Felder, Teilchen, Masse und das Higgs-Boson

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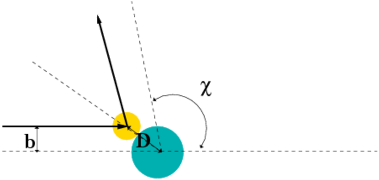
Wie schwer bin ich?

[sueddeutsche.de]

NB: gravitational mass = inertial mass[1]

(NEWTON 1686; EULER 1750)

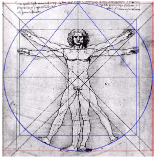
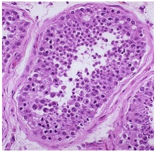
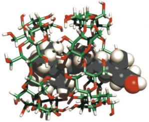
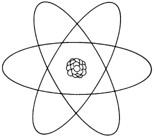
$$F = m\,a$$

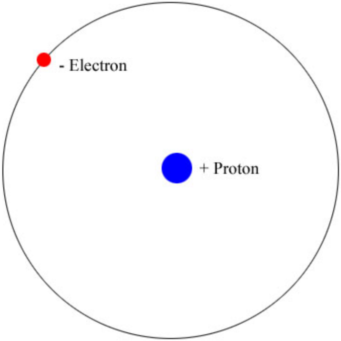


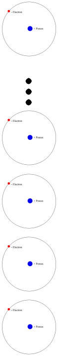
$$\frac{m_1}{m_2} = -\frac{\Delta v_2}{\Delta v_1}$$

[1] equivalence principle → general relativity

Towards the fundamental building blocks

 $\rightarrow$  $\rightarrow$  $\rightarrow$ 

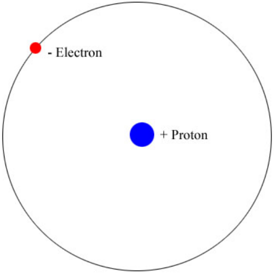


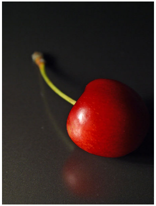


$10^6 \sim$ 

Masses of elementary particles

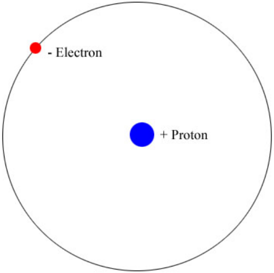
e.g., hydrogen atom





Masses of elementary particles

e.g., hydrogen atom $(c = 1)$

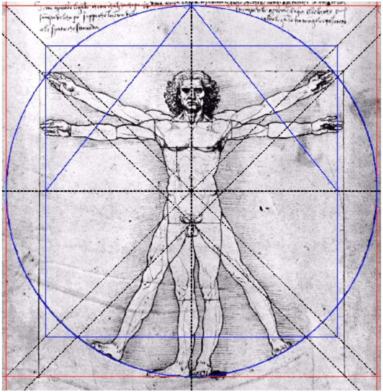


$$m_e = 510998\text{eV} \simeq 511\text{keV}$$

$$1\text{eV} \simeq 1.783 \cdot 10^{-36}\text{kg}$$

$$m_p = 938272013\text{eV} \simeq 938\text{MeV}$$

Masses of elementary particles



$\simeq$ 70 kg protons

$\simeq$ 35 g electrons

Energy – mass equivalence

(Einstein 1905)

$$E = m\,c^2$$

Energy – mass equivalence

(Einstein 1905)

$$E = \sqrt{(\mathbf{p}c)^2 + (m\,c^2)^2}$$

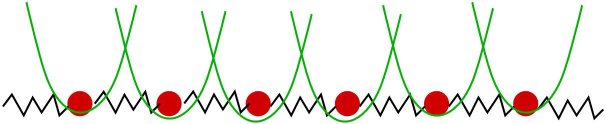
Energy – momentum – *m*ass – relation

(dispersion relation)

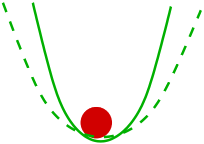
Analogue: linear chain

▷ dispersion relation of a linear chain:

$$\omega = \sqrt{(\mathbf{p}v)^2 + \Omega^2}$$



▷ Ω: restoring force



Particle $\leftrightarrow$ Wave …?

▷ quantum field theory:

$$\text{particles} \;=\; \text{(quantized) excitations of fields}$$

Particle $\leftrightarrow$ Wave . . . ? Field!

▷ quantum field theory:

$$\text{particles} = \text{(quantized) excitations of fields}$$

Particle $\leftrightarrow$ Wave ...? Field!

▷ quantum field theory:

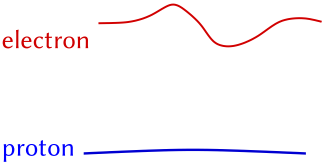
particles = (quantized) excitations of fields

$$E = \sqrt{(\mathbf{p}c)^2 + (m\,c^2)^2}$$

Particles as field excitations

▷ particle mass $\sim$ "restoring force" of quantum field amplitudes

$$E = \sqrt{(\mathbf{p}c)^2 + (m\,c^2)^2}$$



A bit of formalism

▷ energy-momentum dispersion relation ($\hbar = c = 1$)

$$E^2 = \mathbf{p}^2 + m^2$$

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- ▷ corresponding wave equation ($E = p^0$, metric $g_{\mu\nu} = (-,+,+,+)$):

$$0 = (-E^2 + \mathbf{p}^2 + m^2)\phi(E, \mathbf{p}) = (p_\mu p^\mu + m^2)\phi(p)$$

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- in coordinate space:

$$0 = (-\partial^2 + m^2)\phi(x), \qquad \partial^2 = \frac{\partial}{\partial x_\mu}\frac{\partial}{\partial x^\mu}$$

Klein-Gordon equation

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▷ corresponding Langrangian:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}m^2\phi^2, \qquad \text{cf.} \quad L = T - U = \frac{1}{2}\dot{x}^2 - \left(\frac{1}{2}\omega^2 x^2\right)$$

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$\Longrightarrow$ mass appears as prefactor of quadratic term in Lagrangian

penalizes field amplitude excitations

Summary I

- mass
    - gravitational mass (“weight”): source of the graviational field
    - inertial mass

- mass: parameter in relativistic energy momentum dispersion relation

- quantum field theory:
    - particles $\sim$ (quantized) field excitations
    - mass: cf. restoring force for field amplitude

- mass of ordinary matter: 0.05% electrons, 99.95% protons, neutrons

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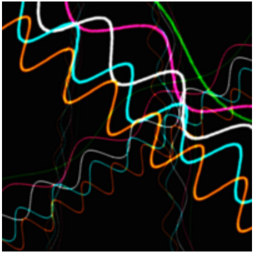
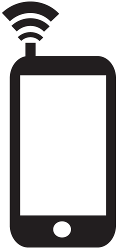
Q?:

Where does the mass of protons, neutrons and electrons come from?

Exercise: Mass of the Photon



Photon γ



▷ Maxwell Lagrangian:

$$\mathcal{L} = \frac{1}{2}\left(\mathbf{E}^2 - \mathbf{B}^2\right) = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} = \frac{1}{2}\left[(\partial_\mu A_\nu)^2 - (\partial_\mu A_\mu)^2\right]$$

▷ use gauge freedom: e.g., Lorenz gauge, $\partial_\mu A_\mu = 0$:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu A_\nu)^2$$

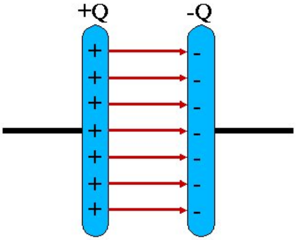
$\Longrightarrow$ No mass term: $m_\gamma = 0$ (gauge symmetry!)

exp.: $\mathrm{m}_\gamma \leq 10^{-18}$ eV (PDG'09)

Gauge symmetry

electric

$$\mathbf{E} = -\nabla A_0 - \frac{1}{c}\frac{\partial}{\partial t}\mathbf{A}$$



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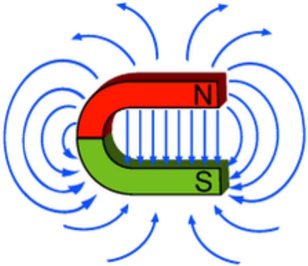
magnetic field strength

$$\mathbf{B} = \nabla \times \mathbf{A}$$



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gauge field $A_\mu = (A_0, \mathbf{A})$

Gauge symmetry

electric

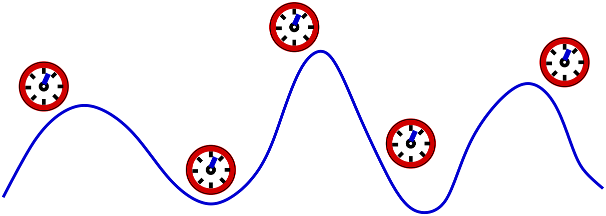
$$\mathbf{E} = -\nabla A_0 - \frac{1}{c}\frac{\partial}{\partial t}\mathbf{A}$$

&

magnetic field strength

$$\mathbf{B} = \nabla \times \mathbf{A}$$

gauge field A_μ $\sim$ 

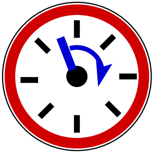


Gauge symmetry

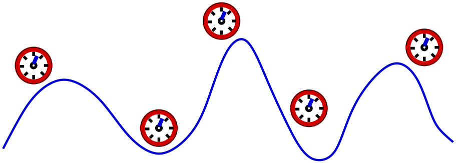
electric & magnetic field strength

$$\mathbf{E} = -\nabla A_0 - \frac{1}{c}\frac{\partial}{\partial t}\mathbf{A}$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$



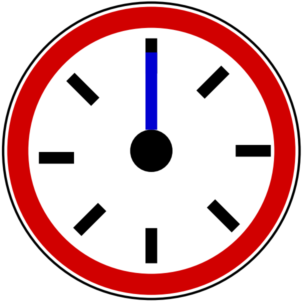
gauge transformation $A_\mu \to A_\mu + \partial_\mu \lambda$



$\Longrightarrow$ $\mathbf{E} \to \mathbf{E}$, $\mathbf{B} \to \mathbf{B}$ gauge invariant!

Gauge symmetry

mass $\sim$ restoring force



theory:

mass term

$$\mathcal{S}_{m_\gamma} = \int \mathcal{L}_{m_\gamma} = \frac{1}{2} \int m_\gamma^2 A_\mu A^\mu$$

$$S_{m_\gamma}[A + \partial_\mu \lambda] \neq S_{m_\gamma}[A]$$

violates symmetry

Is the photon massless?

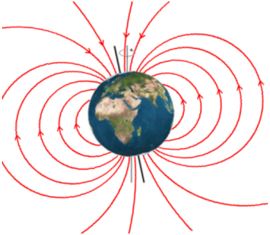
- if gauge invariance is a symmetry of Nature, then

$$m_\gamma = 0$$

Consequences of gauge symmetry

▷ electromagnetic field excitations have the least possible restoring force

▷ long range force:



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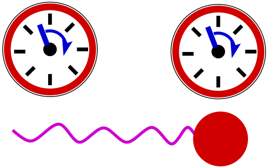
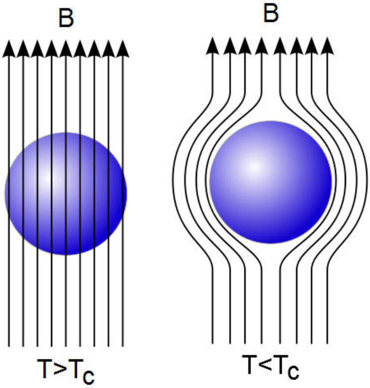
▷ also couplings to charges must obey gauge symmetry



Photon mass from symmetry breaking

▷ Meissner-Ochsenfeld effect in superconductors (type I)



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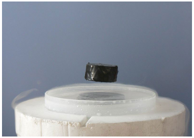

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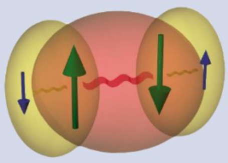
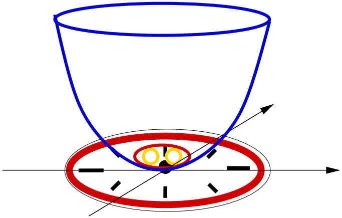
Photon mass from symmetry breaking

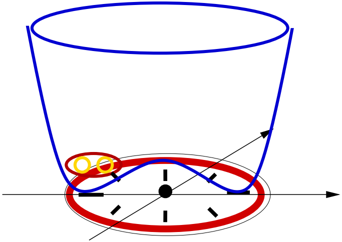
▷ Cooper pairs



$T > T_c$



$T < T_c$



$\Longrightarrow$ vacuum condensate from Cooper pairs:

$$\left\langle \bigcirc\!\bigcirc \right\rangle = \frac{1}{\sqrt{2}}\, v$$

(Bardeen, Cooper, Schrieffer 1957)

A bit of formalism

▷ photon field: A_μ, Cooper pair field: ϕ; minimal coupling:

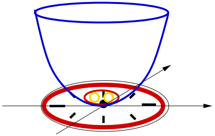
$$\partial_\mu \phi \to D_\mu[A]\phi = (\partial_\mu - i(2e)A_\mu)\phi$$

gauge covariant derivative

▷ Lagrangian:

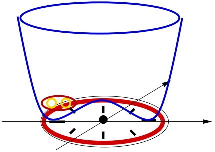
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (D_\mu[A]\phi)^*(D^\mu[A]\phi) - V(\phi^*\phi), \qquad V = \frac{1}{2}m_\phi^2|\phi|^2 + \dots$$

$T > T_c$



$m_\phi^2 > 0$
$\to$ massive Cooper pair
$\to$ massless photon

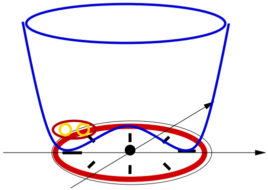
$T < T_c$



$m_\phi^2 \sim (T - T_c) < 0$
$\to$ massive Cooper field excitation
$\to$ massive photon

Photon mass from symmetry breaking

▷ vacuum condensate from Cooper pairs:



$\Big\langle$  $\Big\rangle \equiv \langle \phi \rangle = \frac{1}{\sqrt{2}}\, v$

photon mass below T_c:

$$\mathcal{L} = \ldots (D_\mu[A]\phi)^*(D^\mu[A]\phi)\cdots = \cdots - (2e)^2 A_\mu A^\mu |\phi|^2 \cdots \to \ldots \frac{1}{2}(2e)^2 v^2 A_\mu A^\mu$$

$$m_\gamma = 2ev$$

▷ London penetration depth:

$$\lambda \sim \frac{1}{m_\gamma}, \qquad \mathbf{B} \sim \exp(-x/\lambda)$$

short range

Summary II

- photons: exchange bosons of electromagnetic interactions

  gauge invariance!

- symmetry keeps photon massless

  long range interactions

- exception: condensates (e.g., superconductor) “break”(hide) symmetry

  $m_\gamma > 0 \quad \Longrightarrow$ short range interaction

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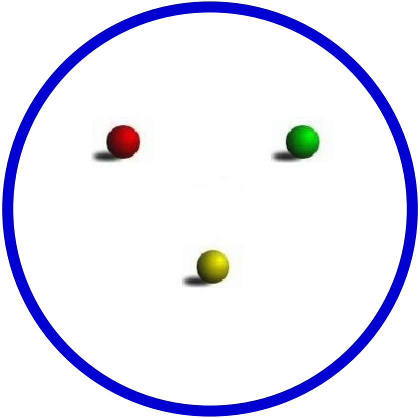
Q?:

Are all masses generated from symmetry breaking?

Where does the proton mass come from?

▷ scattering experiments: proton is a bound state of 3 quarks



BUT: $m_q \simeq 5\,\mathrm{MeV}$; $3 \times 5\,\mathrm{MeV} \neq 938\,\mathrm{MeV} \ldots ?$

Quark masses and chiral symmetry

▷ theory of quark interactions:

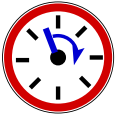
quantum chromodynamics (QCD)

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \bar{q} i \not{D}[A] q + m_{\mathrm{q}} \bar{q} q$$

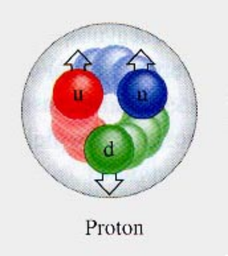
▷ chirality: $q = q_{\mathrm{L}} + q_{\mathrm{R}}$

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \bar{q}_{\mathrm{L}} i \not{D}[A] q_{\mathrm{L}} + \bar{q}_{\mathrm{R}} i \not{D}[A] q_{\mathrm{R}} + m_{\mathrm{q}} (\bar{q}_{\mathrm{L}} q_{\mathrm{R}} + \bar{q}_{\mathrm{R}} q_{\mathrm{L}})$$

▷ if $m_{\mathrm{q}} = 0$, QCD has a chiral symmetry:

$q_{\mathrm{L,R}} \to$  $\times \; q_{\mathrm{L,R}}$, $\quad \mathrm{SU}_{\mathrm{L}}(N_{\mathrm{f}}) \otimes \mathrm{SU}_{\mathrm{R}}(N_{\mathrm{f}})$

QCD: strong interaction

strong  force

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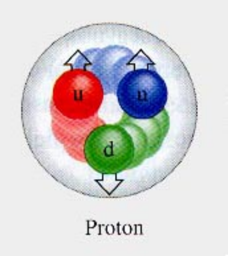
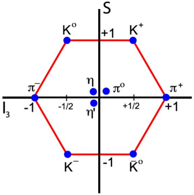
strong  force

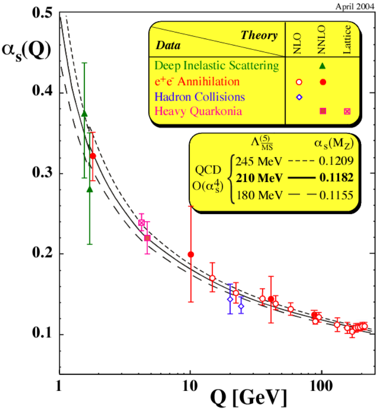
Quantum chromodynamics

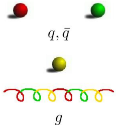
$q, \bar{q}$

g

Quantum chromodynamics



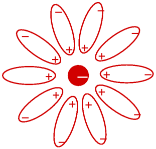


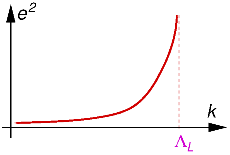


(Gross,Wilczek'73;Politzer'73)

cf. running coupling

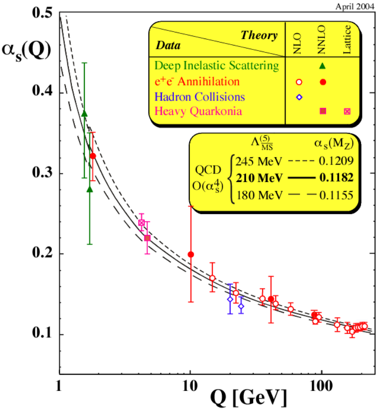
opposite to QED

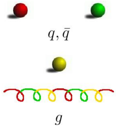




Quantum chromodynamics

- ▷ running coupling
- ▷ confinement
- ▷ mass gap
- ▷ chiral symmetry breaking
- ▷ phase diagram (T, μ)
- ▷ hadron spectrum

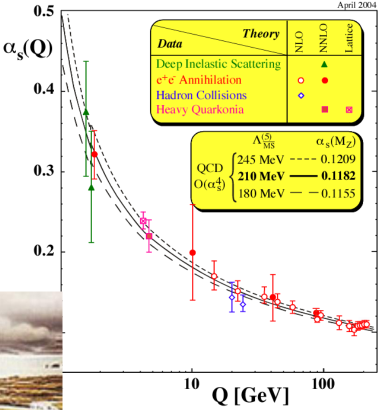


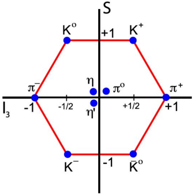


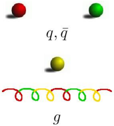
(Gross,Wilczek'73;Politzer'73)

Quantum Chromodynamics

(Bethke'04)







Quantum Chromodynamics

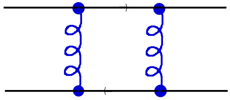
Quantum Chromodynamics

QCD: quarks, gluons
cond-mat: electron states
cold gases: atoms

QCD: mesons, baryons
cond-mat: Cooper-pairs, long-range order
cold gases: BEC, superfluidity

Mass generation from chiral symmetry breaking (sketch!)

▷ dynamics of quarks and gluons generates "effective" interactions:

e.g., $\quad 4\,\text{quark int.} \;\sim\; \bar{q}_L q_R \bar{q}_R q_L \;\sim$ 

▷ quark bilinears form bosons at strong coupling:

$$\text{e.g.,} \quad \phi \sim \bar{q}_L q_R, \;\; \phi^\dagger \sim \bar{q}_R q_L$$

▷ chiral "quark condensates" form at small momentum scales:

$$\langle\phi\rangle = \frac{1}{\sqrt{2}}\,v, \qquad \bar{q}_L q_R \bar{q}_R q_L \sim v(\bar{q}_L q_R + \bar{q}_R q_L)$$

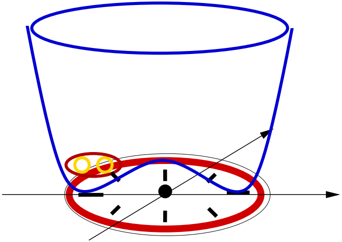
Breaking of chiral symmetry

▷ strong interaction leads to quark bound states:

$$v \sim \langle \bar{q}q \rangle = \Big\langle \quad \Big\rangle$$

▷ "constituent" quark mass:

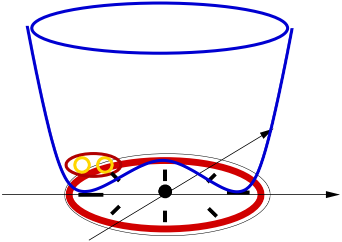
$$m_{\text{constit.}} \sim v$$



▷ symmetry breaking through chiral vacuum condensates

Breaking of chiral symmetry

▷ strong interaction leads to quark bound states:



$$v \sim \langle \bar{q}q \rangle = \langle \quad \rangle$$

▷ "constituent" quark mass:

$$m_{\text{constit.}} \sim v$$

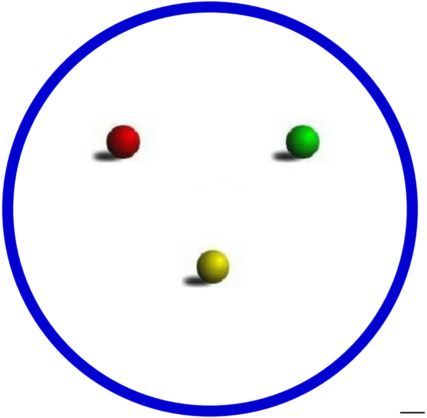
Nobel-Preis 2008:

Yoichiro Nambu

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

Mass of the proton

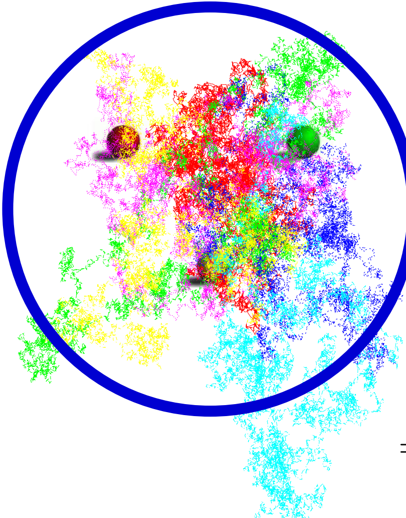
$\approx 3 \quad \times \quad 5 \text{ MeV}$



$= \quad 938 \quad \text{MeV}$

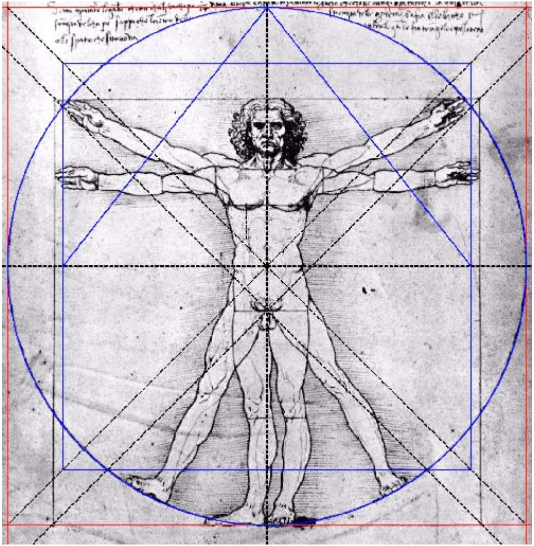
Mass of the proton

$\approx 3 \quad \times \quad 5\ \mathrm{MeV}$ + QCD vacuum condensates



$= \quad 938 \quad \mathrm{MeV}$

Human mass



70 kg human

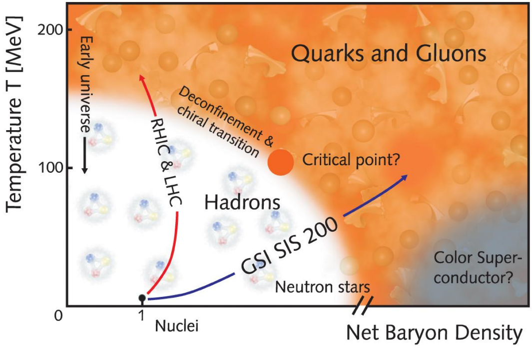
35 g electrons

1,050 kg quarks

68,915 kg vacuum condensates

Is there a T_c for protons?

- ▷ T_c: melting point of condensates?



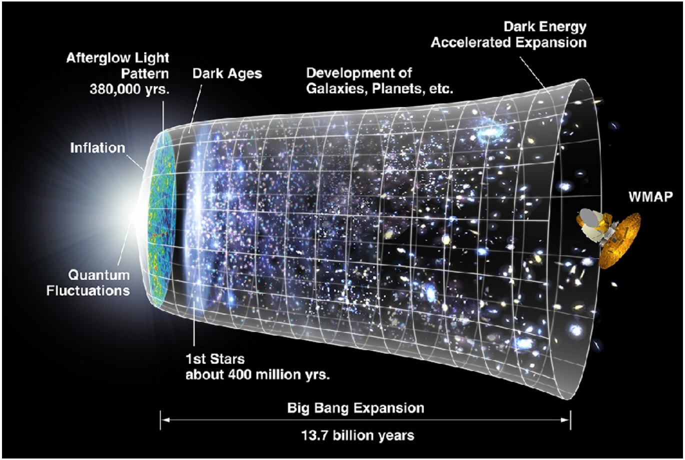
[GSI.DE]

- ▷ $T_c \simeq 156\,\mathrm{MeV} = 1\,810\,000\,000\,000$ Kelvin

- ▷ $T > T_c$: quark-gluon-plasma (chirally symmetric)

QCD phase transition

▷ in the early universe ($\sim 1\,\mu s$ after the Big Bang):

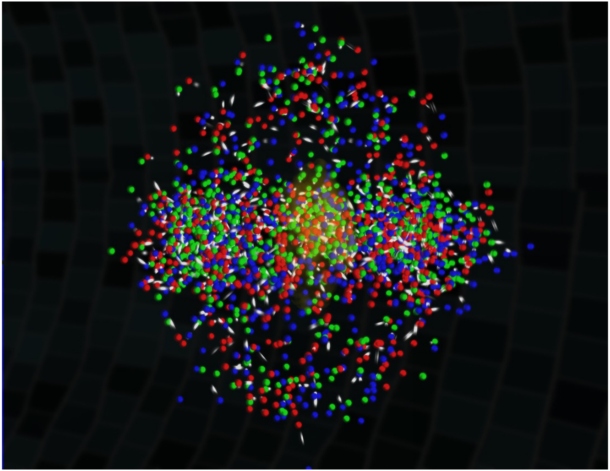


[MAP.GSFC.NASA.GOV/]

QCD phase transition

- in heavy ion collisions

(RHIC@BNL, LHC@CERN seit 2010, FAIR@GSI >2023)



[bnl.gov]

Summary III

- proton/neutron mass (and thus the largest part of all visible matter in the universe) are generated by chiral symmetry breaking

- (approximate) chiral symmetry and its breaking are properties of QCD

  theory of the strong interactions

- restoration of chiral symmetry is investigated in the laboratory

  heavy ion collisions

- quark-gluon plasma: state of matter in the early universe

Q?:

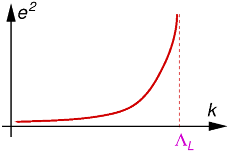
Where does m_{e}, m_{q}, …come from?

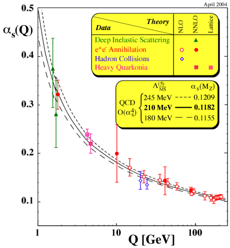
The renormalization group (RG)

▷ QFT: couplings, masses, etc.

- are scale dependent

$\alpha_{\text{QED}}(k), \alpha_{\text{strong}}(k), m_{\text{q}}(k)$





- are parameters of the action:

$$S = \int \mathcal{L} = S(\alpha_i, m_i, \dots)$$

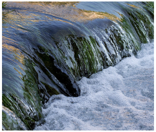
$\Longrightarrow$ idea: promote action S to a scale-dependent quantity

integrate fluctuations scale by scale

$S \to \Gamma_k$ 1PI effective action

(…Gell-Mann,Low;Bogoliubov,Shirkhov;Callan;Symanzik;Kadanoff;Wegner,Houghton;Wilson;Polchinski;Wetterich, …)

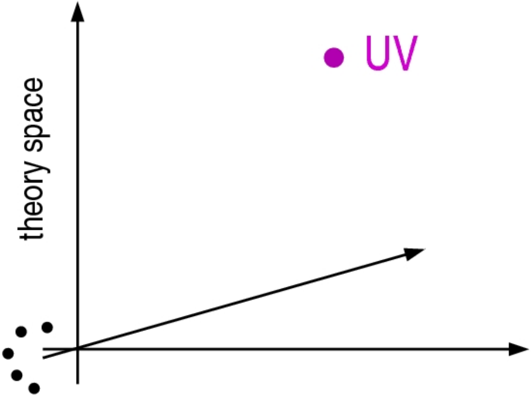
RG flow in Theory Space



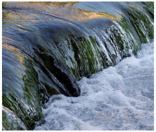
- e.g., Wetterich equation:

$$\partial_k \Gamma_k = \frac{1}{2} \mathrm{Tr} \frac{1}{\Gamma_k^{(2)} + R_k} \partial_k R_k$$

- RG trajectory: $\Gamma_{k=\Lambda} = S_{\text{bare}} = \int \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \bar{q}\,(\mathrm{i}\not{\partial} + g\not{A})\, q$



RG flow in Theory Space



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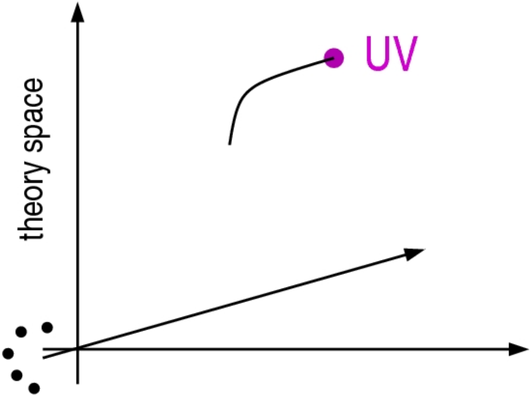

RG flow in Theory Space

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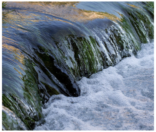
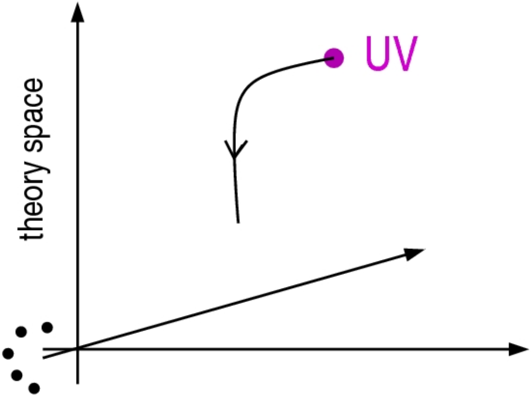


$$\partial_k \Gamma_k = \frac{1}{2} \mathrm{Tr} \frac{1}{\Gamma_k^{(2)} + R_k} \partial_k R_k$$

▷ RG trajectory:



RG flow in Theory Space

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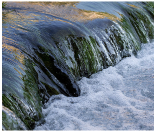
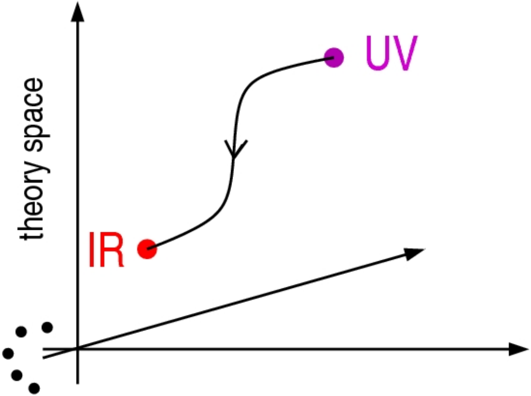


$$\partial_k \Gamma_k \quad = \quad \frac{1}{2} \, \mathrm{Tr} \, \frac{1}{\Gamma_k^{(2)} + R_k} \, \partial_k R_k$$

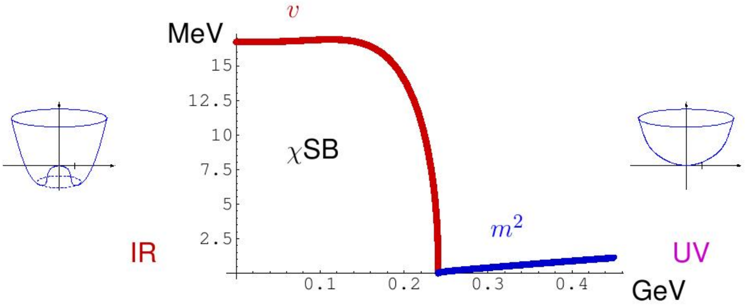
▷ RG trajectory: $\Gamma_{k \to 0} = \Gamma$



Example: RG flow towards chiral symmetry breaking in QCD

▷ Approach to chiral symmetry breaking in SU(3) ($N_f = 1$) QCD:

▷ effective potential for $\phi \sim \langle \bar{q}_R q_L \rangle$:



(without $U_A(1)$ anomaly)

Example: RG flow towards chiral symmetry breaking in QCD

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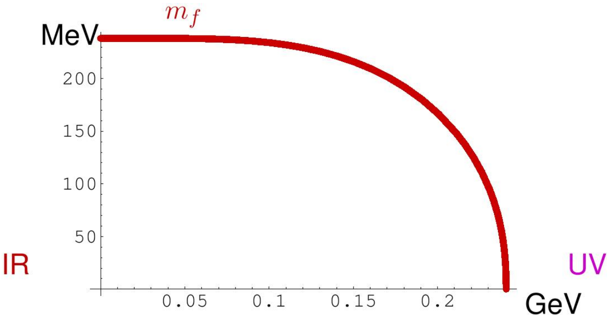


▷ IR prediction: "constituent quark mass"

$$m_f \simeq 250\text{MeV}$$

(without $U_A(1)$ anomaly)

RG flow in strongly coupled systems

QCD: quarks, gluons
cond-mat: electron states
cold gases: atoms

QCD: mesons, baryons
cond-mat: Cooper-pairs, long-range order
cold gases: BEC, superfluidity

RG flow in strongly coupled systems

RG flow in strongly coupled systems

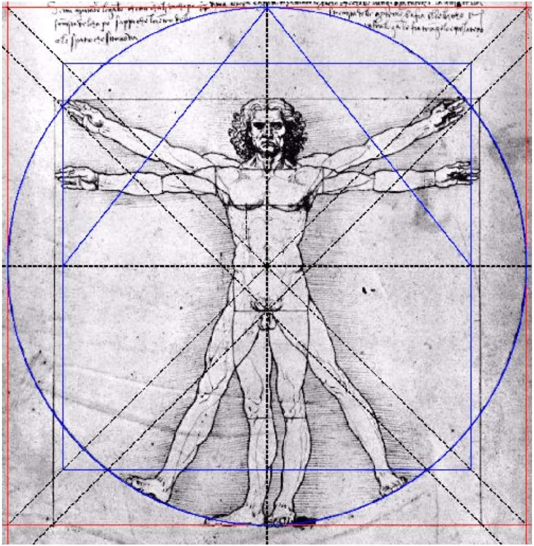
“Wolkenbruch”

Hans-Werner Sahm

Summary IV

- The Renormalization Group: flexible method to investigate strongly-interacting field theories

Where do m_e, m_q, …come from?



70 kg human

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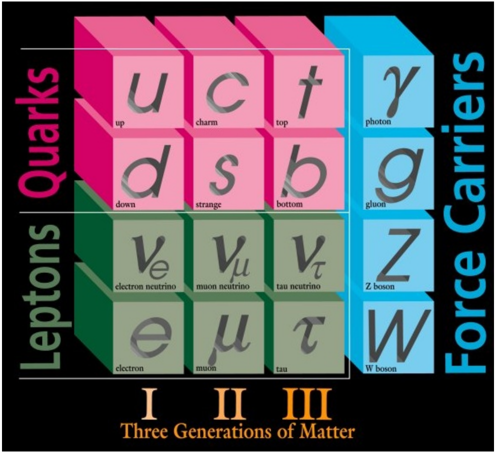
35 g electrons

1,050 kg quarks

68,915 kg vacuum condensates

Building blocks of the universe

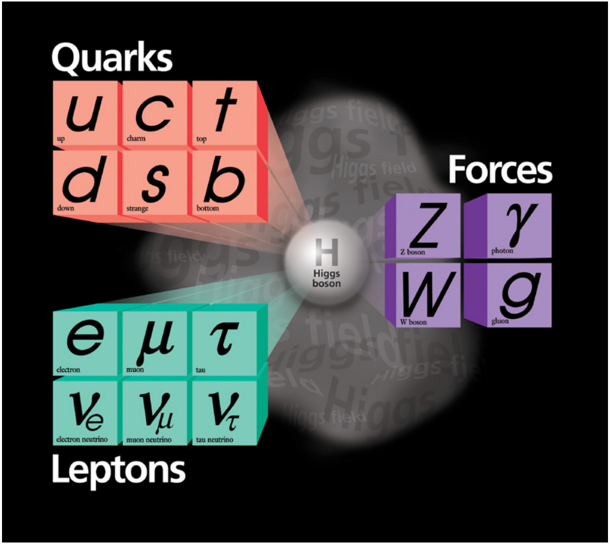


▷ BUT: $m_{\mathrm{e}}, m_{\mathrm{q}}, \dots m_{\mathrm{W}}, m_{\mathrm{Z}} \neq 0$ inconsistent!

problems: electroweak gauge symmetry / renormalizability

Building blocks of the universe

(Englert,Brout,Higgs,Guralnik,Hagen,Kibble 1964)

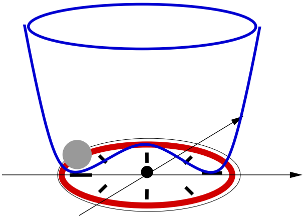


ABEHGHKt'H mechanism

(Anderson, Brout, Englert, Higgs, Guralnik, Hagen, Kibble, t'Hooft)

▷ "spontaneously broken" (hidden) symmetry generates masses

$$\langle H \rangle \sim v \simeq 246\text{GeV}$$ "Fermi scale"



- W, Z masses a la superconductivity:

$$(D_\mu[W]H)^\dagger (D^\mu[W]H) \sim g'^2 v^2 W_\mu W^\mu$$

- $m_\mathrm{e}, m_\mathrm{q}, \ldots$ from Yukawa couplings:

$$y_e \bar{\psi}^a_\mathrm{L} H^a e_\mathrm{R} + \ldots \sim y_e v \bar{e}_\mathrm{L} e_\mathrm{R}$$

ABEHGHKt'H mechanism

(Anderson, Brout, Englert, Higgs, Guralnik, Hagen, Kibble, t'Hooft)

▷ all masses ∼ Fermi scale:

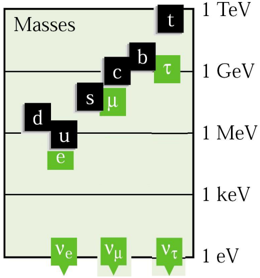
$$m_{W,Z,e,\mu,\tau,u,d,s,c,b,t} \sim v$$

▷ mass values parametrized by (Yukawa) couplings:

$$\text{e.g.,} \quad m_e = y_e v, \;\; m_t = y_t v, \ldots$$

▷ origin of hierarchy ...?

$$y_e \simeq 2.1 \times 10^{-6}, \ldots, y_t \simeq 0.7$$

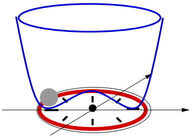


The Higgs Boson

(Higgs 1964)

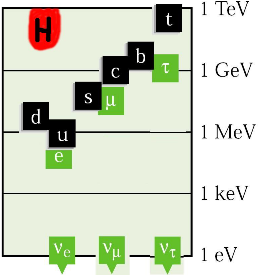
▷ Higgs boson: excitation on top of condensate

$$H(x) \;\sim\; v + h(x)$$



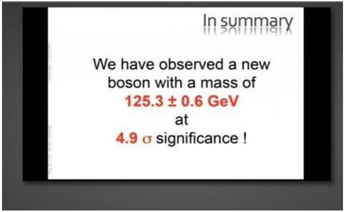
▷ Higgs self-coupling λH^4 induces mass:

$$m_h \;=\; \sqrt{\lambda}\, v$$



Search for the Higgs boson

▷ 4 Jul. 2012
ATLAS & CMS
@CERN



▷ 14 Mar 2013, CERN press release:

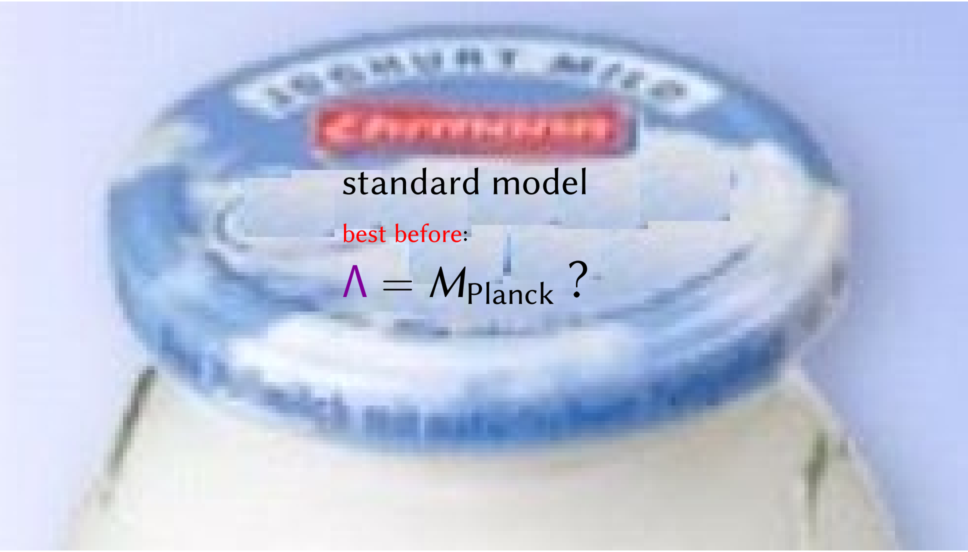
"…the new particle is looking more and more like a Higgs boson …"

$$\text{CMS\& ATLAS'15}: \quad 125.09 \pm 0.21(stat) \pm 0.11(sys) GeV,$$

▷ numbers matter: $\Longrightarrow$


JOGHURT MILD
Ehrmann
Bioghurt
PUR
JOGHURT MILD
Ehrmann
Bioghurt
PUR

Numbers matter



standard model

best before:

$\Lambda = M_{\text{Planck}}$?

Validity range of the standard model

▷ Λ:

- UV cutoff

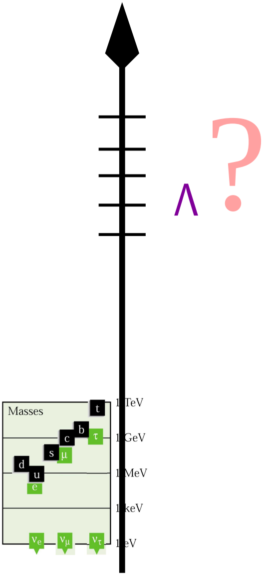
  SM as effective theory

- scale of maximum UV extension

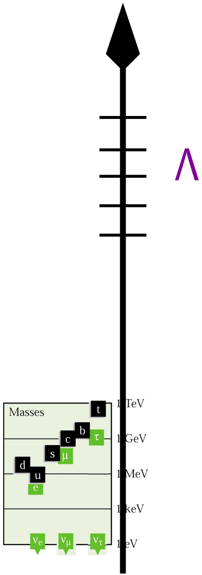
- scale of new physics:
  $\Lambda_{NP} \leq \Lambda$

▷ typical guess: Planck scale

$$\Lambda \stackrel{?}{=} 10^{19}\mathrm{GeV}$$



Reverse engineering the UV physics



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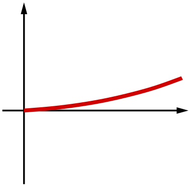

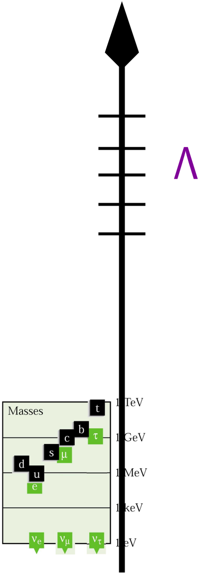

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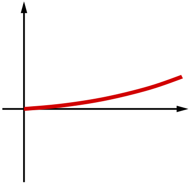

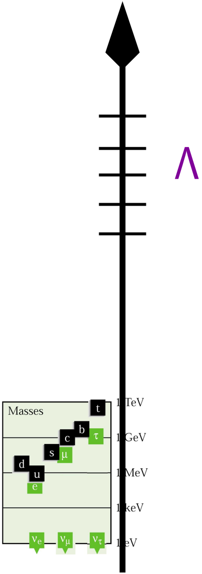

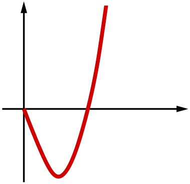

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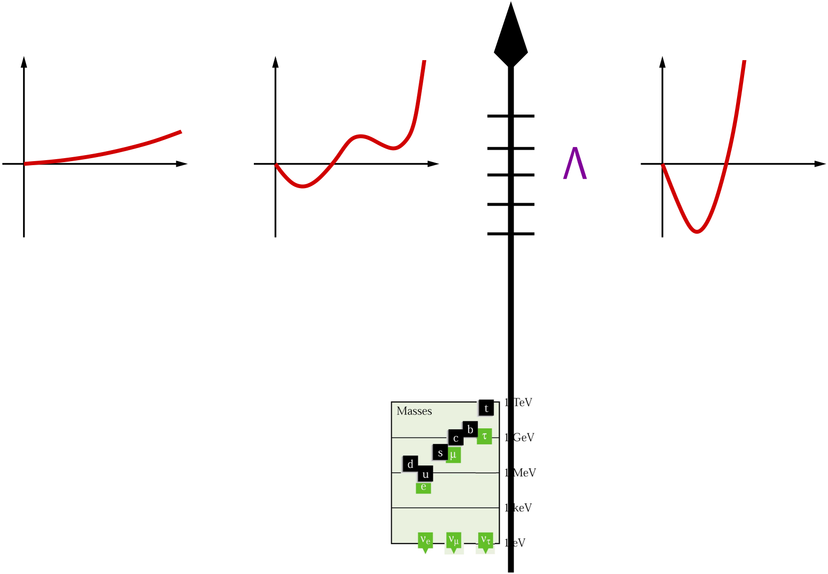

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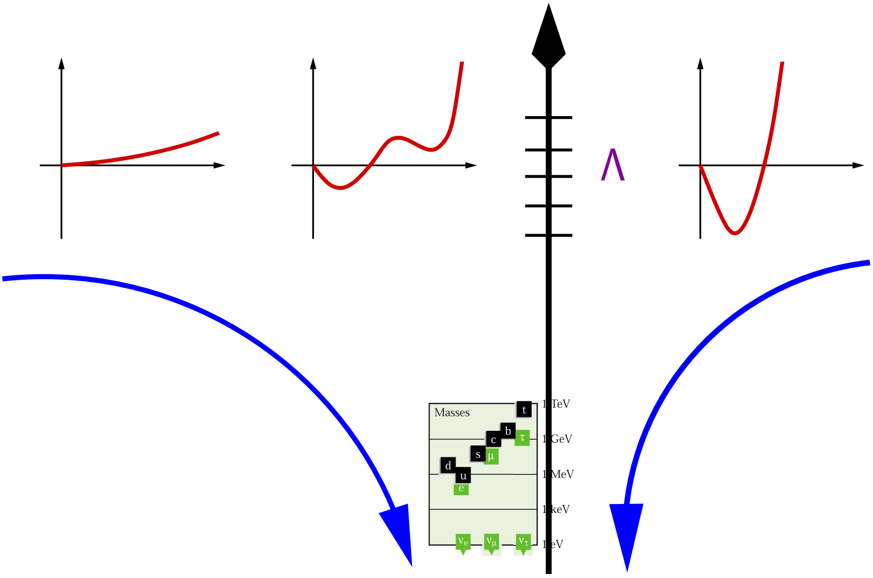

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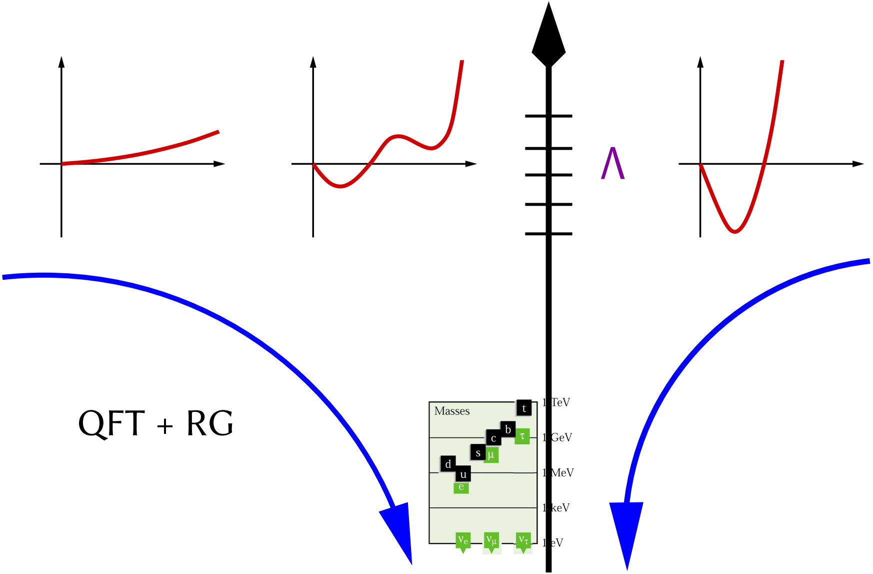
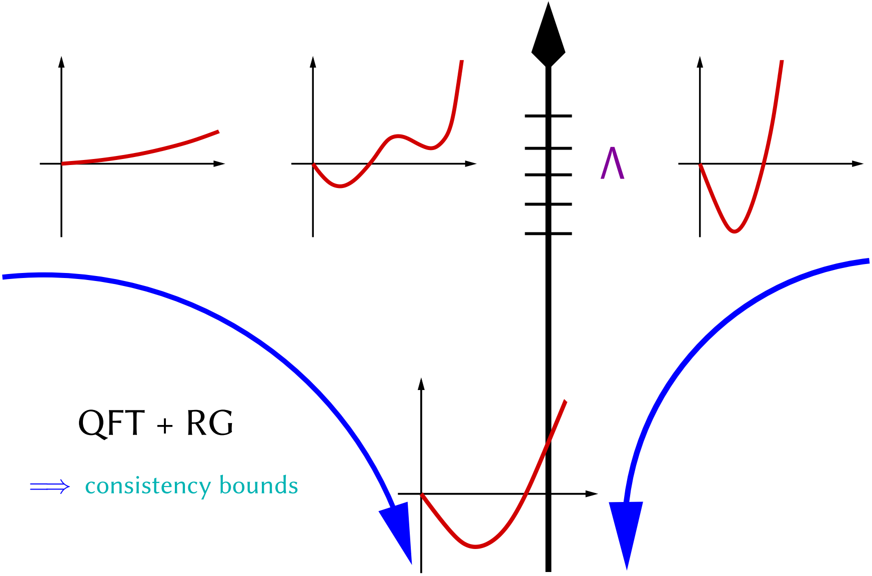


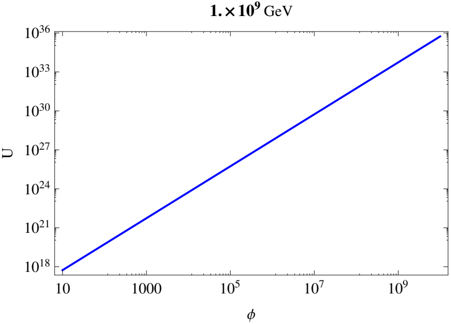
Reverse engineering the UV physics

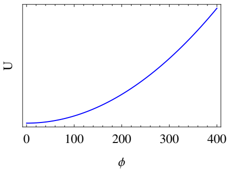


QFT + RG

$\Longrightarrow$ consistency bounds

Effective potential from functional RG

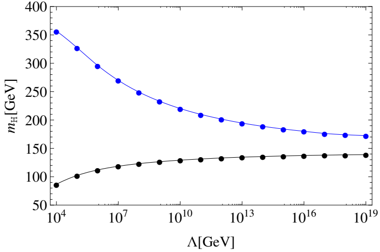


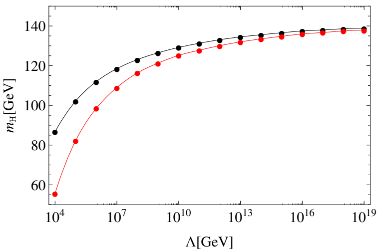


Higgs mass bounds for the Standard Model

(Krive,Linde'76; Maiani,Parisi,Petronzio'78;...HG, Sondenheimer'13,'14)

▷ upper triviality/unitarity bound (∼ strong coupling in UV)





▷ lower "stability" bound (∼ non-interacting/unstable in UV)

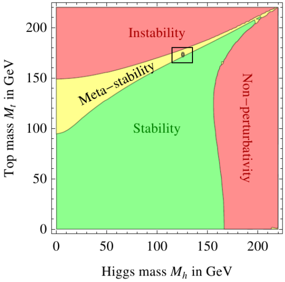
lower "consistency" bound (∼ stable but more involved UV theory)

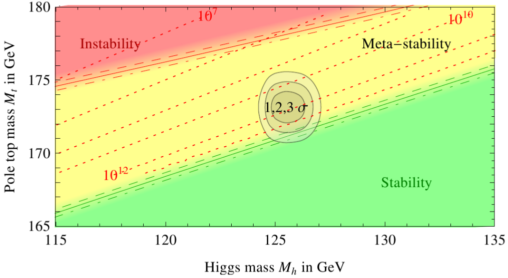
$\Longrightarrow$ if $\Lambda = 10^{19}$GeV, $\quad 128\text{ GeV} \lesssim m_h \lesssim 150\text{ GeV}$

Experiment: $\quad m_h \simeq 125$GeV $\quad$!?!

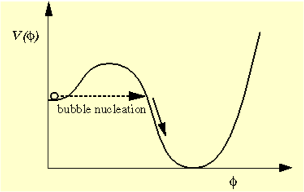
Perturbative lower Bound of Higgs boson mass

▷ "Near critical" standard model: (Buttazzo et al.'13)





NNLO calculation (Degrassi et al.'12)

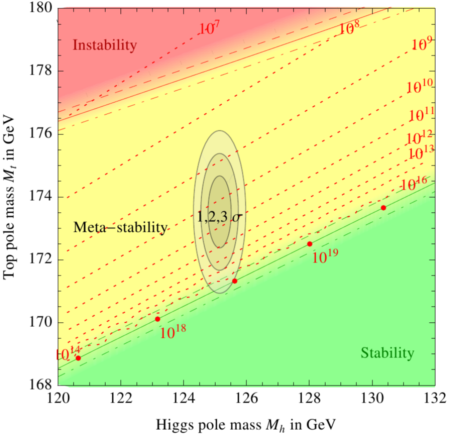


▷ meta-stability:

tunneling time > age of universe

Lower Bound of Higgs boson mass

▷ "Near critical" standard model: (Buttazzo et al.'13: update v4)



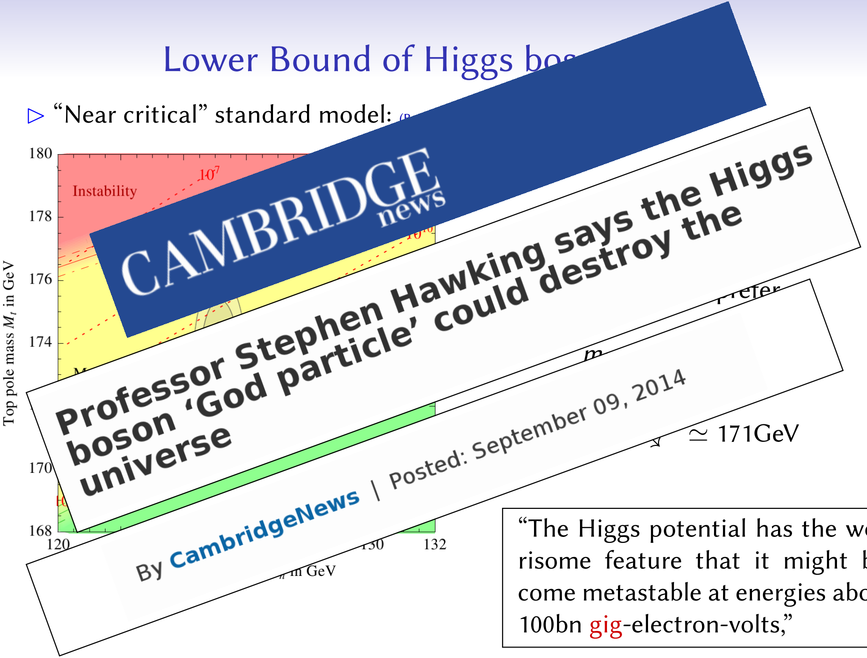
"Stability" seems to prefer

$m_h \nearrow \quad \simeq 130\text{GeV}$

or $m_t \searrow \quad \simeq 171\text{GeV}$

Lower Bound of Higgs bos

▷ "Near critical" standard model:



CAMBRIDGE news

Professor Stephen Hawking says the Higgs boson 'God particle' could destroy the universe

By CambridgeNews | Posted: September 09, 2014

prefer

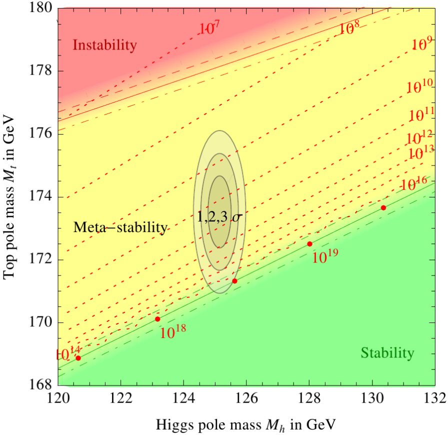
m

$\simeq 171\text{GeV}$

"The Higgs potential has the worrisome feature that it might become metastable at energies above 100bn gig-electron-volts,"

Lower Bound of Higgs boson mass

▷ "Near critical" standard model: (Buttazzo et al.'13: update v4)



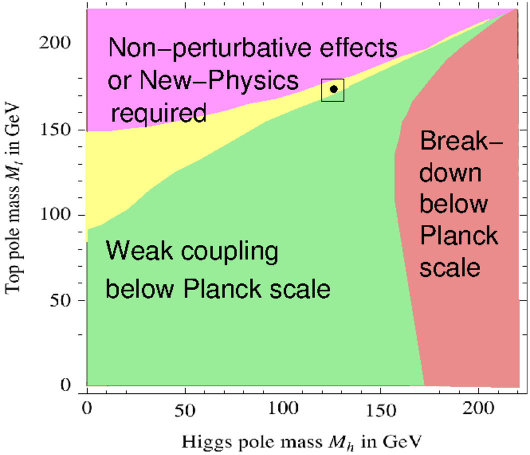
"Stability" seems to prefer

$m_h \nearrow \quad \simeq 130\text{GeV}$

or $m_t \searrow \quad \simeq 171\text{GeV}$

"consistency" bound relaxes tension

"Best-before date" of the Standard Model



▷ Near-Critical Standard Model?

(Buttazzo et al.'13; HG, Gneiting, Sondenheimer'14)

Summary V

- mass parameters $m_{W,Z,\mathrm{e},\mu,\tau,u,d,s,c,b,t}$ from ABEHGHKt'H mechanism

  mass hierarchy parametrized by (Yukawa couplings)

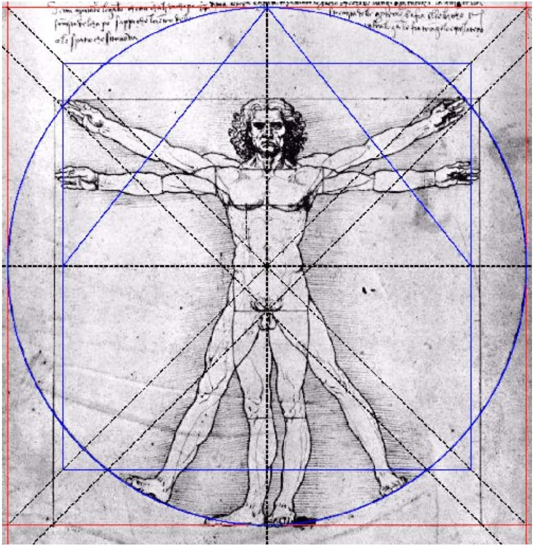
- New massive excitation

  Higgs boson (discovered in 2012)

- m_h, m_t closely related to "best-before date" of standard model

  "Near-criticality" of standard model

Wie schwer bin ich?



70 kg Mensch

35 g Elektronen
(Higgs)

1,050 kg Quarks
(Higgs)

68,915 kg
Vakuumkondensate
(QCD)

Wie schwer bin ich?

…viel Physik hinter einer Zahl …