Brout-Englert-Higgs boson and the boundaries of naturalness domain of the Standard Model

Victor T. Kim

Petersburg nuclear physics institute
NRC «Kurchatov institute»

Outline:

- **Brout-Englert-Higgs boson mass evolution and naturalness crirteria**
- **Naturalness domain boundaries for the Standard Model**
- **Summary**

Running masses in the standard model

Running couplings: α_{QCD}, α_{EW}

Heavy quark (B-quark) running masses

Different mass parameterizations
(different approaches to include higher orders):
- pole (on-shell) mass
- running mass

SM running masses
- fermions and vector bosons: logarithmic
- scalar Brout-Englert-Higgs boson: logarithmic
or/and quadratic ?
quadratic -> "non-naturalness"

Standard Model with 125 GeV BEH-boson

Brout-Englert-Higgs boson:
if only logarithmic mass evolution

Brout-Englert-Higgs boson defines electroweak vacuum density
(meta)stable vacuum up to Planck scales

F. Bezrukov, M. Kalmykov, B. Kiehl & M. Shaposhnikov, JHEP 10 (2012) 140

within MSbar-scheme

One may conclude:
(Almost) no need for a New Physics up to Planck scales
Only needs:
- (~ 1 GeV) BSM neutral leptons to explain Dark Matter
- strong CP-problem
- neutrino masses
- baryon-antibaryon asymmetry

...
- and still explain why there is naturalness (New Physics?!)

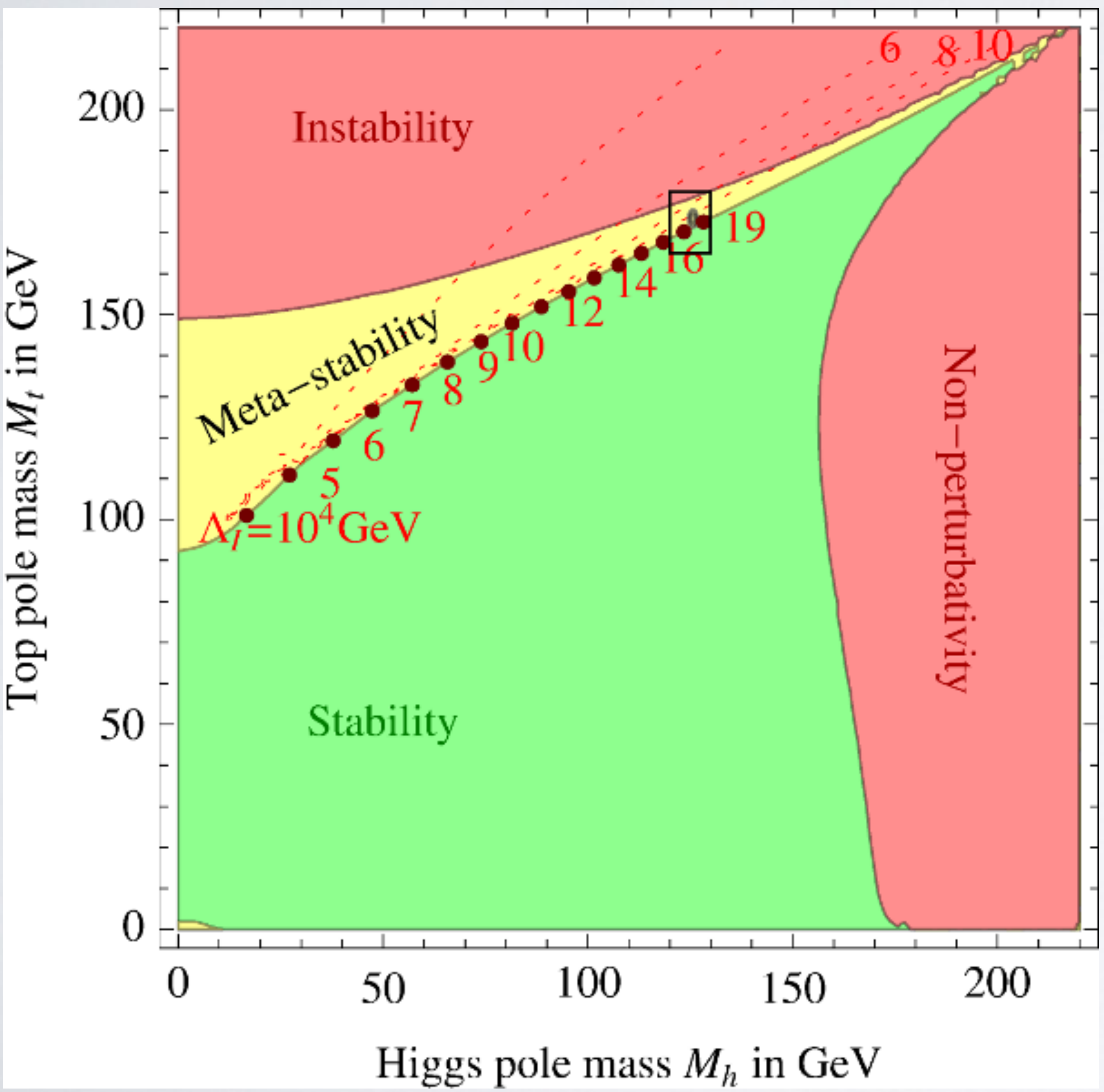
Standard Model with 125 GeV Higgs boson

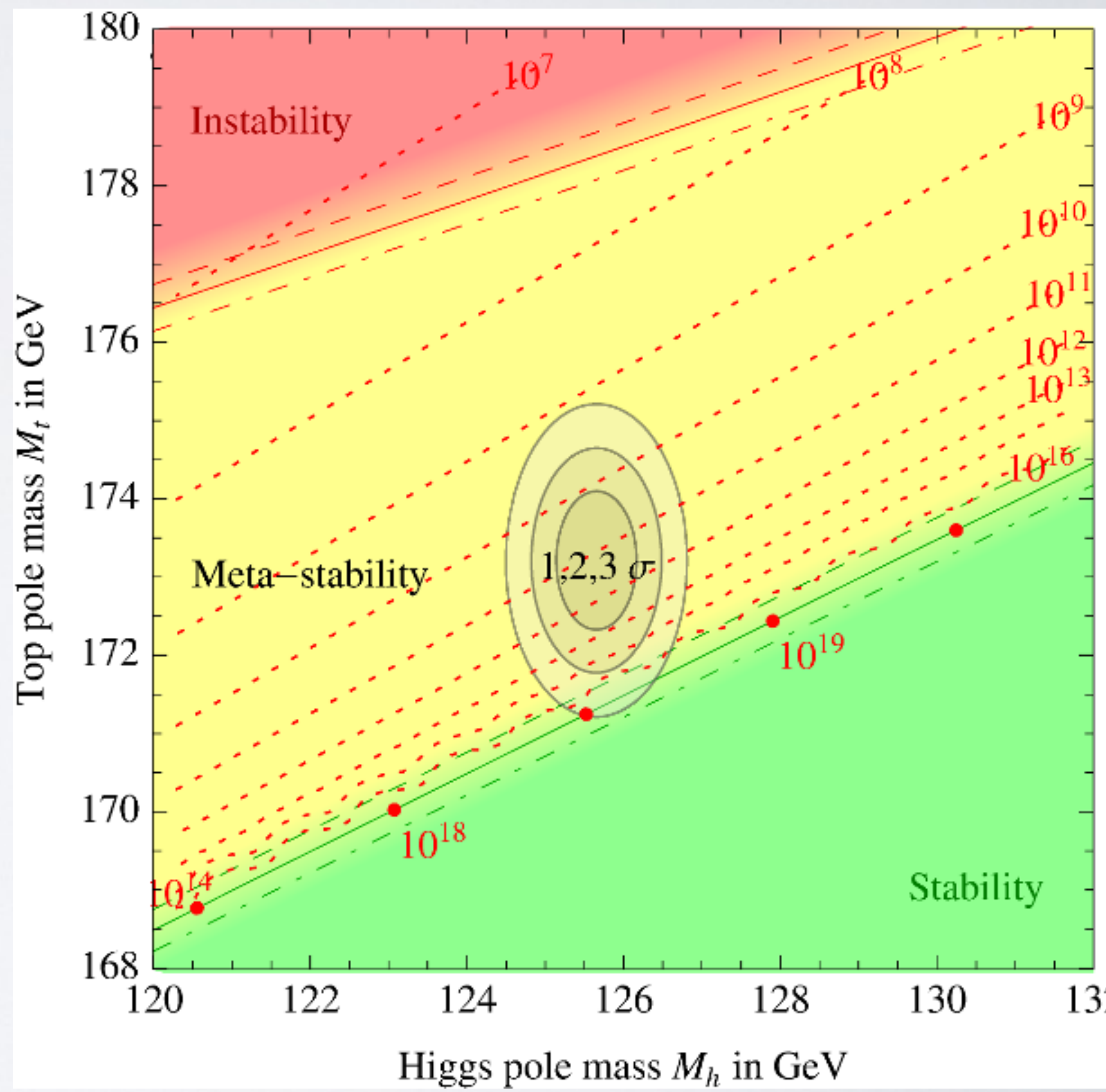
Brout-Englert-Higgs boson mass defines electroweak vacuum density: meta-stable vacuum

G. Degrassi et al., JHEP 08 (2012) 098

D. Butazzo et al., JHEP 12 (2013) 089

A. Bednyakov et al., Phys. Rev. Lett. 115 (2015) 201802





(Non-)Naturalness of the standard model

Logarithmic evolution of theory parameters: weak dependence between low and very large scales -> concept of "Naturalness"

- **Scalar field is simple, but "non-natural": scalar mass evolution is quadratic, not logarithmic**

  K. Wilson, Phys. Rev. D3 (1971) 1818
  L. Susskind, Phys. Rev. D20 (1979) 2619

- **Scalar field is not protected by a symmetry, while fermions are protected by chiral symmetry**

  G. 't Hooft, Proc. Cargese Summer Inst. (1980)

for reviews see, e.g., G. Giudice, (2008)

Standard Model: Higgs boson roles

- provide mass to SM particles by
  Brout-Englert-Higgs mechanism

- restore unitarity for EW vector boson scattering:
  Brout-Englert-Higgs boson cancels quadratic growth of longitudinal components for EW vector bosons with collision energy

- if Higgs could be very light -> no noticeable growth with collision energy

- if Higgs could be very heavy ->
  strong growth of EW vector boson interaction ->
  New SM dynamics: nonpertubative strong EW interaction can lead to heavy EW resonances

Naturalness criteria of the Standard Model

M. Veltman, Acta Phys. Pol. B12 (1981) 437

$$m_H^2 = m_{H0}^2 + \delta m_H^2$$

$$\delta m_H^2 \approx \frac{\Lambda^2}{16\pi^2}\left(24y_t^2 - 6(2y_W^2 + y_Z^2 + y_H^2)\right) \sim 8.2\frac{\Lambda^2}{16\pi^2}$$

$$y_i \equiv \frac{m_i}{v} \qquad v = 246\,\mathrm{GeV}$$

Veltman's criterion:

$$\left|\frac{m^2 - m_0^2}{m_0^2}\right| = \left|\frac{\Delta m^2}{m_0^2}\right| \leq q = 1$$

Non-naturalness of BEH boson at Λ > 550 GeV:

$$\delta m_H^2 \approx m_H^2 \qquad (\Lambda = 550\,\mathrm{GeV},\ m_H = 125\,\mathrm{GeV})$$

Derivative criterion:

$$\left|\frac{\lambda_0}{m^2}\frac{\partial m^2}{\partial \lambda_0}\right| \leq q \simeq 10$$

R. Barbieri, G.F. Giudice, Nucl. Phys. B306 (1988) 63
J.R.Ellis,K.Enquist,D.V.Nanopoulos,F.Zwirner, Mod.Phys.Lett. A1(1986)57

Standard Model: Higgs boson mass evolution

M. Veltman, Acta Phys. Pol. B12 (1981) 437

quadratic mass divergences within MSbar renormalization:

Dim = 4 – 2/L

$m_R^2 = m_B^2 + \xi \Lambda^2$,

where $\xi = \xi(mH, mt, mW, mZ)$

Veltman's condition for absence of quadratic mass divergences:

$$\xi(mH, mt, mW, mZ) = 0$$

Veltman condition holds up to 2-loops:

but in higher orders it cannot be hold in self-consistent way

M.S. Al-sarhi, I. Jack, D.R.T. Jones, Zeit fur Physik Pol. C55 (1992) 283

Veltman condition and Higgs effective potential

M.B. Einhorn, D.R.T. Jones, Phys. Rev. D42 (1992) 5206

Naturalness of the Standard Model

Quantifying Naturalness

Naturalness criterion:

weak sensitivity physical parameters for small variation of bare ones

J.R.Ellis, K.Enquist, D.V.Nanopoulos, F.Zwirner, Mod.Phys.Lett. A1(1986)57

R. Barbieri, G.F. Giudice, Nucl. Phys. B306 (1988) 63

Using BG condition with both quadratic and logarithmic contributions leads to extension of Naturalness domain of SM: up ~ O(10 TeV) instead of ~ O (1 TeV)

V.K., G. Pivovarov, Phys. Rev. D78 (2008) 016001

V.K., Phys. Part. Nucl. 55 (2024) 156

Regular way for scalar boson mass evolution with quadratic mass divergences

G. Pivovarov, Phys. Rev. D81 (2010) 076077

K. Fujikawa, Int. Mod. Phys. A (2016)

Naturalness Criterion

$$m_0^2 = m^2 - \xi(\lambda, g)\Lambda^2$$

$$\lambda_0 = \lambda + \frac{\beta(\lambda, g)}{2} \log\left(\frac{\Lambda^2}{m^2}\right)$$

Logarithmic sensitivity

Transformation matrix

RG mixing -> matrix non-degeneracy -> matrix

V.K., G. Pivovarov, Phys. Rev. D78 (2008) 016001

V.K., Phys. Part. Nucl. 55 (2024) 156

$$\begin{pmatrix} m_0^2 \\ \lambda_0 \end{pmatrix} = A \times \begin{pmatrix} m^2 \\ \lambda \end{pmatrix}$$

$$A = \begin{pmatrix} \frac{\partial \lambda}{\partial \lambda_0} & \frac{\partial \lambda}{\partial m_0^2} \\ \frac{\partial m^2}{\partial \lambda_0} & \frac{\partial m^2}{\partial m_0^2} \end{pmatrix}$$

$$A = \frac{1}{\det(A^{-1})} \begin{pmatrix} 1 & \frac{\beta(\lambda,g)}{2m^2} \\ \xi'(\lambda, g)\Lambda^2 & 1 + \frac{\beta'(\lambda,g)}{2} \log\left(\frac{\Lambda^2}{m^2}\right) \end{pmatrix}$$

$$\det(A^{-1}) = 1 - \xi'(\lambda, g)\frac{\beta(\lambda, g)}{2}\frac{\Lambda^2}{m^2} + \frac{\beta'(\lambda, g)}{2} \log\left(\frac{\Lambda^2}{m^2}\right)$$

BEH-boson mass evolution and naturalness criterion

Logarithmic sensitivity
Transformation matrix
RG mixing -> matrix non-degeneracy -> matrix

V.K., G. Pivovarov, Phys. Rev. D78 (2008) 016001
V.K., Phys. Part. Nucl. 55 (2024) 156

$$m_H^2 = m_{H0}^2 + \delta m_H^2$$

$$\delta m_H^2 \approx \frac{\Lambda^2}{16\pi^2}\left(24y_t^2 - 6(2y_W^2 + y_Z^2 + y_H^2)\right) \sim 8.2\frac{\Lambda^2}{16\pi^2} + C\log(\Lambda/m)$$

Non-naturalness from BEH Higgs boson mass at Λ ~ O (10 TeV)

Previously without logs: Λ ~ O (1 TeV)

SM with "non-natural" Higgs boson

Proper physical consideration with quadratic evolution
for Brout-Englert-Higgs boson mass:

Higgs boson observables (mass, self-coupling, EW vacuum density)
gets critical values at later scales
than in popular "standard" naturalness treatments

-> at those scales ~ O(10 TeV) one should expect
new physics manifestations:
- new strong EW dynamics
- or/and New Physics beyond Standard Model

Summary

- The Standard Model without quadratic evolution for Brout-Englert-Higgs boson mass requires (!) New Physics to have Naturalness

- Naturalness domain of the Standard Model with quadratic evolution for Brout-Englert-Higgs boson mass may be larger than generally accepted: up ~ O(10 TeV) instead of ~ O (1 TeV)

- Present LHC physics: new physics is unavoidable either as a new dynamics of SM or/and a New Physics. Besides search direct search of New Physics it requires 'non-naturalness' studies