# Conformal Standard Model

*Krzysztof A. Meissner*
*University of Warsaw*
*AEI Potsdam*

HermannFest, AEI, 6.09.2012

# Hierarchy Problem

- Standard Model is conformally invariant except for the tree level Higgs mass term
  $-m^2\Phi^\dagger\Phi$

# Hierarchy Problem

- Standard Model is conformally invariant except for the tree level Higgs mass term
  $-m^2\Phi^\dagger\Phi$
- Quantum corrections $m^2 \sim \Lambda^2 \Rightarrow$
  why $m \ll M_P$?
  (with UV cutoff $\Lambda$ = scale of ‘new physics’)

# Hierarchy Problem

- Standard Model is conformally invariant except for the tree level Higgs mass term
  $-m^2\Phi^\dagger\Phi$
- Quantum corrections $m^2 \sim \Lambda^2 \Rightarrow$
  why $m \ll M_P$?
  (with UV cutoff $\Lambda$ = scale of 'new physics')
- Most popular proposal: SM $\longrightarrow$ (N)MSSM
  (but LHC does not seem to pointedly like it...)

# Hierarchy Problem

- Standard Model is conformally invariant except for the tree level Higgs mass term
  $-m^2\Phi^\dagger\Phi$
- Quantum corrections $m^2 \sim \Lambda^2 \Rightarrow$
  why $m \ll M_P$?
  (with UV cutoff $\Lambda$ = scale of 'new physics')
- Most popular proposal: SM $\longrightarrow$ (N)MSSM
  (but LHC does not seem to pointedly like it...)
- conformal symmetry also solves the HP:
  only 2 new parameters (MSSM 116)
  built-in breaking (conf. anomaly, Coleman-Weinberg)

# Conformal Standard Model – assumptions

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

- Classical conformal symmetry in SM, all masses from conformal anomaly

# Conformal Standard Model – assumptions

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

- Classical conformal symmetry in SM, all masses from conformal anomaly
- see-saw mechanism for neutrinos

# Conformal Standard Model – assumptions

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

- Classical conformal symmetry in SM, all masses from conformal anomaly
- see-saw mechanism for neutrinos
- the model viable up to $M_{Pl}$, no GUTs, no new scales, no low energy SUSY

# Conformal Standard Model – assumptions

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

- Classical conformal symmetry in SM, all masses from conformal anomaly
- see-saw mechanism for neutrinos
- the model viable up to $M_{Pl}$, no GUTs, no new scales, no low energy SUSY
- classical conformal symmetry $\Rightarrow$ Ward Ids $\Rightarrow$ all corrections logarithmic (Bardeen)

*K.A.M, H. Nicolai, Phys. Lett. B660 (2008) 260*

# Nonconformal $\rightarrow$ conformal?

- we expect at $M_{Pl}$ a non-conformal theory
  is it possible to get at low energies
  a (classically) conformal FT + gravity?

# Nonconformal $\rightarrow$ conformal?

- we expect at $M_{Pl}$ a non-conformal theory
  is it possible to get at low energies
  a (classically) conformal FT + gravity?
- example:
  gauged $N = 4$ supergravity with $\kappa \rightarrow 0$
  $\Rightarrow$ supergravity + conformal $N = 4$ SYM

*K.A.M., H. Nicolai, Phys.Rev. D80:086005,2009*

# The Model

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

$$\mathcal{L}' := \Big( \bar{L}^i \Phi Y^E_{ij} E^j + \bar{Q}^i \epsilon \Phi^* Y^D_{ij} D^j + \bar{Q}^i \epsilon \Phi^* Y^U_{ij} U^j + \\ + \bar{L}^i \epsilon \Phi^* Y^\nu_{ij} \nu^j_R + \varphi \nu^{iT}_R \mathcal{C} Y^M_{ij} \nu^j_R + \text{h.c.} \Big) \\ - \frac{\lambda_1}{4} (\Phi^\dagger \Phi)^2 - \frac{\lambda_2}{2} |\varphi|^2 (\Phi^\dagger \Phi) - \frac{\lambda_3}{4} |\varphi|^4$$

# The Model

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

$$\mathcal{L}' \;:=\; \Big(\bar{L}^i \Phi Y^E_{ij} E^j + \bar{Q}^i \epsilon \Phi^* Y^D_{ij} D^j + \bar{Q}^i \epsilon \Phi^* Y^U_{ij} U^j + \\ + \bar{L}^i \epsilon \Phi^* Y^\nu_{ij} \nu^j_R + \varphi \nu^{iT}_R \mathcal{C} Y^M_{ij} \nu^j_R + \text{h.c.}\Big) \\ - \frac{\lambda_1}{4}(\Phi^\dagger \Phi)^2 - \frac{\lambda_2}{2}|\varphi|^2(\Phi^\dagger\Phi) - \frac{\lambda_3}{4}|\varphi|^4$$

- $Y^M_{ij} \sim O(1)$, $Y^\nu_{ij} \sim O(10^{-6})$ (see-saw)

# The Model

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

$$\mathcal{L}' := \Big( \bar{L}^i \Phi Y^E_{ij} E^j + \bar{Q}^i \epsilon \Phi^* Y^D_{ij} D^j + \bar{Q}^i \epsilon \Phi^* Y^U_{ij} U^j + $$
$$+ \bar{L}^i \epsilon \Phi^* Y^\nu_{ij} \nu^j_R + \varphi \nu^{iT}_R \mathcal{C} Y^M_{ij} \nu^j_R + \text{h.c.} \Big)$$
$$- \frac{\lambda_1}{4} (\Phi^\dagger \Phi)^2 - \frac{\lambda_2}{2} |\varphi|^2 (\Phi^\dagger \Phi) - \frac{\lambda_3}{4} |\varphi|^4$$

- $Y^M_{ij} \sim O(1)$, $Y^\nu_{ij} \sim O(10^{-6})$ (see-saw)
- new (complex) scalar necessary!

# The Model

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

# The Model

- Standard Model + very light neutrinos
  + heavy neutrinos ($\sim$ 1 TeV))
  + complex new scalar
- Calculation of the CW effective action
  – numerical analysis (no 2 loops...)

# The Model

- Standard Model + very light neutrinos
  + heavy neutrinos ($\sim$ 1 TeV))
  + complex new scalar
- Calculation of the CW effective action
  – numerical analysis (no 2 loops...)
- BEH mechanism for EW symm. $\langle\Phi\rangle \neq 0$
  SSB of the lepton number symm. $\langle\varphi\rangle \neq 0$

# The Model

- Standard Model + very light neutrinos
  + heavy neutrinos ($\sim$ 1 TeV))
  + complex new scalar
- Calculation of the CW effective action
  – numerical analysis (no 2 loops...)
- BEH mechanism for EW symm. $\langle \Phi \rangle \neq 0$
  SSB of the lepton number symm. $\langle \varphi \rangle \neq 0$
- axion – (pseudo)GB of global lepton number symmetry

$$L^i \to e^{\mathrm{i}\alpha} L^i, \;\; E^i \to e^{\mathrm{i}\alpha} E^i, \; \nu_R^i \to e^{\mathrm{i}\alpha} \nu_R^i, \;\; \varphi \to e^{-2\mathrm{i}\alpha} \varphi$$

# Results

- At the minimum Higgs and the new scalar mix

$$H' = H\cos\beta + \phi\sin\theta, \qquad \phi' = -H\sin\beta + \phi\cos\theta$$

of masses $M_1$ and $M_2$.

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

# Results

- At the minimum Higgs and the new scalar mix

$$H' = H\cos\beta + \phi\sin\theta, \qquad \phi' = -H\sin\beta + \phi\cos\theta$$

of masses $M_1$ and $M_2$.

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

- propagator

$$\frac{\mathrm{i}\cos^2\theta}{p^2 - M_1^2 + \mathrm{i}M_1\Gamma_{SM}(M_1)\cos^2\theta} + \left\{ \begin{array}{c} \cos\theta \to \sin\theta \\ M_1 \to M_2 \end{array} \right\}$$

in cross section there should be two “bumps”:
heights as for Higgs
widths smaller by $\cos^2(\sin^2)\theta$

# Phenomenology

- no other new particles at LHC except standard Higgs and new scalar

# Phenomenology

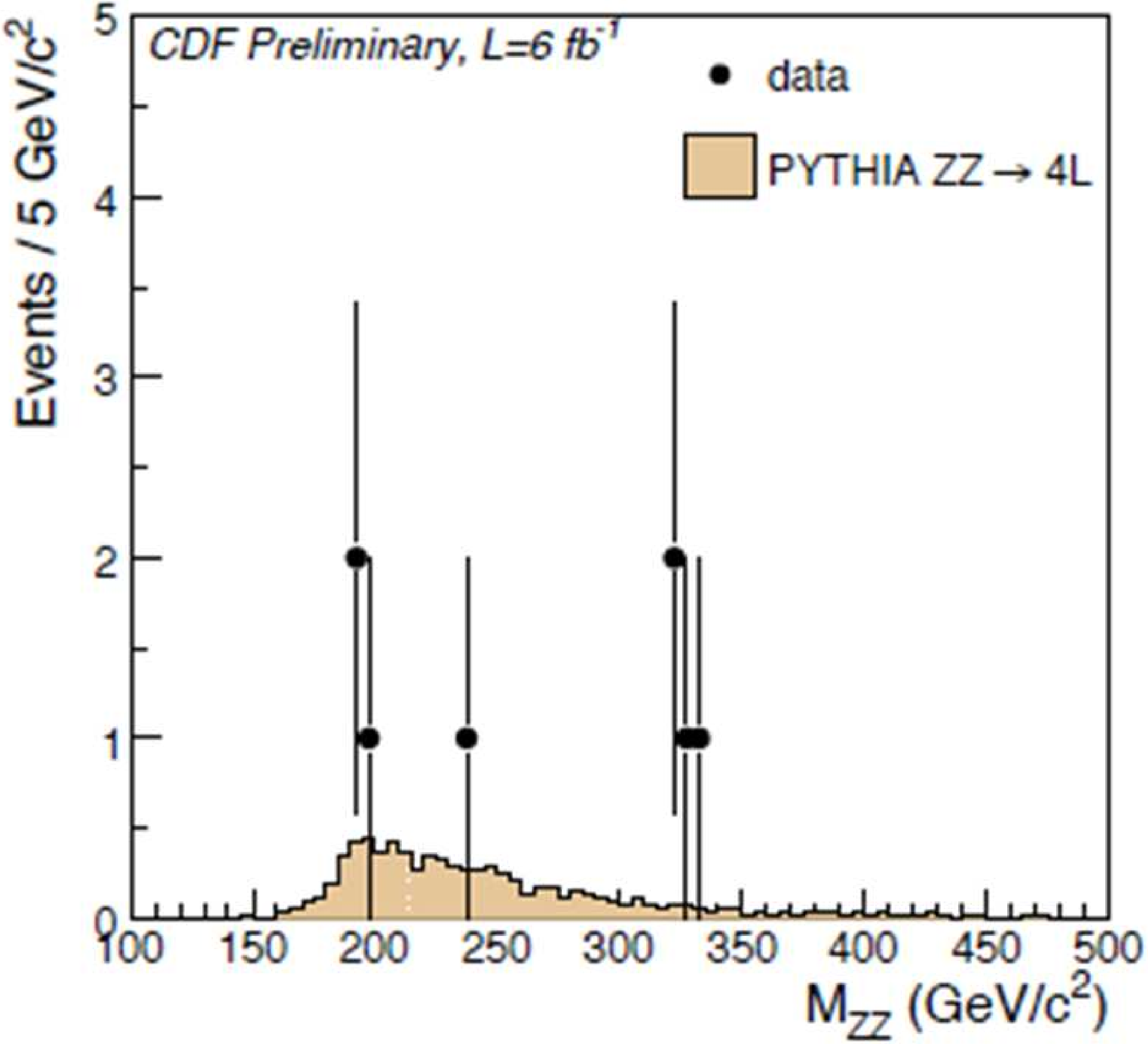
- no other new particles at LHC except standard Higgs and new scalar
- LHC has announced the mass 125 GeV ($M_1$?)

# Phenomenology

- no other new particles at LHC except standard Higgs and new scalar
- LHC has announced the mass 125 GeV ($M_1$?)
- CDF has seen a $5\sigma$ excess of events
  $2Z \to l^+ l^- l^+ l^-$
  at the same invariant mass 325 GeV
  we conjecture that it is a narrow resonance corresponding to $\phi'$ ($M_2 = 325$ GeV?)

*K.A.M., H. Nicolai, arXiv:1208.5653[hep-ph]*

# CDF 4 lepton cases



# Axion

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

- axion: phase of the new scalar $\phi$
  Goldstone boson of spontaneously broken lepton number symmetry

# Axion

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

- axion: phase of the new scalar $\phi$
  Goldstone boson of spontaneously broken lepton number symmetry
- the $a\gamma\gamma$ coupling is calculable and very small (because of small neutrino masses!)

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

# Axion

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

- axion: phase of the new scalar $\phi$
  Goldstone boson of spontaneously broken lepton number symmetry
- the $a\gamma\gamma$ coupling is calculable and very small (because of small neutrino masses!)

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

- $agg$ coupling (calculable)
  non-local, for small momenta $\sim$ anomaly
  $\Rightarrow$ solution of the strong $CP$ problem

# Axion

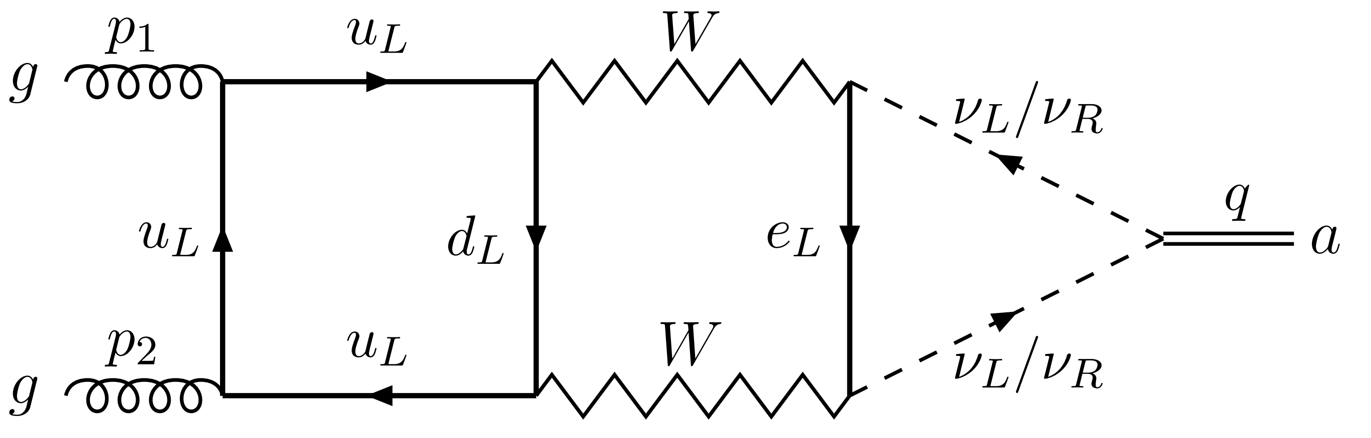
*K.A.M., H. Nicolai, Eur.Phys.J.C57:493,2008*

- axion: phase of the new scalar $\phi$
  Goldstone boson of spontaneously broken lepton number symmetry
- the $a\gamma\gamma$ coupling is calculable and very small (because of small neutrino masses!)

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

- $agg$ coupling (calculable)
  non-local, for small momenta $\sim$ anomaly
  $\Rightarrow$ solution of the strong $CP$ problem
- a very good candidate for CDM

# Axion coupling to gluons




*A. Latosiński, K.A.M., H. Nicolai, arXiv:1203.3886 [hep-ph]*

# Summary

- assumption of classical CS solves problems of SM (hierarchy, strong $CP$,...)

# Summary

- assumption of classical CS solves problems of SM (hierarchy, strong $CP$,...)
- the model has 1 more parameter than SM (MSSM 116) and uses quantum symmetry breaking (conformal anomaly)

# Summary

- assumption of classical CS solves problems of SM (hierarchy, strong $CP$,...)
- the model has 1 more parameter than SM (MSSM 116) and uses quantum symmetry breaking (conformal anomaly)
- it has a definite (unique) prediction for LHC – 2 scalars with SM Higgs cross sections scaled by $\cos^2(\sin^2)\theta$, no other particles

# Summary

- assumption of classical CS solves problems of SM (hierarchy, strong $CP$,...)
- the model has 1 more parameter than SM (MSSM 116) and uses quantum symmetry breaking (conformal anomaly)
- it has a definite (unique) prediction for LHC – 2 scalars with SM Higgs cross sections scaled by $\cos^2(\sin^2)\theta$, no other particles
- there is an extremely light and weakly coupled particle (axion)

# Summary

- assumption of classical CS solves problems of SM (hierarchy, strong $CP$,...)
- the model has 1 more parameter than SM (MSSM 116) and uses quantum symmetry breaking (conformal anomaly)
- it has a definite (unique) prediction for LHC – 2 scalars with SM Higgs cross sections scaled by $\cos^2(\sin^2)\theta$, no other particles
- there is an extremely light and weakly coupled particle (axion)
- if true the CSM is a theory descending directly from the Planck scale

*HAPPY BIRTHDAY!*