Higgs Boson and Naturalness Problem in the Standard Model

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Outline:

- Running masses in the standard model (SM)
- Higgs boson mass evolution and naturalness problem
- the standard model: naturalness, hierarchy & fine-tuning and new physics
- Summary

In collaboration with G. Pivovarov (INR RAS, Moscow)

Running masses in the standard model

Running couplings: α_{QCD}, α_{EW}

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

Running masses: parameterization of HO corrections

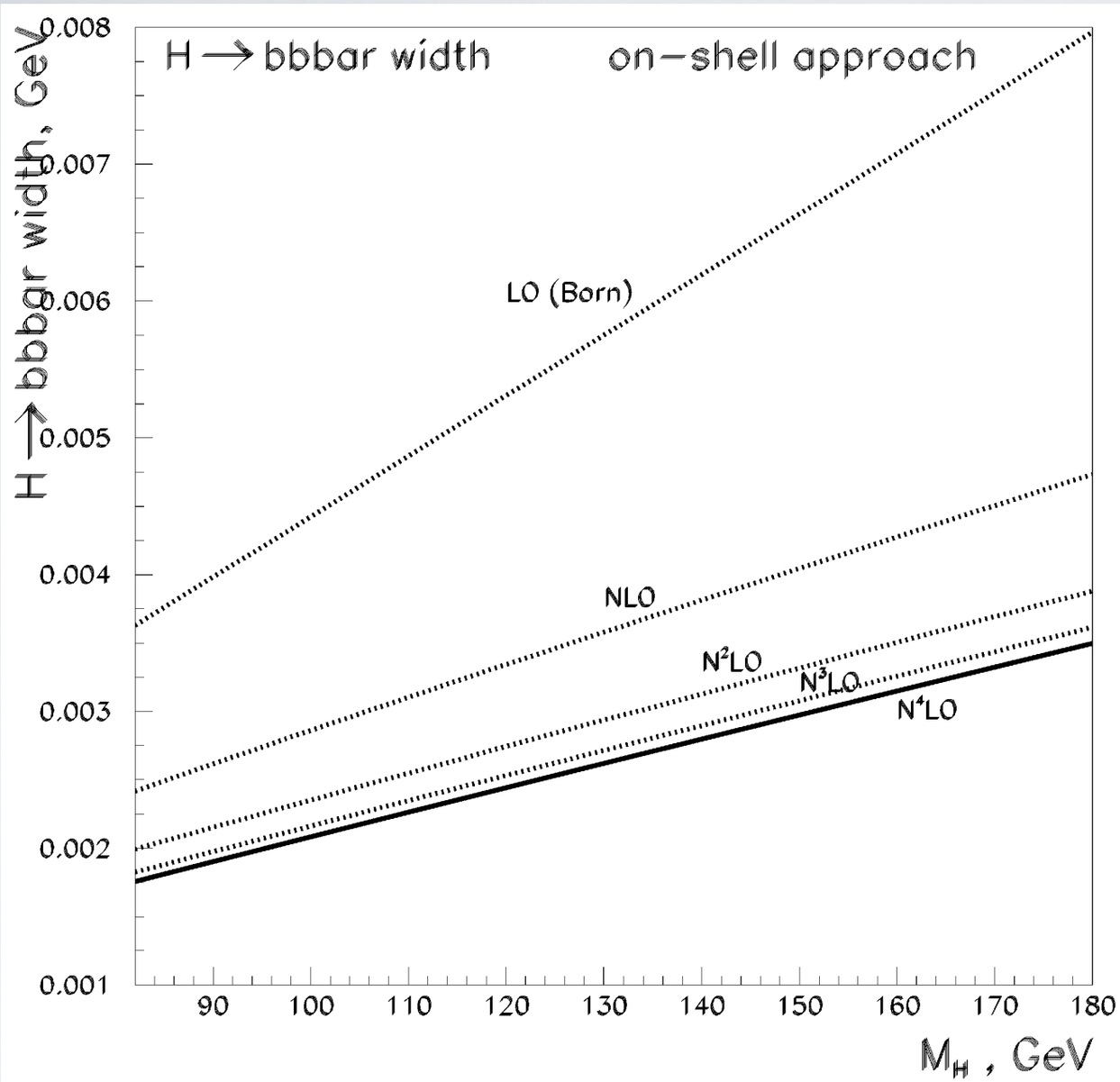
SM running masses
- fermions and vector bosons: logarithmic
- scalar Higgs boson: logarithmic and quadratic?
quadratic -> "non-naturalness"

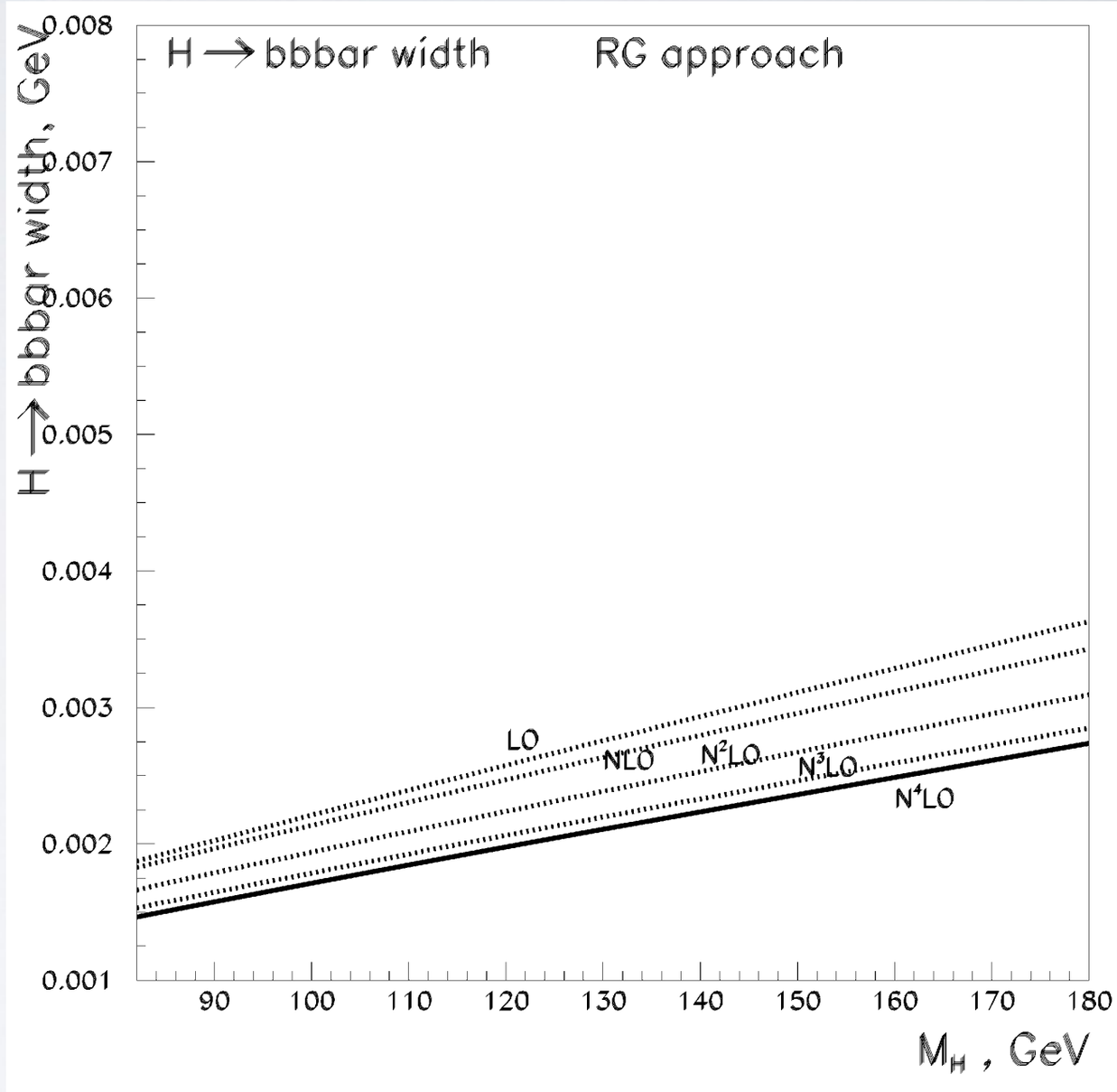
K. Wilson 1971
L. Susskind 1979
't Hooft 1980

Higgs boson decay width

Width of Higgs boson decay into b-quarks (up to N^{4}LO)

P. Baikov, K. Chetyrkin, J. Kuhn (2006)
A. Kataev, V. K. (2008)





Running b-quark mass: ~ 4.5 GeV at Upsilon mass scale
~ 2.8 GeV at Higgs boson mass scale

Higgs boson of the Standard Model

Higgs boson discovery of CMS and ATLAS in 2012 is most important physics result at LHC upto now

ATLAS, Phys. Lett. B 716 (2012) 1
CMS, Phys. Lett. B 716 (2012) 30

Brout-Englert-Higgs-Guralnik-Hagen-Kibble mechanism of spontaneous symmetry breaking

R. Brout, F. Englert, Phys. Rev. Lett. 13 (1964) 321
P.W. Higgs, , Phys. Lett. 12 (1964) 132; Phys. Rev. Lett. 13 (1964) 508
G.S. Guralnik, C.R. Hagen, T.W.B. Kibble, Phys. Rev. Lett. 13 (1964) 585

P. Higgs & F. Englert: Nobel Prize (2013)
CMS and ATLAS: EPS Prize (2013)

Higgs boson is only scalar elementary particle known up to now

Naturalness problem of the Standard Model at 1-loop

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: $|m^2 - m_0^2| < m_0^2$

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

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

Standard Model: Higgs boson mass evolution

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

quadratic mass divergences within MSbar renormalization:

Dim = 4 – 2/L

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

where P = P (mH, mt, mW, mZ)

Veltman condition for absence of quadratic mass divergences:

$$P = 0$$

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 criteria in the Standard Model

$$m^2 = m_0^2 + \Lambda^2 P(\lambda_0, g)$$

$$P(\lambda_0, g) = 3(3g_2^2 + g_1^2 + 2\lambda_0 - 4y_t^2)/(32\pi^2)$$

Veltman's criterion:

$$\Lambda^2 < \frac{m^2}{2P(\lambda, g)}$$

Barbieri-Guidice criterion:

$$\left|\frac{\lambda_0}{m^2}\frac{\partial m^2}{\partial \lambda_0}\right| < q$$

$$\Lambda^2 < q\frac{m^2}{\lambda\big(\partial P(\lambda, g)/\partial\lambda\big)}$$

q ≃ 10

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

Naturalness problem of the Standard Model at 1-loop

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

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

$$A^{-1} \equiv B = \begin{pmatrix} \frac{\partial \lambda_0}{\partial \lambda} & \frac{\partial \lambda_0}{\partial m^2} \\ \frac{\partial m_0^2}{\partial \lambda} & \frac{\partial m_0^2}{\partial m^2} \end{pmatrix}$$

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

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

$$\beta(\lambda, g) = \frac{6}{8\pi^2}(\lambda^2 - \lambda[\frac{1}{4}g_1^2 + \frac{3}{4}g_2^2 - y_t^2] + \frac{1}{16}g_1^4 + \frac{1}{8}g_1^2 g_2^2 + \frac{3}{16}g_2^4 - y_t^4)$$

$$\det(B) = -\frac{\Lambda^2}{m^2} P'(\lambda, g) \frac{\beta(\lambda, g)}{2} + \log(\frac{\Lambda^2}{m^2}) \frac{\beta'(\lambda, g)}{2} + 1$$

$$A = \begin{pmatrix} 0 & 0 \\ -\frac{2m^2}{\beta(\lambda,g)} & 0 \end{pmatrix}$$

$$|\frac{2\lambda}{\beta(\lambda, g)}| < q$$

q ‘ ≃ 2 q ≃ 20

The Standard Model is more ”natural” than one may think

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

Naturalness problem of the Standard Model at 1-loop

$$A = \begin{pmatrix} 0 & 0 \\ -\frac{2m^2}{\beta(\lambda,g)} & 0 \end{pmatrix}$$

$$\beta(\lambda, g) = \frac{6}{8\pi^2}(\lambda^2 - \lambda[\frac{1}{4}g_1^2 + \frac{3}{4}g_2^2 - y_t^2] + \frac{1}{16}g_1^4 + \frac{1}{8}g_1^2 g_2^2 + \frac{3}{16}g_2^4 - y_t^4)$$

$$|\frac{2\lambda}{\beta(\lambda, g)}| < q$$

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

Improved Barbieri-Guidice criterion:

$$\frac{4m_H^2 v^2}{|p(m_H, m_Z, m_W, m_t)|} < \frac{3q}{4\pi^2}$$

q ‘ ≃ 2 q ≃ 20

$$p(m_H, m_Z, m_W, m_t) = m_H^4 + m_H^2(2m_t^2 - m_Z^2 - 2m_W^2) - 4m_t^4 + m_Z^4 + 2m_W^4$$

It leads to extension of Naturalness domain of the SM:
from ~ O (1 TeV) to ~ O(10 TeV)
The Standard Model is more ”natural”
than one may think!

(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 (2008,2013), N. Craig (2022)

(Non-)Naturalness in physics

concept of ”Naturalness”

- **Hierarchy problem:**
  dimensionless parameter significantly differs from unity
  big numbers **P. Dirac**
  cosmological constant

- **Fine-tuning**
  high sensitivity of parameter to different scales

- **Restoration of a symmetry**
  G. ‘t Hooft, Proc. Cargese Summer Inst. (1980)

for reviews see, e.g., G. Giudice (2008,2013), N. Craig (2022)

Standard Model with 125 GeV Higgs boson

Higgs boson: if no quadratic divergences

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

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

SM+heavy sterile leptons: M. Shaposhnikov (2007)
No New Physics ("particle desert") up to Planck scales
Still needs to explain:
- (~ 1 GeV) BSM neutral leptons to explain Dark Matter
- strong CP-problem
- neutrino masses
- baryon-antibaryon asymmetry

...

Quardratic divergence: S. Mooij, M. Shaposhnikov (2021)
an artefact of the standard QFT formulation

Standard Model with 125 GeV Higgs boson

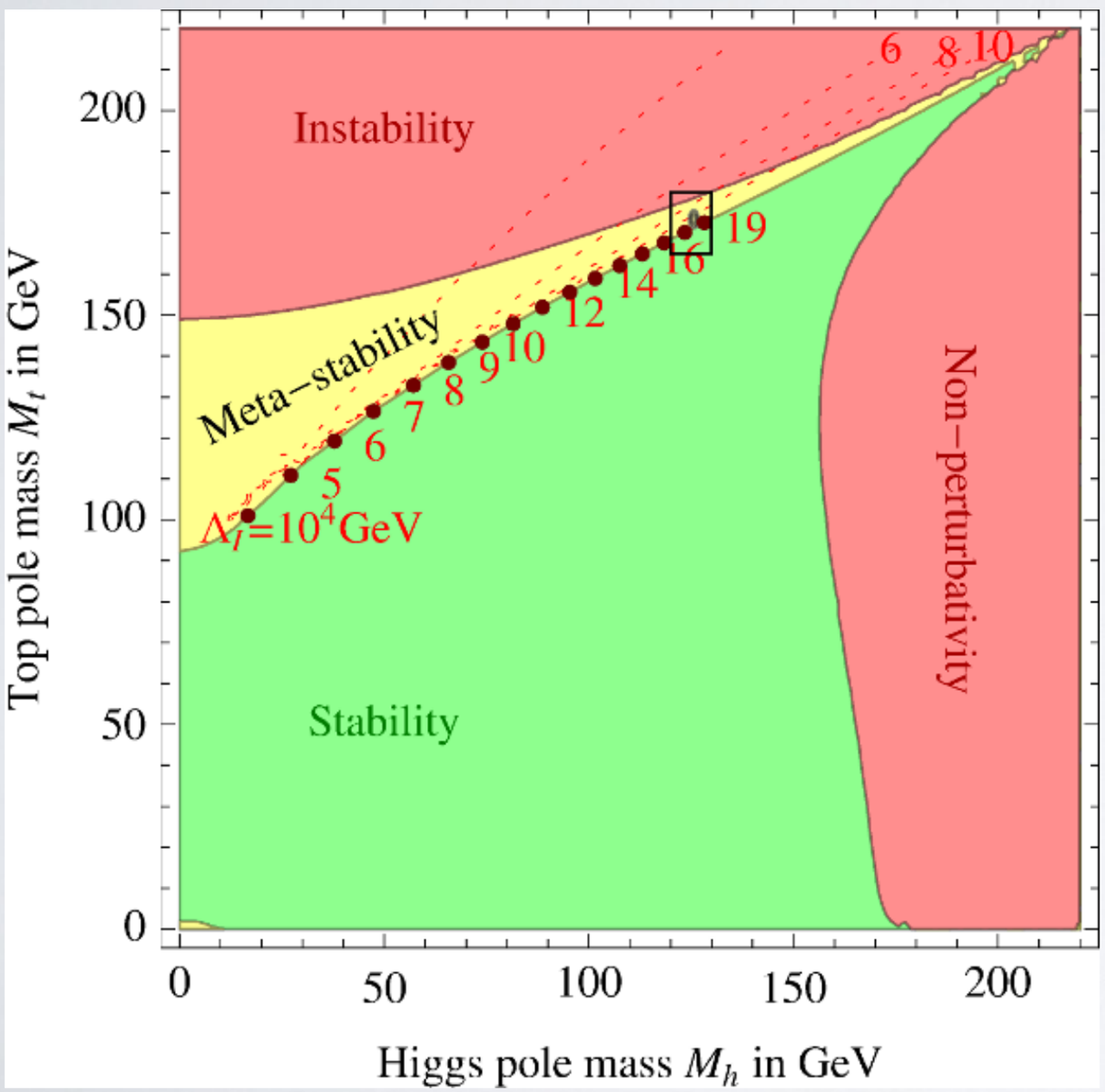
Higgs boson mass defines electroweak vacuum density

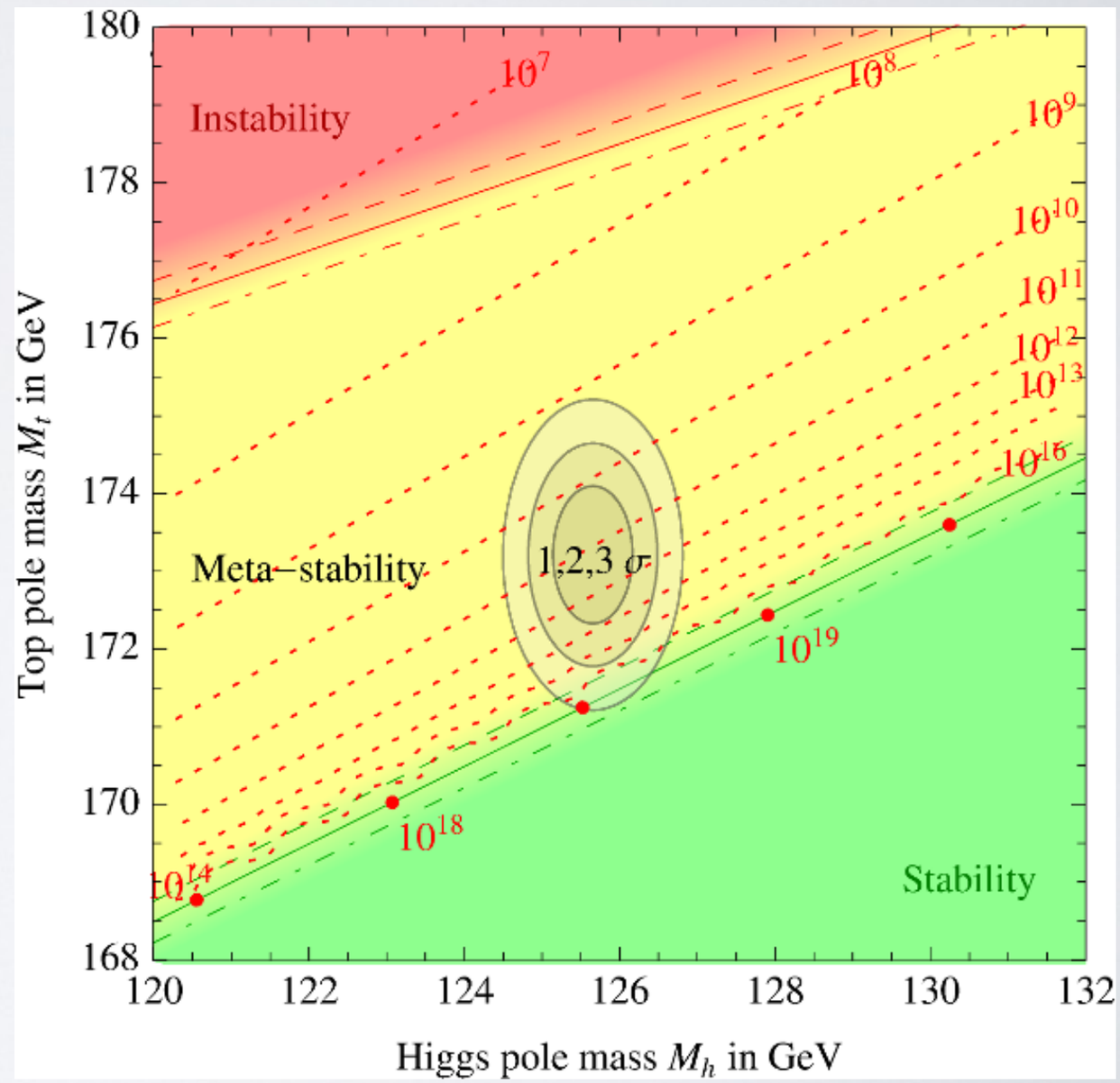
Meta-stable vacuum

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

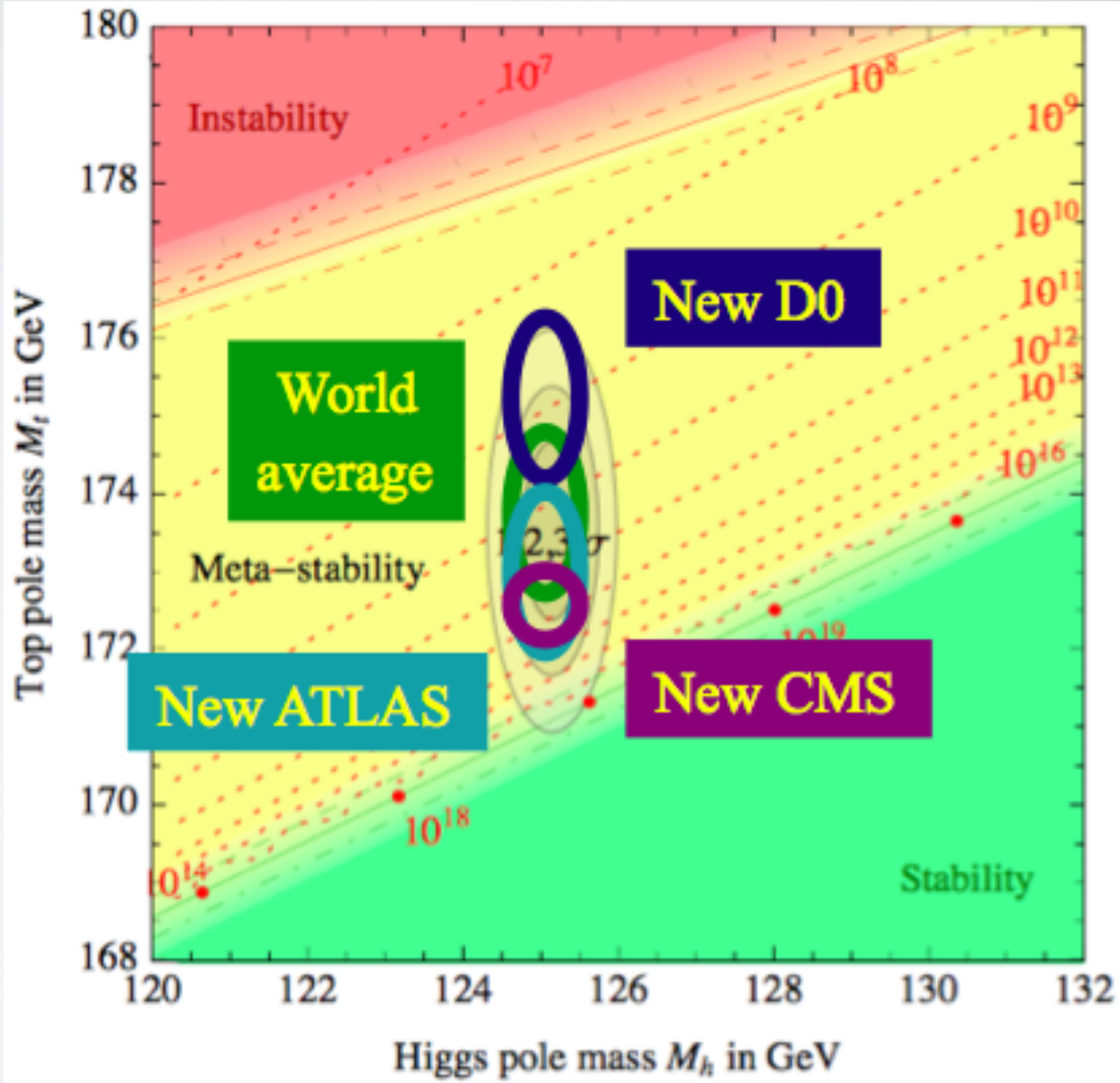




Standard Model vacuum stability vs new LHC data

J. Ellis, arXiv: 1702.05436 (2017)

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



Standard Model: Higgs boson mass evolution

The previously discussed calculations were done within MSbar renormalization: based on popular dimensional regularization (DR)

-> no quadratic mass divergences in "standard" prescription

Also, used as an argument for a necessity of SUSY

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

Physical renormalization: momentum substraction (MOM) scheme

-> there are quadratic mass divergences

Naturalness of Standard Model

Barbieri-Giudice (BG) condition:
sensitivity physical parameters for small variation of bare ones
R. Barbieri, G.F. Giudice, Nucl. Phys. B306 (1988) 63

Using improved BG condition with both quadratic and logarithmic contributions leads to extention of Naturalness domain of SM:
up ~ O(10 TeV) instead of ~ O (1 TeV)
VK, G. Pivovarov, Phys. Rev. D78 (2008) 016001

A regular way for scalar boson mass evolution with quadratic mass divergences
G. Pivovarov, Phys. Rev. D81 (2010) 076077

Landau pole like in λH^4:

$$\lambda(Q) \simeq \frac{\lambda(v)}{1 - \frac{3}{4\pi^2}\lambda(v)\ln\left(Q^2/v^2\right)}$$

Standard Model: Higgs boson roles

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

- restore unitarity for EW vector boson scattering:
  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

SM with “non-natural” Higgs boson

Proper physical consideration with quadratic evolution for Higgs boson mass:

Higgs boson observables (mass, self-coupling, EW vacuum density) gets critical values at much earlier scales than “standard” treatments without quadratic divergences

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

Summary

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

- **Naturalness domain of Standard Model with quadratic evolution for Higgs boson mass may be larger than generally accepted: ~ 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.**

Search for New Physics requires (non-)Naturalness studies