Title: Conformal Standard Model

Date: Apr 23, 2014 02:00 PM

URL: http://pirsa.org/14040061

Abstract: I will describe a proposal of an enlargement of the Standard Model based on a softly broken conformal symmetry. It contains the usual particles of the SM with right-chiral neutrinos and predicts two new particles: a scalar mixing with the usual Higgs and a naturally weakly coupled axion. I will argue that the Planck scale should be treated as a real physical scale and discuss the hierarchy problem and renormalization from this point of view. I will show that the model does not need any intermediate scales and can be viable up to the Planck scale (in distiction to the Standard Model). I will present experimental predictions of the model.

Conformal Standard Model

Krzysztof A. Meissner
University of Warsaw

Perimeter Institute, 23.04.2014

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K.A.M., H. Nicolai, Phys.Lett. B648 (2007) 312

assumptions:

- SM enlarged as little as possible

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- spontaneous symmetry breaking of local $SU(2) \times U(1)$ and global lepton symmetry
- the model viable to M_P without any new scales between M_W and M_P
- "non-gravitational" problems solved:
  hierarchy problem,
  strong CP problem,
  Cold Dark Matter candidate

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- a new complex scalar necessary
- its real part mixes with the usual Higgs (2 mass eigenstates)
- its phase – axion – (pseudo)GB solving strong CP problem and CDM candidate
- there exists a range of parameters satisfying all the assumptions (not the case for pure SM)

Hierarchy Problem

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  (with UV cutoff Λ = scale of 'new physics' in our case $\Lambda \sim M_P$)
- Most popular proposal:
  SM $\longrightarrow$ (p,C,N...)MSSM

Hierarchy Problem

P.H. Chankowski, A. Lewandowski, K.A.M., H. Nicolai, arXiv: 1404.0548[hep-ph]

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$$\lambda_B(\lambda_R, \Lambda) = \lambda_R + \sum_{L=1}^{\infty} \sum_{\ell=1}^{L} a_{L\ell} \lambda_R^{L+1} \left(\ln \frac{\Lambda^2}{\mu^2} \right)^{\ell},$$

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Hierarchy Problem

- for dimensionful parameters

$$m_B^2(\lambda_R, m_R, \Lambda) = m_R^2 - \hat{f}^{\text{quad}}(\mu, \lambda_R, \Lambda)\,\Lambda^2 + m_R^2 \sum_{L=1}^{\infty} \sum_{\ell=1}^{L} c_{L\ell}\, \lambda_R^L \left(\ln \frac{\Lambda^2}{\mu^2} \right)^{\ell} .$$

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- it is crucial that

$$\hat{f}^{\rm quad}(\mu, \lambda_R, \Lambda) \equiv f^{\rm quad}(\lambda_B(\mu, \lambda_R, \Lambda)) = f^{\rm quad}(\lambda_B).$$

is a function of bare parameters only

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  – no Landau poles or instabilities for $\mu_{EW} \leq \mu \leq M_P$

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SBCS class

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  – constraints on the parameters at M_P

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- in SUSY $f_i^{\text{quad}}(\lambda_B) = 0$ identically at all scales but $m_B \ll \Lambda$ has to be imposed separately
- in theories without scalars (like QED or QCD) there are no quadratic divergences so they belong to SBCS if there are no Landau poles

Conformal Standard Model

- Conformally invariant $\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}'$:

$$
\begin{aligned}
\mathcal{L}' \;:=\;& \mathrm{SM} + \left(\bar{L}^i \epsilon H^* Y^{\nu}_{ij} \nu^j_R + \varphi \nu^{iT}_R \mathcal{C} Y^M_{ij} \nu^j_R + \mathrm{h.c.} \right) \\
& - \frac{\lambda_1}{4}(H^\dagger H)^2 - \frac{\lambda_2}{2}|\varphi|^2 (H^\dagger H) - \frac{\lambda_3}{4}|\varphi|^4 \\
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- $Y^M_{ij} \sim O(1)$, $Y^{\nu}_{ij} \sim O(10^{-6})$ (see-saw)

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- particle content:
  Standard Model with very light neutrinos
  + heavy neutrinos ($\sim$ 1 TeV))
  + complex new scalar

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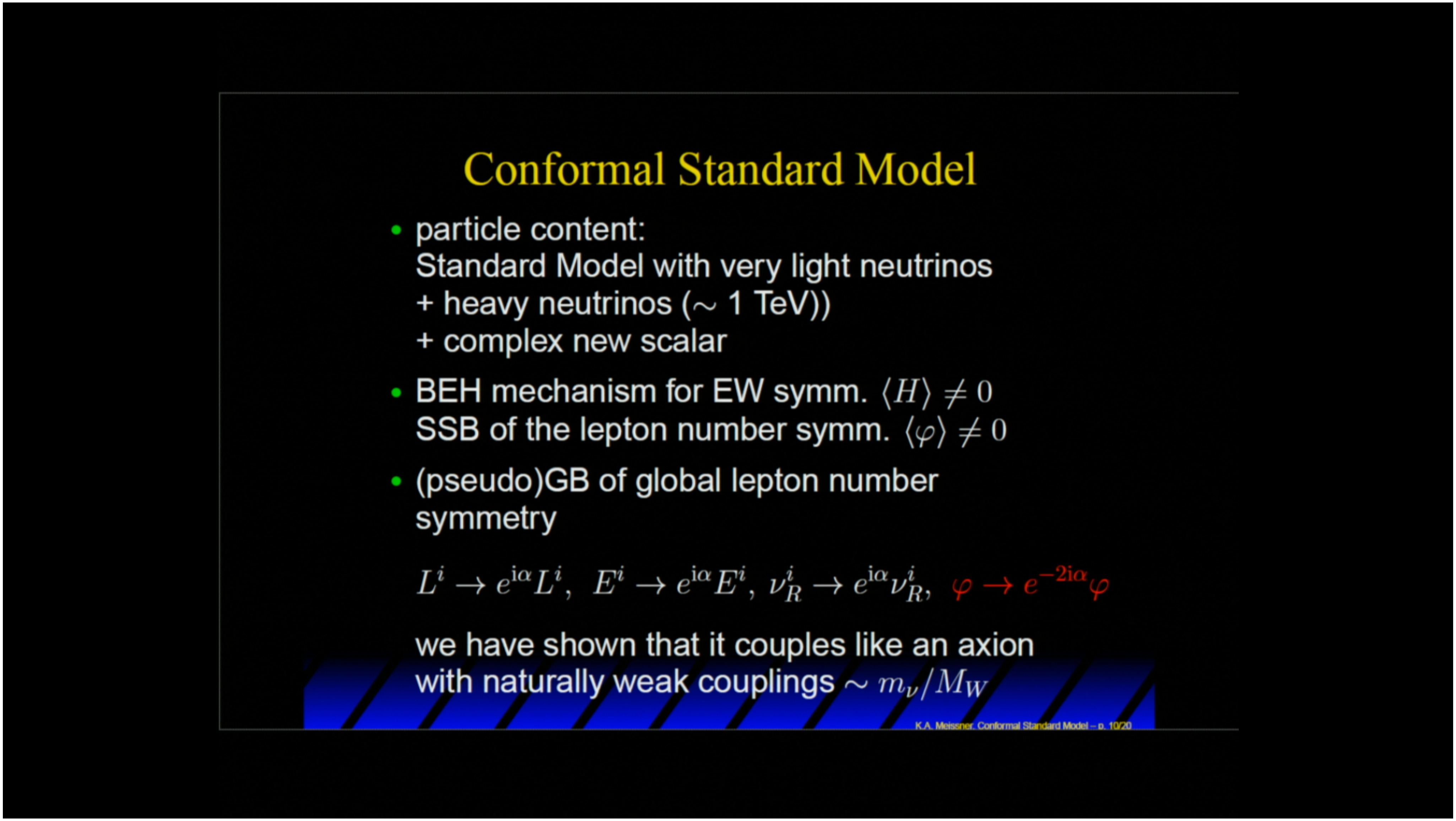
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BEH mechanism for EW symm. $\langle H \rangle \neq 0$
SSB of the lepton number symm. $\langle \varphi \rangle \neq 0$
(pseudo)GB of global lepton number symmetry
$L^i \to e^{i\alpha} L^i, \; E^i \to e^{i\alpha} E^i, \; \nu_R^i \to e^{i\alpha} \nu_R^i, \; \varphi \to e^{-2i\alpha} \varphi$
we have shown that it couples like an axion
with naturally weak couplings $\sim m_\nu / M_W$
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Conformal Standard Model

- in CSM we assume vanishing of quadratic divergences at Λ

$$f_1^{\text{quad}}(\lambda, g, y) = 6\lambda_1 + 2\lambda_3 + \frac{9}{4}g_w^2 + \frac{3}{4}g_y^2 - 6y_t^2 = 0$$

$$f_2^{\text{quad}}(\lambda, g, y) = 4\lambda_2 + 4\lambda_3 - \sum_i y_{N_i}^2 = 0.$$

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- At the minimum the mass eigenstates consist of the mixed Higgs and the new scalar:

$$\begin{pmatrix} h^0 \\ \varphi^0 \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \sqrt{2}\,\mathrm{Re}(H_2 - \langle H_2 \rangle) \\ \sqrt{2}\,\mathrm{Re}(\phi - \langle \phi \rangle) \end{pmatrix}$$

with masses M_h and M_φ. There is also a CP-odd axion $a^0 = \sqrt{2}\,\mathrm{Im}\phi$.

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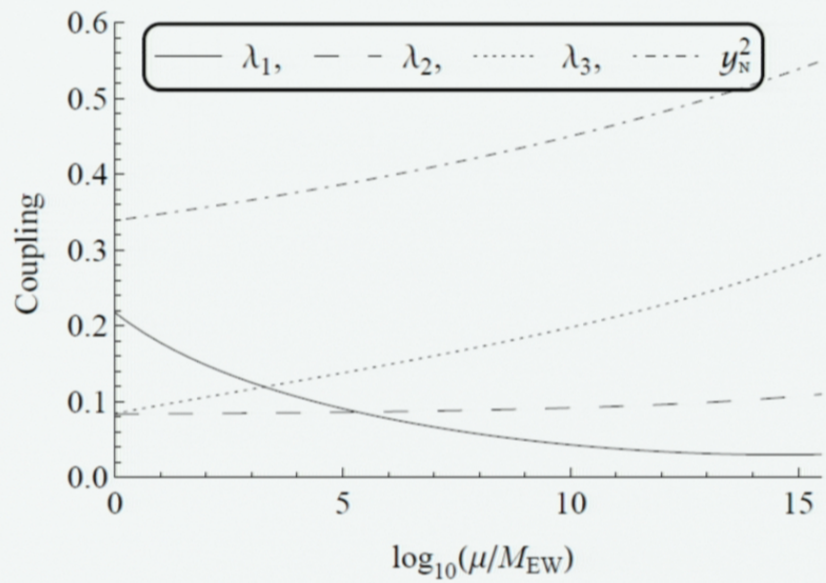
- we impose the conditions:
  – $m_{h^0} = 125$ GeV and $\langle H_2 \rangle = 246$ GeV
  – all couplings remain small and positive between μ_{EW} and M_P

Running coupling constants



LHC phenomenology

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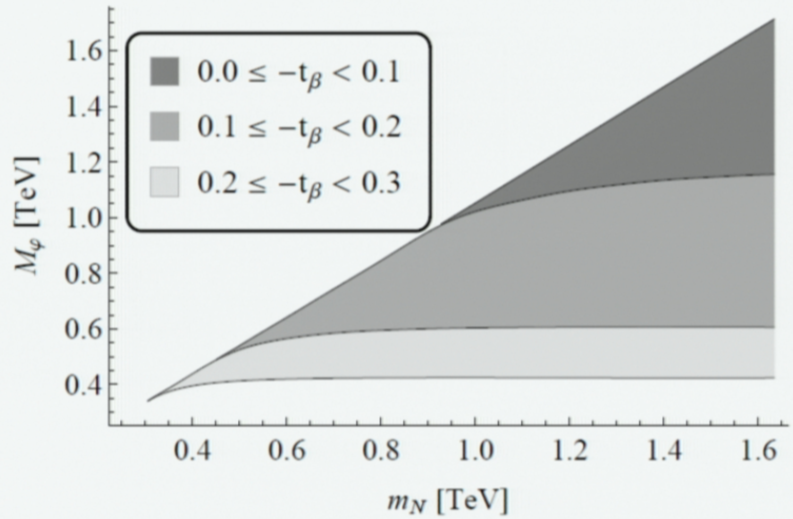
- the width of the new scalar:

$$\Gamma_{\varphi^0} = \Gamma_{SM}\sin^2\beta + \delta\Gamma_{\varphi^0\to 2,3h^0} + \delta\Gamma_{\varphi^0\to 2a} + \delta\Gamma_{\varphi^0\to 2\nu_R}$$

Predicted scalar and heavy neutrino masses



Axion

K.A.M., H. Nicolai, Eur.Phys.J.C57:493,2008

- axion: phase of the new scalar ϕ
  GB of SB lepton number symmetry

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$$\approx \frac{\alpha_w \alpha m_\nu}{8\pi^2 M_W^2}\, a\, \vec{E}\cdot\vec{B} \approx 10^{-15}\ \mathrm{GeV}^{-1}\, a\, \vec{E}\cdot\vec{B}$$

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- In the presence of magnetic field B we have a direct conversion $a \leftrightarrow \gamma$ with amplitude $B g_{a\gamma\gamma}$
- present experiments give

$$g_{a\gamma\gamma} < 10^{-10}\ \mathrm{GeV}^{-1}$$

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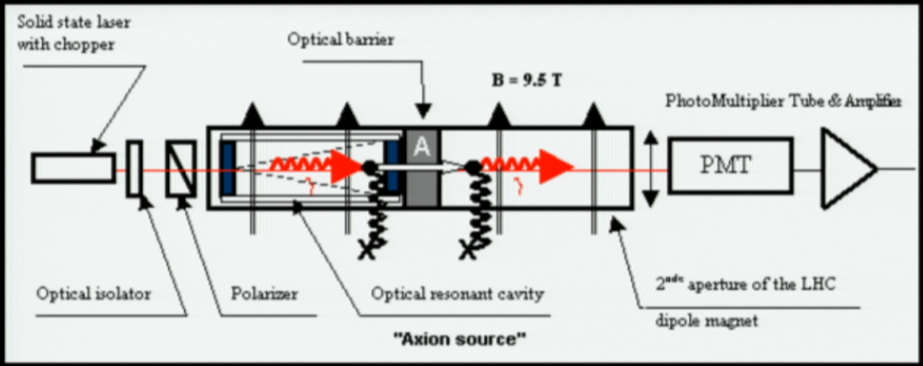
Experiment OSQAR (CERN)

"shining through the wall" – two strings of magnets separated by a wall (that axions can penetrate) – photon reemerges on the other side



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Axion-gluon coupling

- calculable (3-loops), finite and very small solution of the strong CP problem

$$L \approx -\frac{1}{2}\partial_\mu a \partial^\mu a + \frac{\alpha_s a(x)}{4\pi f_a}\,\varepsilon^{\mu\nu\rho\sigma}\,\mathrm{Tr}\,G_{\mu\nu}\,G_{\rho\sigma}$$

f_a in CSM $\sim M_W^2/(m_\nu \alpha_w^2)$ i.e. $\sim 10^{16}$ GeV
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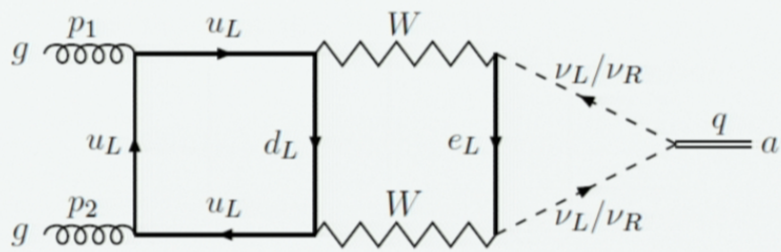
Axion coupling to gluons



the diagram is finite!

A. Latosiński, K.A.M., H. Nicolai, Nucl. Phys. B 868 (2012) 596-626, arXiv:1203.3886

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  f_a in CSM $\sim M_W^2/(m_\nu \alpha_w^2)$ i.e. $\sim 10^{16}$ GeV (very large since neutrinos very light)

- the effective potential has minimum at $a = 0$ and axion mass:

$$m_a \approx f_a^{-1} \Lambda_{QCD}^2 \approx 10^{-8}\mathrm{eV}$$

- a very good candidate for CDM

Summary

- CSM satisfies SBCS (SM doesn't), solves problems of SM (hierarchy, strong CP, CDM) and can be viable up to M_P

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- it has definite (unique) predictions for LHC – 2 mass eigenstates (mixed Higgs + new scalar), heavy neutrinos $\sim$ 1 TeV
- all cross sections and decay rates calculable and therefore the theory is falsifiable by LHC
- necessary part of CSM: light and naturally weakly coupled axion – CDM candidate