The mass of the Higgs boson

Fa. 7



## LHC: Higgs particle observation





CMS 2011/12



## a prediction...

#### Asymptotic safety of gravity and the Higgs boson mass

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#### Abstract

There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson  $m_H$  can be predicted. For a positive gravity induced anomalous dimension  $A_{\lambda} > 0$  the running of the quartic scalar self interaction  $\lambda$  at scales beyond the Planck mass is determined by a fixed point at zero. This results in  $m_H = m_{\min} = 126$  GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well.

s in  $m_H = m_{\min} = 126$  GeV, with o

## Higgs boson found





## standard model Higgs boson





#### T.Plehn, M.Rauch

## Spontaneous symmetry breaking confirmed at the LHC





## Higgs mechanism verified



**Brout** 

Englert

Higgs



## Spontaneous symmetry breaking

## Physics only describes probabilities





#### Gott würfelt

## Physics only describes probabilities

#### Gott würfelt

#### Gott würfelt nicht



"Es scheint hart, dem Herrgott in die Karten zu gucken. Aber dass er würfelt und sich telepatischer Mittel bedient (wie es ihm von der gegenwärtigen Quantentheorie zugemutet wird), kann ich keinen Augenblick glauben.."

Einstein: Brief an Cornelius Lanczos am 21. März 1942

## Physics only describes probabilities

Gott würfelt

#### Gott würfelt nicht



humans can only deal with probabilities



## Spontaneous symmetry breaking

$$-\mathcal{L}_{\varphi} = \frac{1}{2} \partial^{\mu} \varphi^{\dagger} \partial_{\mu} \varphi + V(\varphi)$$

$$V(\varphi) = -\mu^2 \varphi^{\dagger} \varphi + \frac{1}{2} \lambda (\varphi^{\dagger} \varphi)^2$$
$$= \frac{1}{2} \lambda (\varphi^{\dagger} \varphi - \varphi_0^2)^2 + \text{const.})$$

$$\mu^2 > 0$$

$$\varphi_0^2 = \frac{\mu^2}{\lambda}$$

Fermi scale

$$\varphi_0 = 175 \text{ GeV}$$

## Scalar potential



$$V(\varphi) = -\mu^2 \varphi^{\dagger} \varphi + \frac{1}{2} \lambda (\varphi^{\dagger} \varphi)^2$$
$$= \frac{1}{2} \lambda (\varphi^{\dagger} \varphi - \varphi_0^2)^2 + \text{const.})$$

## Radial mode and Goldstone mode

### expand around minimum of potential

$$\varphi = \varphi_0 + \sigma + i\eta$$

$$\varphi_0, \sigma, \eta$$
: real

$$-\mathcal{L}_{\varphi} = \frac{1}{2}\partial^{\mu}\sigma\partial_{\mu}\sigma + \frac{1}{2}\partial^{\mu}\eta\partial_{\mu}\eta + \frac{1}{2}m^{2}\sigma^{2} + \dots$$

mass term for radial mode

$$m^2 = 2\lambda \varphi_0^2$$



## massless Goldstone mode

$$-\mathcal{L}_{\varphi} = \frac{1}{2}\partial^{\mu}\sigma\partial_{\mu}\sigma + \frac{1}{2}\partial^{\mu}\eta\partial_{\mu}\eta + \frac{1}{2}m^{2}\sigma^{2} + \dots$$



## Abelian Higgs mechanism supraconductivity

coupling of complex scalar field to photon

$$-\mathcal{L}_{\varphi} = \frac{1}{2} (D^{\mu} \varphi)^* D_{\mu} \varphi + V(\varphi)$$
$$+ \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$D_{\mu} = \partial_{\mu} - ieA_{\mu}$$

$$F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$$

## Abelian Higgs mechanism supraconductivity

$$\frac{1}{2}(D^{\mu}\varphi)^*D_{\mu}\varphi = \frac{1}{2}\partial^{\mu}\sigma\partial_{\mu}\sigma$$

$$+\frac{1}{2}e^2\varphi_0^2 A^\mu A_\mu$$

$$+\frac{1}{2}\partial^{\mu}\eta\partial_{\mu}\eta - e\varphi_0 A^{\mu}\partial_{\mu}\eta$$

$$+e^2\varphi_0\sigma A^\mu A_\mu+\ldots$$

#### massive photon !

$$\varphi = \varphi_0 + \sigma + i\eta$$

$$D_{\mu} = \partial_{\mu} - ieA_{\mu}$$

## Gauge symmetry

$$\delta\varphi(x) = -i\xi(x)\varphi(x) \quad \delta A_{\mu}(x) = -\frac{1}{e}\partial_{\mu}\xi(x)$$

$$\delta \Big( D_{\mu} \varphi(x) \Big) = -i\xi(x) D_{\mu} \varphi_{\mu} \varphi(x)$$
$$-i\partial_{\mu} \xi(x) \varphi(x)$$
$$-ie\delta A_{\mu}(x) \varphi(x)$$
$$= -i\xi(x) D_{\mu} \varphi(x)$$

Goldstone boson is gauge degree of freedom no physical particle can be eliminated by gauge transformation in favor of longitudinal component of massive photon

## Photon mass $m = e \phi$





Standard – Model of electroweak interactions : Higgs - mechanism

The masses of all fermions and gauge bosons are proportional to the (vacuum expectation) value of a scalar field \u03c6<sub>H</sub> (Higgs scalar)
 For electron, quarks, W- and Z- bosons :







## Vacuum is complicated

# mass generated by vacuum properties

particles: excitations of vacuum

Their properties depend on properties of vacuum

## vacuum is not empty !



## Fundamental "constants" are not constant

Have coupling constants in the early Universe other values than today ?



Fundamental couplings in quantum field theory

Masses and coupling constants are determined by properties of **vacuum** !

Similar to Maxwell – equations in matter

Condensed matter physics : laws depend on state of the system

Ground state , thermal equilibrium state ...
 Example : Laws of electromagnetism in superconductor are different from Maxwells' laws

## Standard model of particle physics :

Electroweak gauge symmetry is spontaneously broken by expectation value of Higgs scalar

## **Cosmology**:

Universe is not in one fixed state
Dynamical evolution
Laws are expected to depend on time

Restoration of symmetry at high temperature in the early Universe

Low T SSB  $\langle \phi \rangle = \phi_0 \neq 0$  High T SYM <φ>=0

high T : Less order More symmetry





Example: Magnets Standard – Model of electroweak interactions : Higgs - mechanism

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In hot plasma of early Universe :

## masses of electron und muon not different!

similar strength of electromagnetic and weak interaction

## electromagnetic phase transition in early universe

10<sup>-12</sup> s after big bang

most likely smooth crossover

could also be more violent first order transition



## Varying couplings

#### How strong is present variation of couplings ?

Can variation of fundamental "constants" be observed ?

Fine structure constant  $\alpha$  (electric charge)

Ratio electron mass to proton mass

Ratio nucleon mass to Planck mass
# Time evolution of couplings and scalar fields

Fine structure constant depends on value of cosmon field : α(φ)

*in standard model: couplings depend on value of Higgs scalar field* 

Time evolution of φ Time evolution of α

Jordan,...

# Static scalar fields

In Standard Model of particle physics :

- Higgs scalar has settled to its present value around 10<sup>-12</sup> seconds after big bang.
- Chiral condensate of QCD has settled at present value after quark-hadron phase transition around 10<sup>-6</sup> seconds after big bang.
- No scalar with mass below pion mass.
- No substantial change of couplings after QCD phase transition.
- Coupling constants are frozen.

# Observation of time- or spacevariation of couplings



# **Physics beyond Standard Model**

Particle masses in quintessence cosmology

#### can depend on value of cosmon field

similar to dependence on value of Higgs field



# Standard model of particle physics could be valid down to the Planck length

The mass of the Higgs boson, the great desert, and asymptotic safety of gravity

# a prediction...

#### Asymptotic safety of gravity and the Higgs boson mass

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s in  $m_H = m_{\min} = 126$  GeV, with o



- great desert
- solution of hierarchy problem at high scale
- high scale fixed point
- vanishing scalar coupling at fixed point



#### Planck scale, gravity

#### no multi-Higgs model

no technicolor

no low scale higher dimensions

no supersymmetry

# Quartic scalar coupling

prediction of mass of Higgs boson

prediction of value of quartic scalar coupling  $\lambda$  at Fermi scale

=

 $M_{\rm s}^2 = 2\lambda(\varphi_{\rm L}^2)\varphi_{\rm L}^2$ 

# Radial mode = Higgs scalar

expansion around minimum of potential

$$\varphi = \varphi_0 + \sigma + i\eta$$

Fermi scale

$$\varphi_0 = 175 \text{ GeV}$$

$$-\mathcal{L}_{\varphi} = \frac{1}{2}\partial^{\mu}\sigma\partial_{\mu}\sigma + \frac{1}{2}\partial^{\mu}\eta\partial_{\mu}\eta + \frac{1}{2}m^{2}\sigma^{2} + \dots$$

mass term for radial mode

$$m^2 = 2\lambda \varphi_0^2$$



Running couplings, Infrared interval, UV-IR mapping

### renormalization

#### couplings depend on length scale, or mass scale k

Running quartic scalar coupling  $\lambda$ and Yukawa coupling of top quark h

$$\partial_t \lambda = \beta_\lambda(\lambda, h, g^2)$$
  $t = \ln(k/\chi)$ 

neglect gauge couplings g

$$\beta_{\lambda} = \frac{3}{4\pi^2} (\lambda^2 + h^2 \lambda - h^4)$$
$$\partial_t h = \beta_h = \frac{9}{32\pi^2} h^3 \qquad m_t = h(\varphi)$$

# running SM couplings



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## Partial infrared fixed point

become comparable.Indeed, for strong enough  $h_t$  the RGE for the ratio  $\lambda/h_t^2$ ,

$$\frac{d}{dt}\left(\frac{\lambda}{h_{t}^{2}}\right) = \frac{h_{t}^{2}}{16\pi^{2}} \left\{ 12\left(\frac{\lambda}{h_{t}^{2}}\right) + 3\frac{\lambda}{h_{t}^{2}} - 12 \right\}^{(16)}$$

is governed by an infrared fixpoint.<sup>13]</sup> The ratio  $\lambda/h_t^2$  remains constant if the right hand side of (16) vanishes. This happens for

$$\frac{\lambda}{k_{\pm}^{2}} = \left(\frac{65}{64}\right)^{\frac{1}{2}} - \frac{1}{8} = x_{0} \qquad (17)$$

and corresponds to a mass ratio

$$\frac{M_{\rm H}}{m_{\rm t}} \approx 1.3 \tag{18}$$

$$\left(\frac{\lambda}{h^2}\right) = (\sqrt{65} - 1)/8$$

## infrared interval

allowed values of λ or λ/h<sup>2</sup> at UV-scale Λ : between zero and infinity are mapped to finite infrared interval of values of λ/h<sup>2</sup> at Fermi scale

## infrared interval



L. Maiani, G. Parisi and R. Petronzio, Nucl. Phys. <u>B136</u> (1978) 115 N. Cabbibo, L. Maiani, G. Parisi and R. Petronzio, Nucl. Phys. <u>B158</u> (1979) 295

- M. Lindner, Z. Phys. C31 (1986) 295.
- B. Grzadkowski and M. Lindner, Phys. Lett. B178, 81 (1986);
- M. Lindner, M. Sher, and H. W. Zaglauer, Phys. Lett. B228, 139 (1989);
- M. Sher, Phys. Rept. 179, 273 (1989);

# realistic mass of top quark (2010), ultraviolet cutoff: reduced Planck mass

$$M_P = (8\pi G_N)^{-1/2} = 2.4 \times 10^{18} \text{ GeV}$$

# $m_{min} = 126 GeV , \ m_{max} = 174 GeV$

# ultraviolet- infrared map

Whole range of small  $\lambda$ at ultraviolet scale is mapped by renormalization flow to lower bound of infrared interval! Prediction of Higgs boson mass close to 126 GeV

# high scale fixed point

## high scale fixed point

#### with small λ

predicts Higgs boson mass close to 126 GeV



- great desert
- solution of hierarchy problem at high scale
- high scale fixed point
- vanishing scalar coupling at fixed point

### fixed point in short-distance theory

- short-distance theory extends SM
- minimal: SM + gravity
- higher dimensional theory ?
- grand unification ?
- (almost) second order electroweak phase transition guarantees (approximate) fixed point of flow
- needed : deviation from fixed point is an irrelevant parameter (A>2)

# asymptotic safety for gravity

Weinberg, Reuter

# running Planck mass

$$M_P^2(k) = M_P^2 + 2\xi_0 k^2$$

#### infrared cutoff scale k,

for k=0 : 
$$M_P = (8\pi G_N)^{-1/2} = 2.4 \times 10^{18} \text{ GeV}$$

# fixed point for dimensionless ratio M/k



# scaling at short distances

 $q^2 \gg M_p^2$ 

 $G_N(q^2)$  scales as  $\frac{1}{16\pi\xi_0 q^2}$ 

infrared unstable fixed point: transition from scaling to constant Planck mass

 $k_{tr} = \frac{M_P}{\sqrt{2\xi_0}} \approx 10^{19} \text{ GeV}$ 

 $M_P^2(k) = M_P^2 + 2\xi_0 k^2$ 



## modified running of quartic scalar coupling in presence of metric fluctuations

$$\beta_{\lambda} = \frac{a_{\lambda}}{16\pi\xi_0}\lambda + \frac{1}{16\pi^2}(24\lambda^2 + 12\lambda h^2 - 6h^4) + \dots$$

#### for a > 0 and small h:

 $\lambda$  is driven fast too very small values !

e.g. a=3 found in gravity computations

# short distance fixed point at $\lambda = 0$

interesting speculation

$$\lambda(k_{tr}) \approx 0$$
,  $\beta_{\lambda}(k_{tr}) \approx 0$ 

top quark mass "predicted" to be close to minimal value, as found in experiment

# running quartic scalar coupling



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# Sensitivity to Higgs boson mass for given top quark mass

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Higgs mass  $M_h$ =127 GeV



top "prediction" for known Higgs boson mass

for  $m_{H} = 126 \text{ Gev}$  :  $m_{t} = 171.5 \text{ GeV}$ 

# conclusions

- observed value of Higgs boson mass is compatible with great desert
- short distance fixed point with small λ predicts Higgs boson mass close to 126 GeV
- prediction in SM+gravity, but also wider class of models
- desert: no new physics at LHC and future colliders
  relevant scale for neutrino physics may be low or intermediate ( say 10<sup>11</sup> GeV ) - oasis in desert ?




# gauge hierarchy problem and fine tuning problem

### quantum effective potential

$$U = \frac{1}{2}\lambda(\varphi^{\dagger}\varphi)^{2} + \gamma(\varphi^{\dagger}\varphi)\chi^{2} + U_{\chi},$$

$$\frac{\varphi_0}{M} = \sqrt{-\frac{\gamma}{\lambda}}.$$

scalar field  $\chi$  with high expectation value M, say Planck mass

#### anomalous mass dimension

$$\partial_t \gamma = A_\mu(\lambda, h, g^2) \gamma$$

$$A_{\mu} = \frac{3}{8\pi^2} (\lambda^2 + h^2)$$

one loop, neglect gauge couplings g

# fixed point for $\gamma = 0$

zero temperature electroweak phase transition (as function of γ ) is essentially second order
 fixed point with effective dilatation symmetry
 no flow of γ at fixed point

$$\partial_t \gamma = A_\mu(\lambda, h, g^2) \gamma$$

 naturalness due to enhanced symmetry
 small deviations from fixed point due to running couplings: leading effect is lower bound on Fermi scale by quark-antiquark condensates

# critical physics

- second order phase transition corresponds to critical surface in general space of couplings
- flow of couplings remains within critical surface
- once couplings are near critical surface at one scale, they remain in the vicinity of critical surface
- gauge hierarchy problem : explain why world is near critical surface for electroweak phase transition
- explanation can be at arbitrary scale !

#### critical physics in statistical physics

use of naïve perturbation theory (without RG – improvement) would make the existence of critical temperature look "unnatural"

artefact of badly converging expansion

## self-tuned criticality

- deviation from fixed point is an irrelevant parameter (A>2)
- critical behavior realized for wide range of parameters
  in statistical physics : models of this type are known for d=2
- d=4: second order phase transitions found , self-tuned criticality found in models of scalars coupled to gauge fields (QCD), Gies...
   realistic electroweak model not yet found

## SUSY vs Standard Model

- natural predictions
- baryon and lepton number conservation SM
  flavor and CP violation described by CKM matrix SM
  absence of strangeness violating neutral currents SM
  g-2 etc. SM
  dark matter particle (WIMP) SUSY

## gravitational running

$$k\frac{dx_j}{dk} = \beta_j^{\rm SM} + \beta_j^{grav}$$

$$\beta_j^{grav} = \frac{a_j}{8\pi} \frac{k^2}{M_p^2(k)} x_j$$

$$x_j(k) \sim k^{A_j} \quad A_j = \frac{a_j}{16\pi\xi_0}$$

a < 0 for gauge and Yukawa couplings asymptotic freedom

#### bound on top quark mass

# quartic scalar coupling has to remain positive during flow

(otherwise Coleman-Weinberg symmetry breaking at high scale)

$$\begin{split} \beta^{\rm SM}_\lambda &= \frac{1}{16\pi^2} \left[ 24\lambda^2 + 12\lambda h^2 - 9\lambda \left( g_2^2 + \frac{1}{3}g_1^2 \right) \right. \\ & \left. - 6h^4 + \frac{9}{8}g_2^4 + \frac{3}{8}g_1^4 + \frac{3}{4}g_2^2g_1^2 \right] \,. \end{split}$$

$$m_t \geq m_t^{\min}$$

~170 GeV