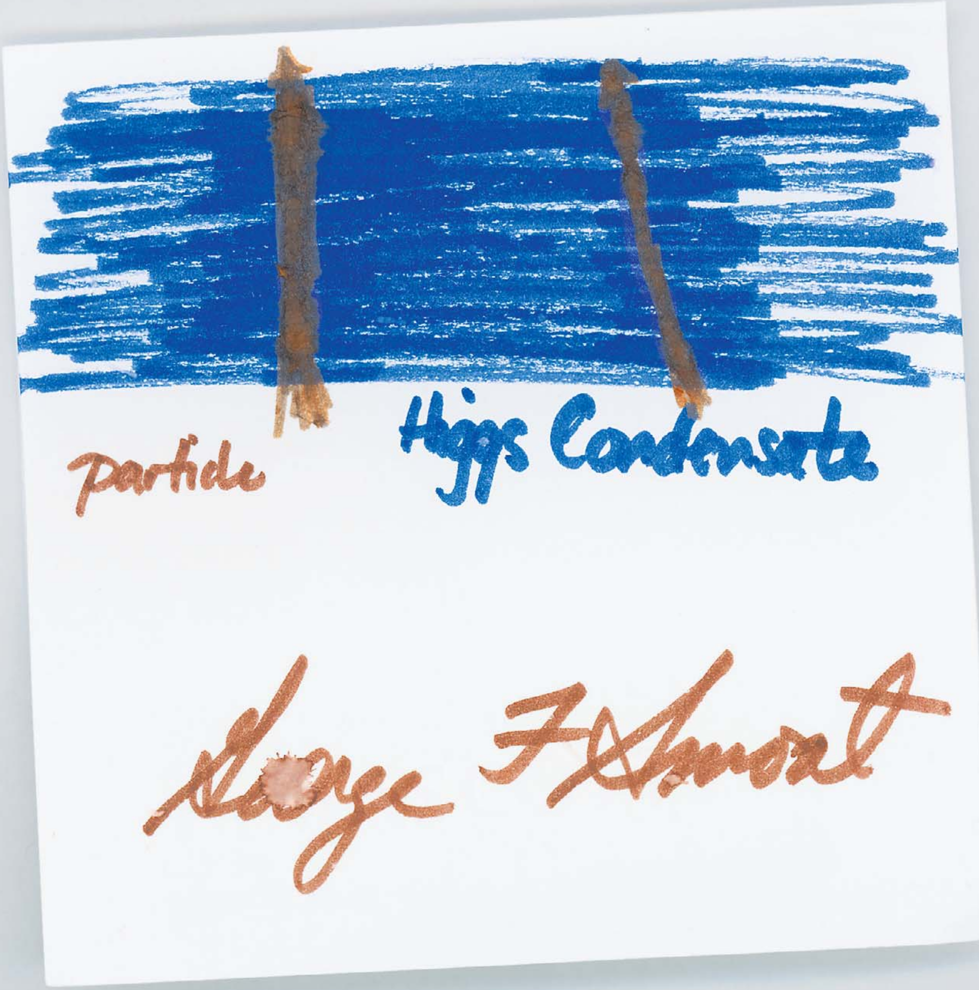
Ein neues Teilchen! Ist es das Higgs?

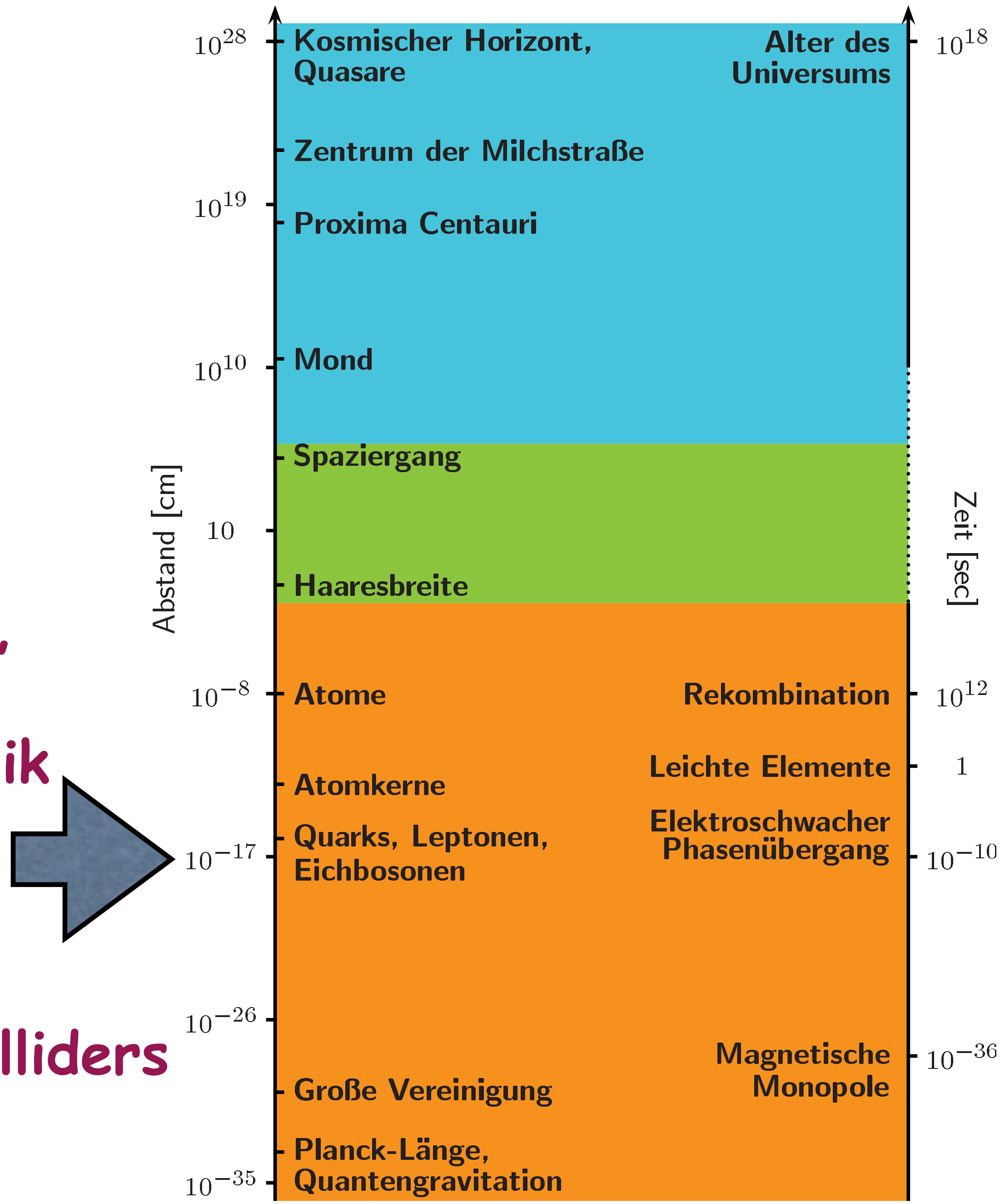
(Physikalische Interpretation)



FAZ, 5.Juli

“Standardmodell” der Teilchenphysik

“Auflösungs-vermögen” des Large Hadron Colliders



“Standard Model” of Particle Physics

$$\mathcal{L} = -\frac{1}{2}\mathrm{tr}\left[F_{\mu\nu}F^{\mu\nu}\right] + \overline{\Psi}_L i\gamma^\mu D_\mu \Psi_L + \mathrm{tr}\left[\left(D_\mu\Phi\right)^\dagger D^\mu\Phi\right]$$

$$+ \mu^2\,\Phi^\dagger\Phi - \frac{1}{2}\lambda\left(\Phi^\dagger\Phi\right)^2 + \left(\frac{1}{2}h\overline{\Psi_L^c}\Phi\Psi_L + \mathrm{h.c.}\right)$$

1973

$F_{\mu\nu}$: photon, W boson, Z boson

Ψ_L : quarks, electron, neutrino, ...

Φ : Higgs field

$D_\mu\Psi_L = \left(\partial_\mu 1 + gA_\mu\right)\Psi_L$; interaction with photon, ...

Note: no mass terms, only interaction with Higgs field!

Relativistic, renormalizable, chiral quantum field theory

Glashow, Weinberg, Salam; 'tHooft, Veltman; Gross, Wilczek

Higgs Field & Higgs Particle

$$\Phi = \begin{pmatrix} v + \frac{1}{\sqrt{2}} H(x) \\ 0 \end{pmatrix}, \quad H = H^*$$

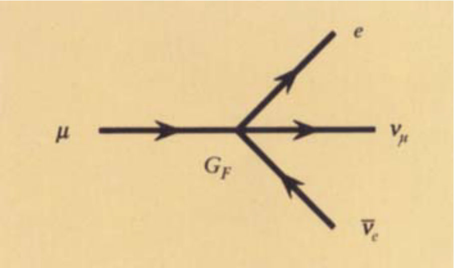
$$v = \text{ homogeneous background field}$$

$$H(x) = \text{ quantum field}$$

3 scalars eliminated by gauge transformation, yields massive W-, Z-bosons; background Higgs field and Fermi constant:

$$v = 174 \text{ GeV}; \quad G_F = \left(2\sqrt{2}v^2\right)^{-1}$$

$$\tau_\mu = \frac{1536\pi^3}{m_\mu^5} v^4$$



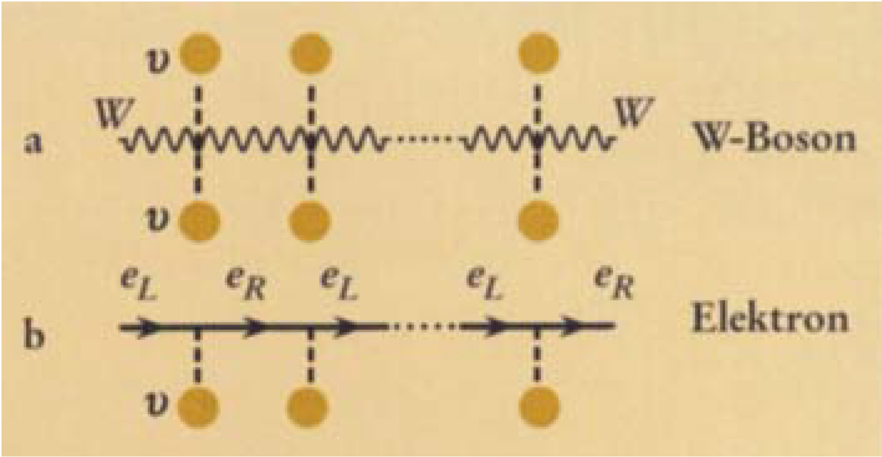
Mass Generation (Higgs [BEH] Mechanism)

$$m_W = \frac{1}{\sqrt{2}} g v \ ,$$

$$m_e = h_e v \ ,$$

$$\ldots$$

$$m_H = \sqrt{2\lambda} v$$



Well known: analogy to superconductivity; Higgs field corresponds to to density of Cooper pairs (Bardeen, Cooper, Schrieffer); Higgs model: Ginsburg-Landau theory; our world: "superconducting vacuum" main difference: SM non-Abelian superconductor! [Note: most mass from strong interactions (QCD), also spontaneous symmetry breaking]

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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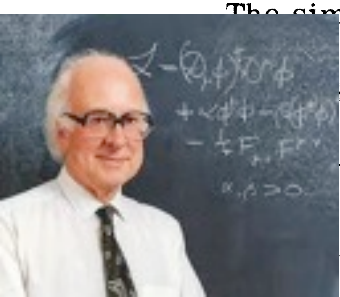
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero. This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson[3] has drawn attention: that the scalar zero-mass excitations of a superconducting neutral Fermi gas become longitudinal plasmon modes of finite mass when the gas is charged.

The simplest theory which exhibits this be-



a gauge-invariant version of a model
oldstone[2] himself: Two real[4] scalar
φ_2 and a real vector field A_μ interact
he Lagrangian density

$$\tfrac12(\nabla\varphi_1)^2-\tfrac12(\nabla\varphi_2)^2$$

about the "vacuum" solution $\varphi_1(x)=0$, $\varphi_2(x)=\varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1)-e\varphi_0A_\mu\}=0, \tag{2a}$$

$$\{\partial^2-4\varphi_0^2V''(\varphi_0^2)\}(\Delta\varphi_2)=0, \tag{2b}$$

$$\partial_\nu F^{\mu\nu}=e\varphi_0\{\partial^\mu(\Delta\varphi_1)-e\varphi_0A_\mu\}. \tag{2c}$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c) may be transformed, by the introduction of new variables

$$B_\mu=A_\mu-(e\varphi_0)^{-1}\partial_\mu(\Delta\varphi_1),$$

$$G_{\mu\nu}=\partial_\mu B_\nu-\partial_\nu B_\mu=F_{\mu\nu}, \tag{3}$$

into the form

$$\partial_\mu B^\mu=0,\quad \partial_\nu G^{\mu\nu}+e^2\varphi_0^2B^\mu=0. \tag{4}$$

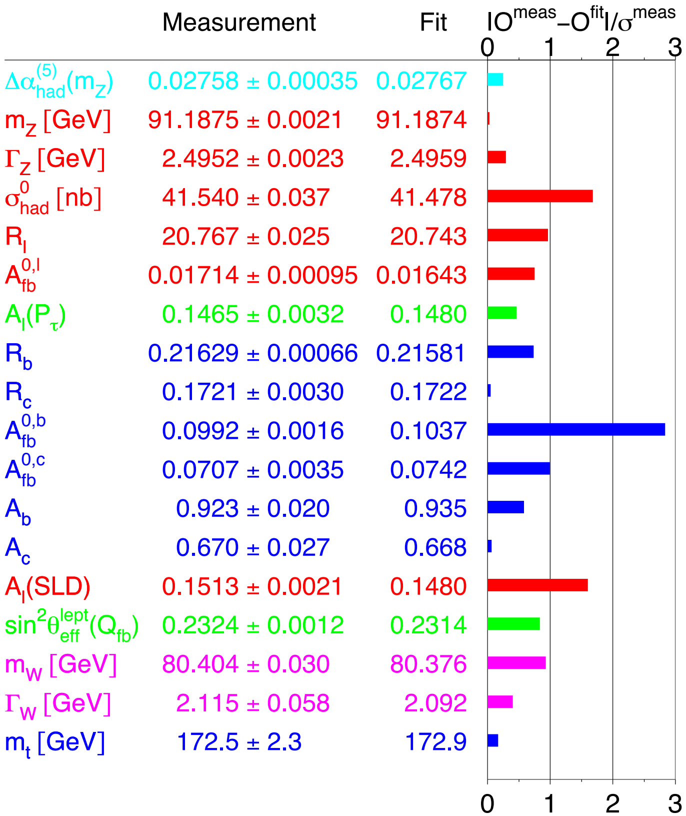
Equation (4) describes vector waves whose quanta have (bare) mass $e\varphi_0$. In the absence of the gauge field ... -
ent: ... ss
scalar and vector bosons, respectively. In passing, we note that the right-hand side of (2c) is

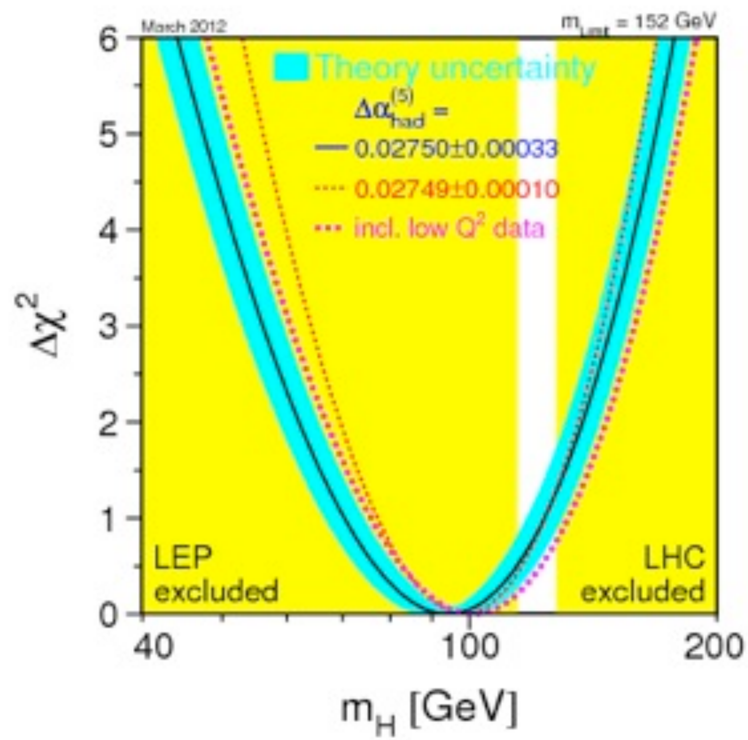
also Brout & Englert 1964

40 Years of “Higgs Physics” (also @ II. Inst. for Theor. Physics & DESY Theory)

- Quantum corrections: Higgs production
- Quantum corrections: Higgs decays
- Electroweak precision tests
- Electroweak phase transition
- Higgs inflation
- Alternatives to Higgs mechanism
- Cosmological constant problem

Predictive power of SM: electroweak precision data constrain Higgs mass via quantum corrections:



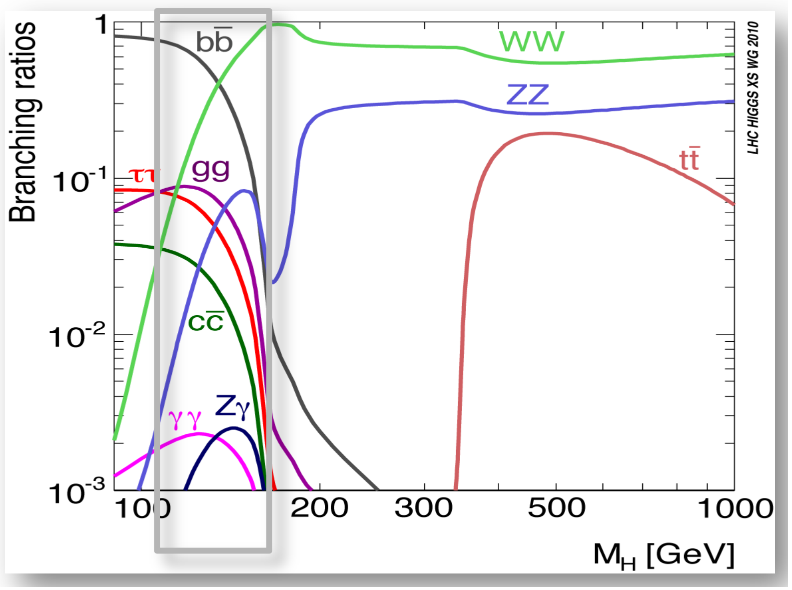


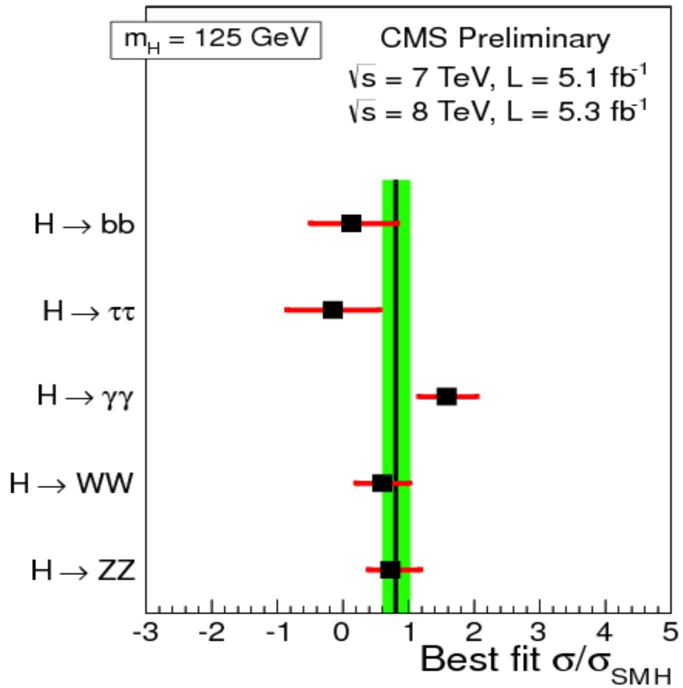
ATLAS: $m_H \simeq 126.5\ \text{GeV}$ **CMS:** $m_H \simeq 125.3\ \text{GeV}$

consistent within 68%CL; great success of EW theory!!

"What's next?"

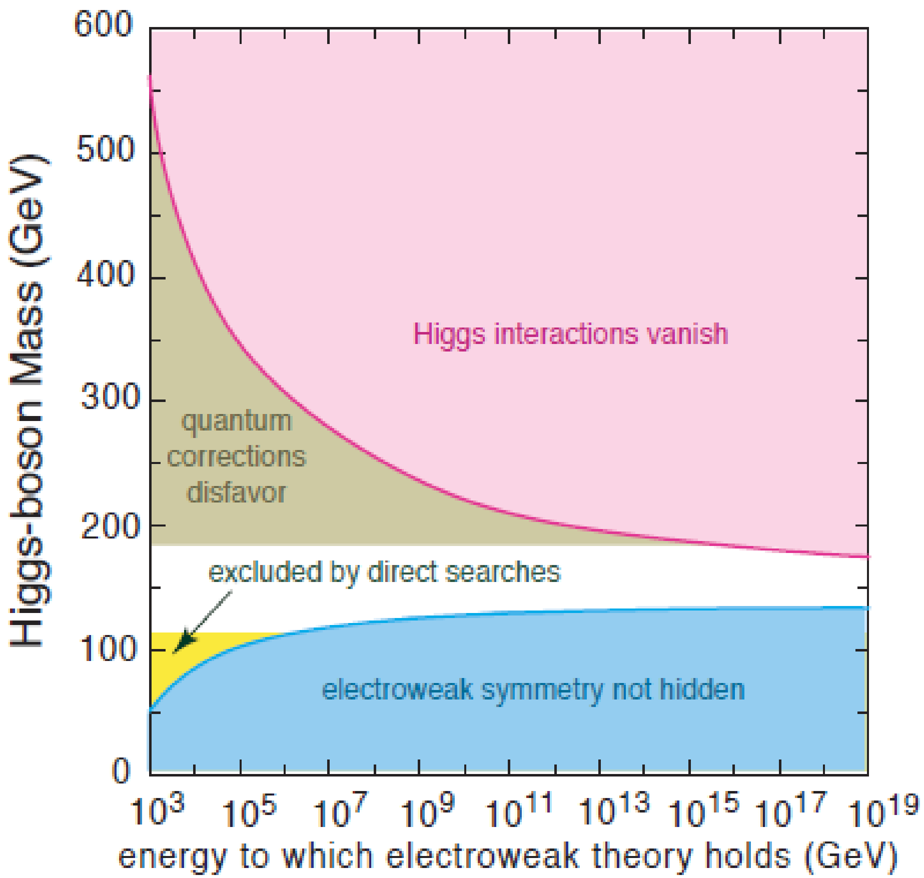
Check the Higgs profile (production and final states) !





SM predictions: $\Gamma(H \to f\bar{f}) = \frac{G_F m_H m_f^2}{4\pi\sqrt{2}} N_c \,, \quad \Gamma(H \to W_L W_L) = \frac{G_F m_H^3}{16\pi\sqrt{2}} \,, \ldots$

Implication: Extrapolation to GUT scale



[GUT: Grand Unified Theory]

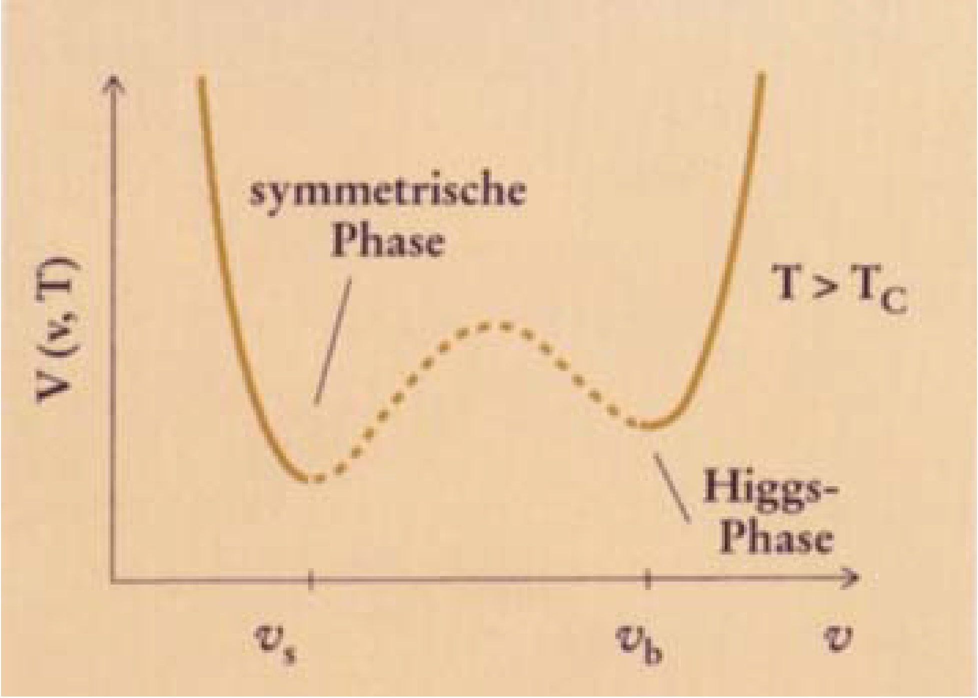
"Landau pole"
(upper) bound &
"vacuum stability"
(lower) bound

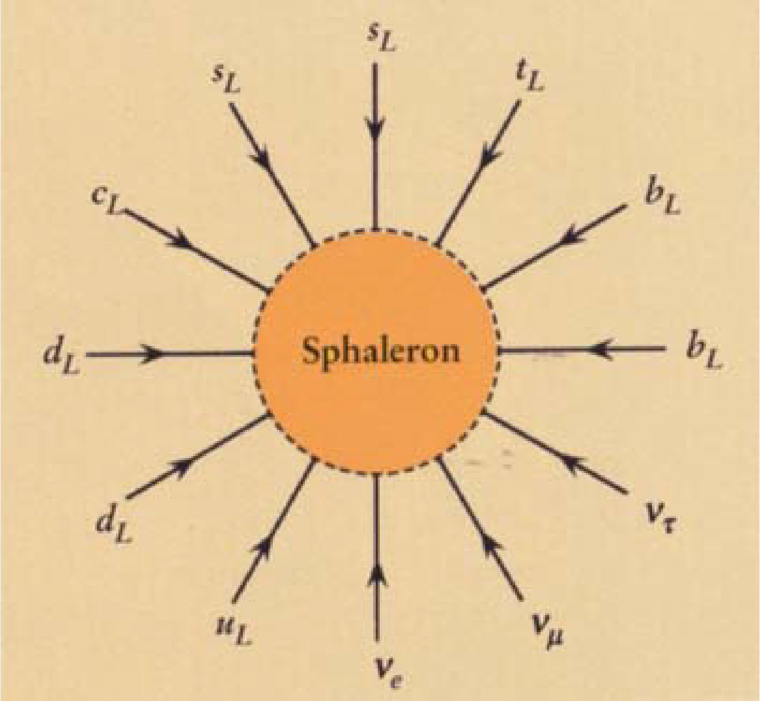
Quigg '07

Higgs mass in window consistent with high scale extrapolation!

(Currently debate on quantum corrections to vacuum stability bound)

Implication: Electroweak Phase Transition





At temperature ~ 100 GeV (10^15 K) transition to high-temperature "symmetric phase"; because of "large" Higgs mass only smooth cross-over, crucial for generation of matter-antimatter-asymmetry in early universe; baryon- and lepton-number processes in thermal equilibrium

Implication: Vacuum Energy Density (?)

Vacuum energy density of background Higgs field:

$$V_{\text{vacuum}} = -\frac{\lambda}{2} v^4 = -\frac{1}{8\sqrt{2}} \frac{m_H^2}{G_F} \sim -(100 \text{ GeV})^4$$

Cosmology (WMAP...): $V_{\text{vacuum}} = +(10^{-3}\text{eV})^4$

Sign and order of magnitude wrong!! Together with vacuum quantum fluctuations severe conceptual "cosmological constant problem"; Veltman (...Dec. 2012): no Higgs!!

"Pauli und ich (Stern) haben Anfang der 20er Jahre die Frage der Nullpunkts-energie dauernd diskutiert...sie, wie aus der Erfahrung evident ist, auch kein Gravitationsfeld erzeugt..."

Hamburg, 1923 - 1928

Ausblick

- Ist es ein Higgs? ("ja")
- Weitere Tests: Kopplungen an Fermionen, Spin
- Ist das Higgs elementar oder zusammengesetzt?
  Hoffnung: weitere Teilchen am LHC
- Extrapolation bis zur GUT Skala ?
  Hoffnung: weitere Teilchen am LHC (SUSY?)
- Offen: kosmologische Fragen (Zusammenhang mit
  Inflation und kosmologischer Konstanten)