Pi_5$ to be a DM candidate
  - Add small SU(4)-breaking mass for DM candidate $\Pi_5$

$$V_{\text{br}} = \frac{1}{2}\mu_M^2 \left[ (\Pi_5)^2 + (\tilde{\Pi}_5)^2 \right], \qquad \mu_M \ll v$$

- This breaking is minimal
  - It preserves the discrete $Z_2$ symmetry within the original SU(4) symmetry under which $\Pi_5 \to -\Pi_5$ and $\tilde{\Pi}_5 \to -\tilde{\Pi}_5$
  - Leads to a stable DM candidate

# One-loop potential

- We then calculate the one-loop potential
  - $V^{(1)}(\Phi) = \frac{1}{64\pi^2}\mathrm{Str}\left[M^4(\Phi)\left(\log\frac{M^2(\Phi)}{\mu_0^2} - C\right)\right]$
- The electroweak and top sectors break the global $\mathrm{SU}(4)$ symmetry at one-loop level
  - Picks a preferred value for the vacuum angle $\theta$
  - Gives mass to the pseudo-Goldstone boson $\Pi_4$
  - Mixing between $\sigma$ and $\Pi_4$

III

# Results

# The setting

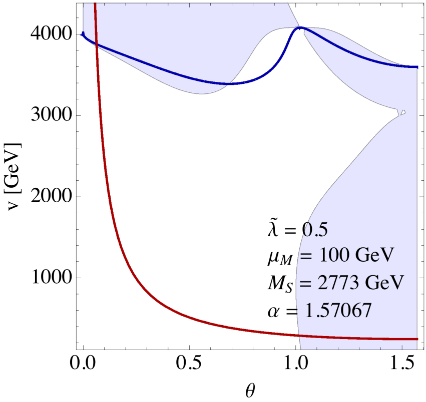
- Study the limit where all the massive scalars have equal tree-level mass, $M_S$
  - Free parameters of the model are $M_S, \tilde{\lambda}, v, \theta$ and $\mu_M$
- The $\sigma$ and $\Pi_4$ states mix
  - Denote the mass eigenstates by $h$ and $H$
  - Then $\sigma$ and $\Pi_4$ can be written as

$$\begin{pmatrix} \sigma \\ \Pi_4 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

  - Identify the lightest eigenstate, $h$, with the observed 125 GeV scalar

# Vacuum

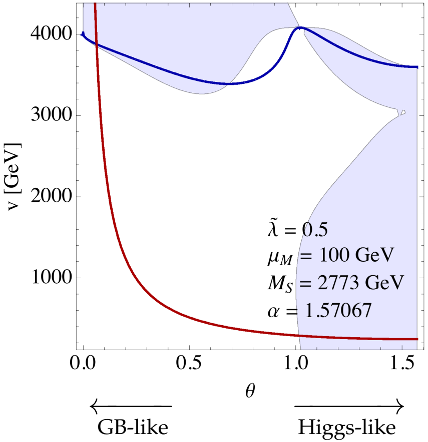
- Pick solutions that give observed EW spectrum




- Red curve gives the correct EW spectrum
- Blue curve gives extremum with respect to the vacuum angle
- On blue regions this extremum is a minimum
- At the intersection of the curves $m_h = 125$ GeV

# Spectrum

- The top correction dominates over the EW gauge contributions preferring small values of the angle $\theta$




- Fixing the renormalization scale brings the $\theta$ dependence on the scalar sector as well $\Rightarrow$ A small nonzero value of the vacuum angle is preferred
- The 125 GeV Higgs boson is mostly $\Pi_4$, i.e. pseudo-Goldstone boson

# Collider limits

- The difference compared with the SM couplings for the gauge and fermion sectors can be parameterized by two coefficients,

$$c_V = \frac{g_{hVV}}{g_{hVV}^{\text{SM}}} = \sin(\theta + \alpha) \quad \text{and} \quad c_f = \frac{y_{hff}}{y_{hff}^{\text{SM}}} = \sin(\theta + \alpha).$$

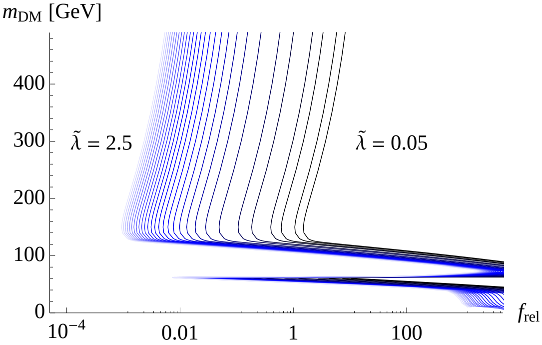
- Even for very large values $\tilde{\lambda} \leq 10$ these differ from the SM values less than 3%.
  - Current bounds from the CMS experiment are (*CMS Collaboration 2014*)

$$c_V = 1.01^{+0.07}_{-0.07}, \quad \text{and} \quad c_f = 0.89^{+0.14}_{-0.13},$$

  - Good agreement with these
- The trilinear Higgs coupling is highly suppressed
  - An interesting probe for future collider experiments

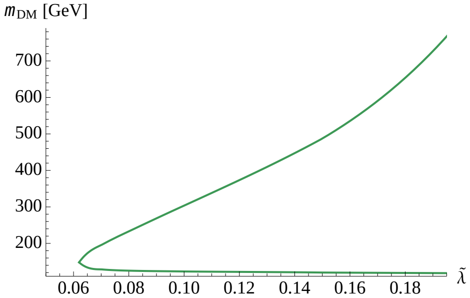
# pGB Dark Matter

- The fifth pseudo-Goldstone boson is a DM candidate
- It gets mass from the small SU(4) breaking
- Compute its relic density




- $f_{\rm rel}$ is the fraction of the total observed amount of dark matter abundance
- Different curves correspond to different effective couplings $\tilde{\lambda}$

# pGB Dark Matter

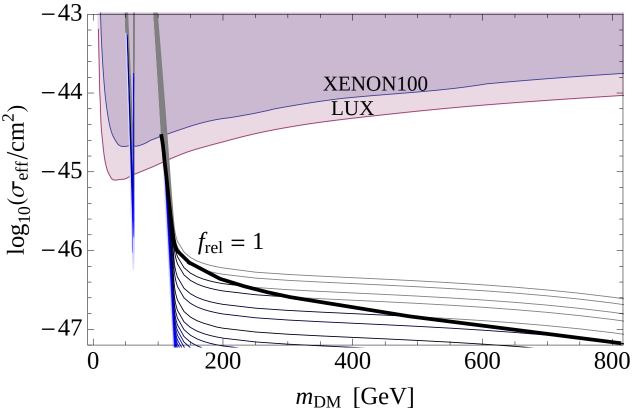



- The $f_{rel} = 1$ contour in $(\tilde{\lambda}, m_{DM})$ plane

- For the mass range $m_{DM} \gtrsim m_h$ we find solutions that produce the full observed DM relic abundance

# DM observation bounds

- Compare with the direct observation limits from LUX and XENON100
- On the mass range $m_{DM} \gtrsim m_h$, we pass the stringent LUX limits




- This mass range is in agreement with the Fermi-LAT results as well

# Conclusion

- We extend the SM scalar sector to a model with global $\mathrm{SU}(4)$ symmetry
  - Want both the Higgs and the DM particles to be pGB's associated with the spontaneous breaking $\mathrm{SU}(4) \to \mathrm{Sp}(4)$
- The (top-)Yukawa and electroweak sectors break $\mathrm{SU}(4)$
  - This determines the vacuum structure at one-loop level
  - Results in a pGB-like Higgs
- Also DM candidate is a pGB
- Possibility to explain the observed amount of DM without conflicting the DM observation bounds

# Outlook

- More scalar degrees of freedom compared to the SM case
  - Already simple hidden sectors can improve the vacuum stability of the SM (*Alanne et al. 2014*, [1407.0688])
  - Is it possible to solve the meta-stability problem of the SM vacuum?
- The SU(4)-symmetric potential allows for complex couplings
  - A new source for $CP$-violation
  - Would it be possible to explain the matter-antimatter asymmetry?