# Das Standardmodell der Elementarteilchen

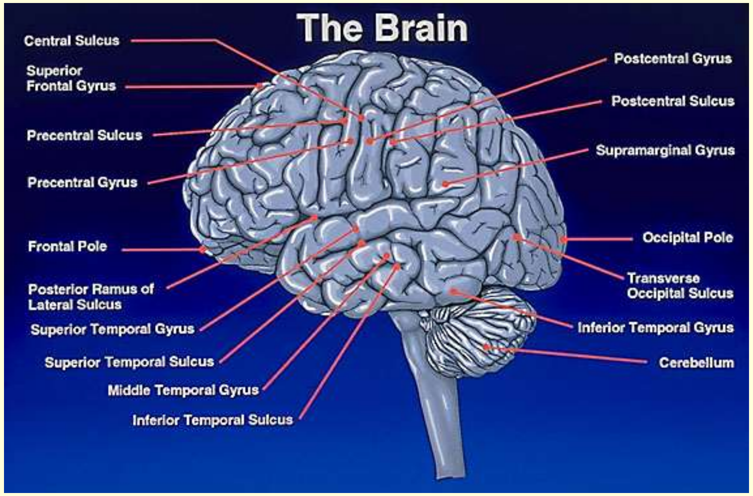
Claus Grupen
Universität Siegen

*„Ob mir durch Geistes Kraft und Mund nicht manch Geheimnis würde kund ... Daß ich erkenne, was die Welt im Innersten zusammenhält, schau' alle Wirkenskraft und Samen, und tu' nicht mehr in Worten kramen."*

*Goethe, Faust I*

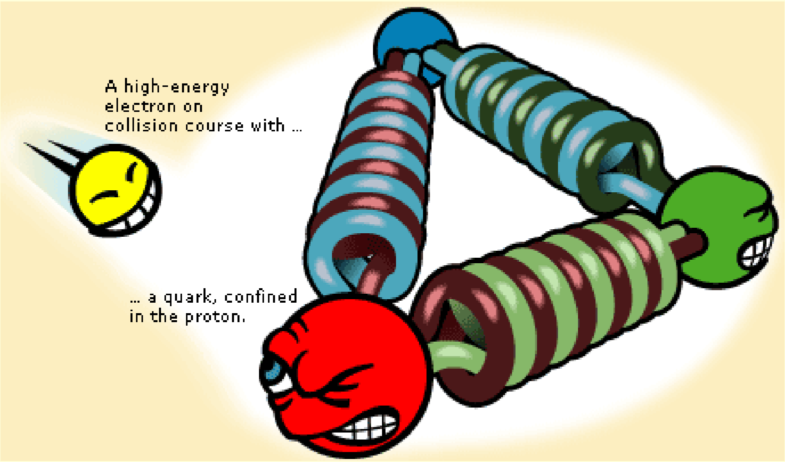
- Das Komplexe, das Kleine und das  Große
  (Quarks und Galaxien)
- Entdeckung von Elementarteilchen
  (ein wenig Historie)
- Klassifizierung der Elementarteilchen
  (Das Periodensystem der Elementarteilchen)
- Die Kräfte, die die Welt zusammenhalten
- Vereinigung der Kräfte
- Das fehlende Higgsteilchen
- Der Large Hadron Collider
  (SUSY und Higgs-Suche)
- Kosmologischer Ausblick

# Die drei großen Fragen

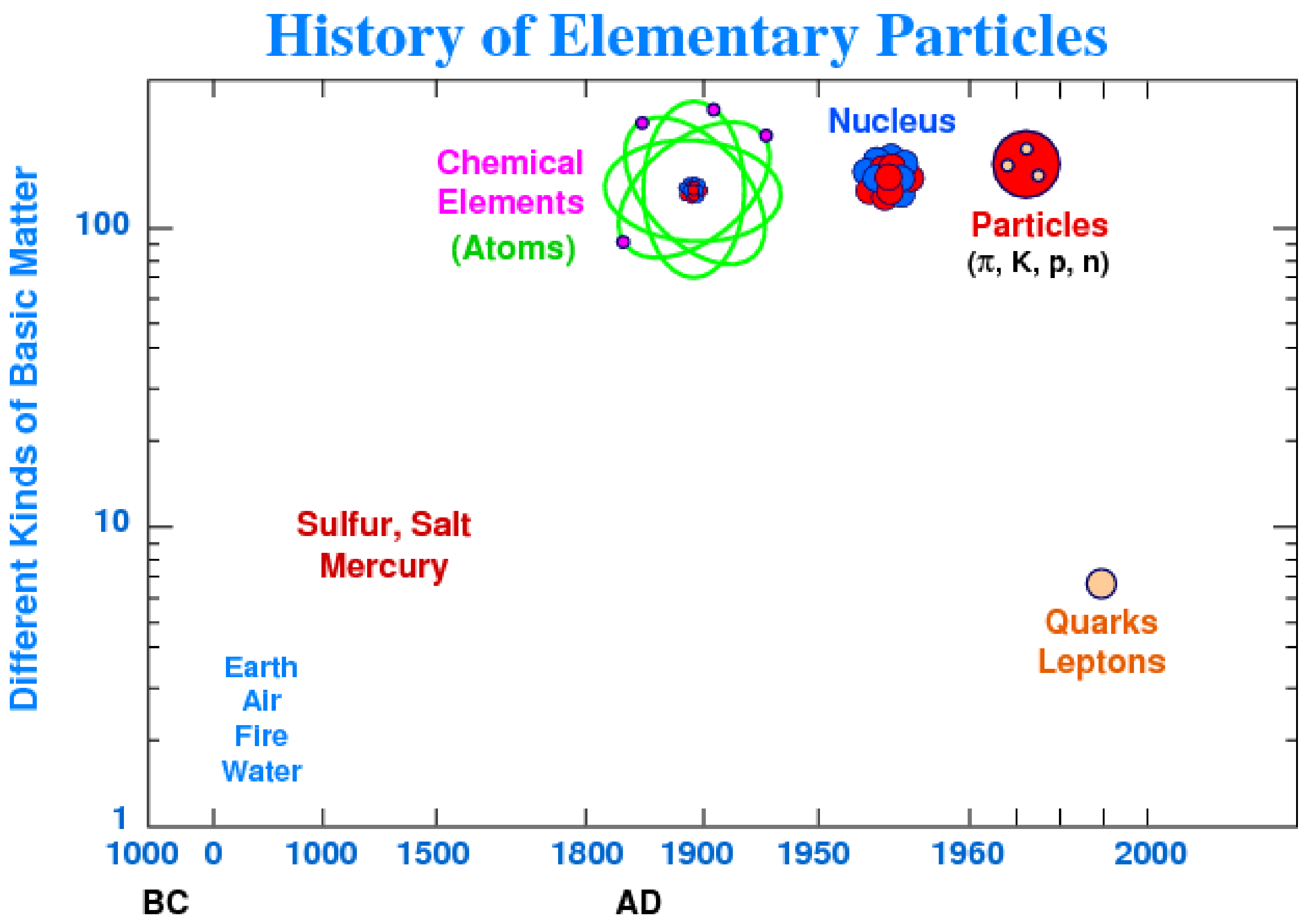


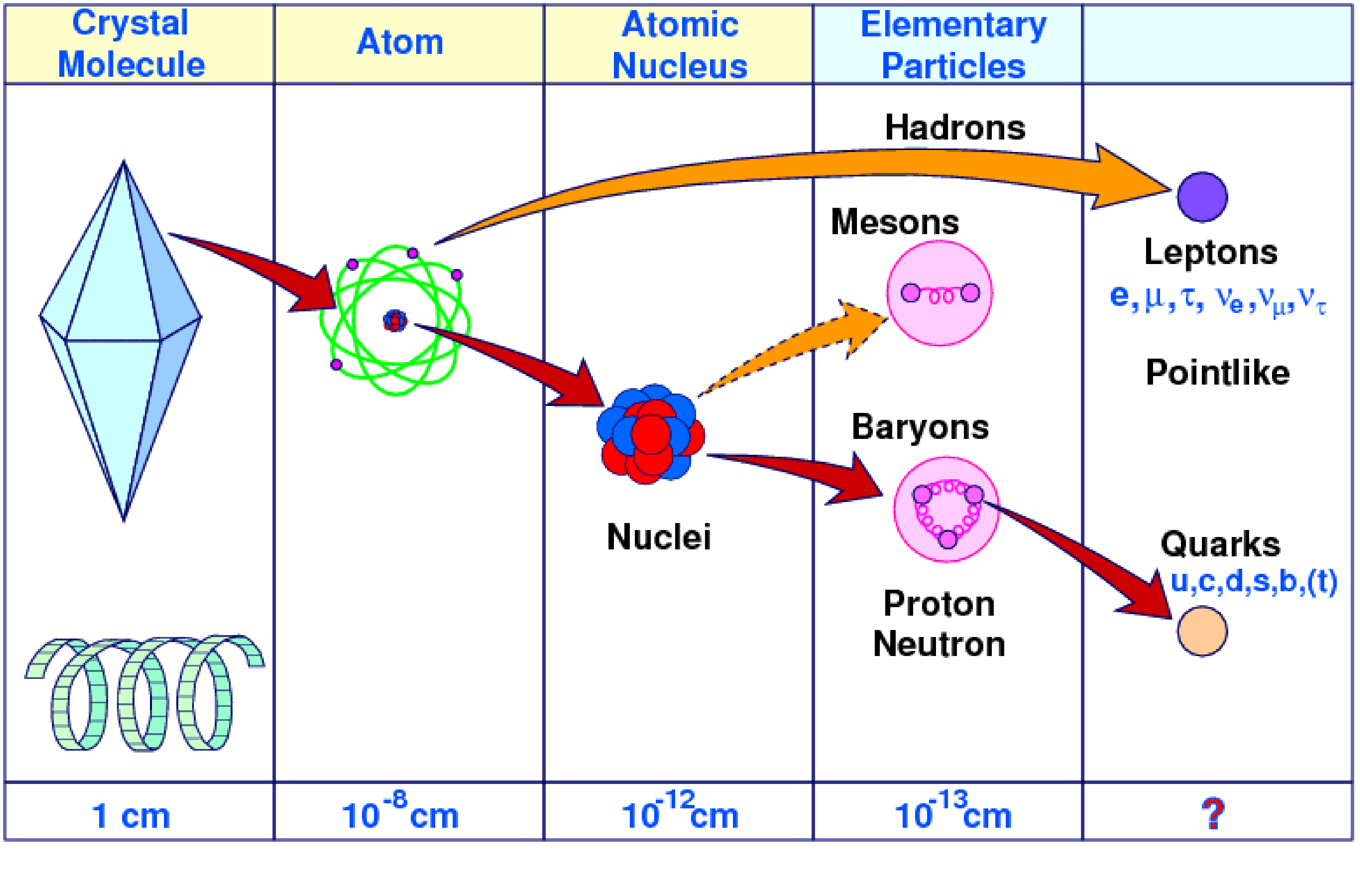

$10^{14}$ Synapsen, 6 x $10^{25}$ Atome

$10^{11}$ Galaxien mit $10^{22}$ Sternen




Quarks und Elektronen < 10 $^{-18}$ Meter

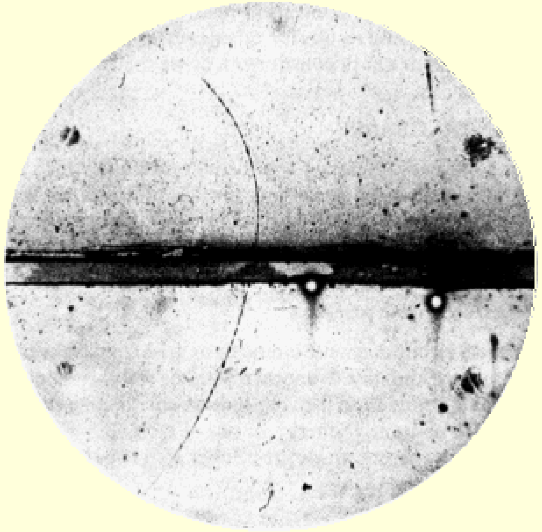

History of Elementary Particles
Different Kinds of Basic Matter
100
10
1
1000
0
1000
1500
1800
1900
1950
1960
2000
BC
AD
Chemical
Elements
(Atoms)
Nucleus
Particles
(π, K, p, n)
Sulfur, Salt
Mercury
Earth
Air
Fire
Water
Quarks
Leptons



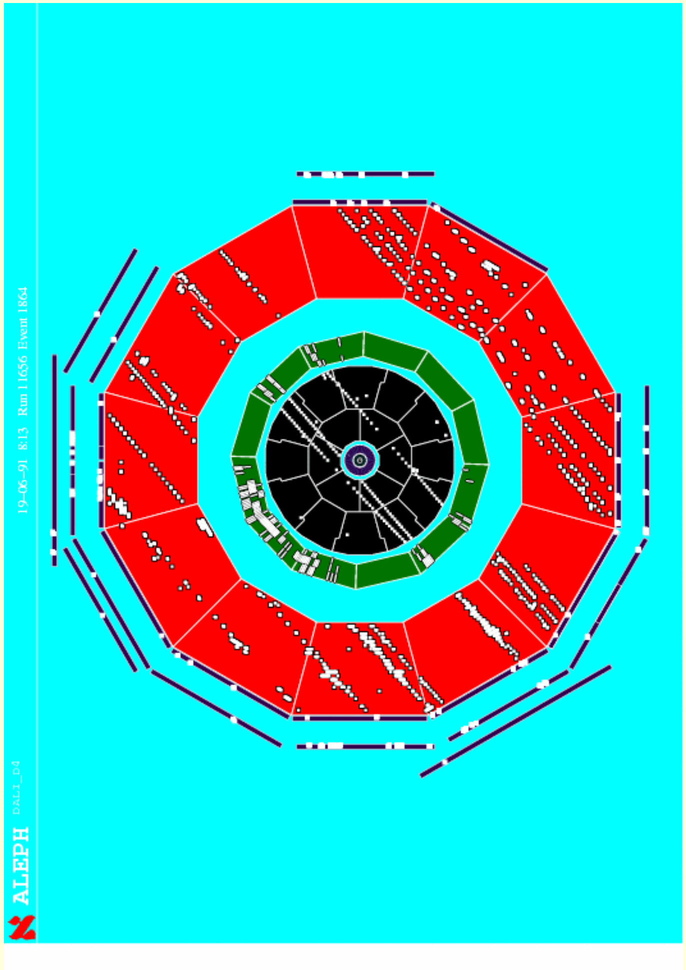
Crystal Molecule
Atom
Atomic Nucleus
Elementary Particles
Hadrons
Mesons
Leptons
e, μ, τ, $\nu_e$, $\nu_\mu$, $\nu_\tau$
Pointlike
Baryons
Nuclei
Quarks
u,c,d,s,b,(t)
Proton
Neutron
1 cm
$10^{-8}$cm
$10^{-12}$cm
$10^{-13}$cm
?

# Entdeckung der Elementarteilchen

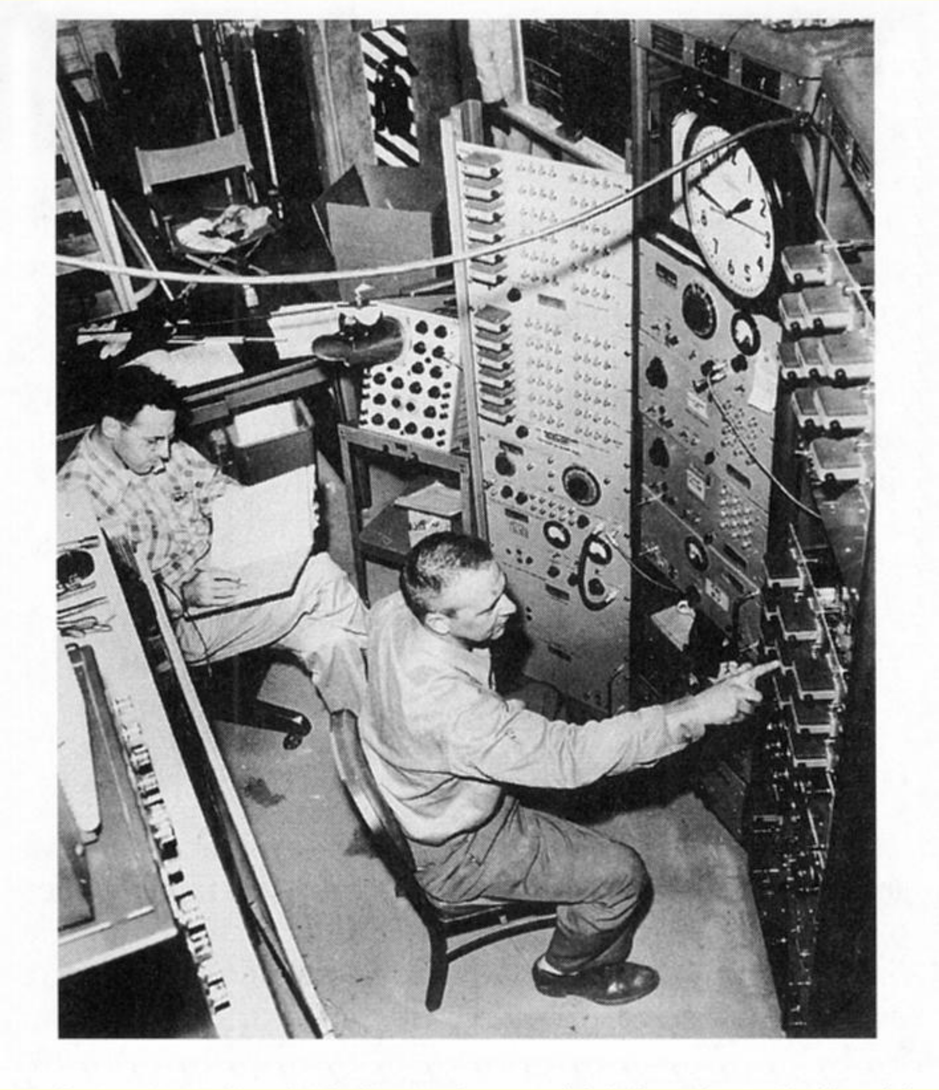

1897 Elektron



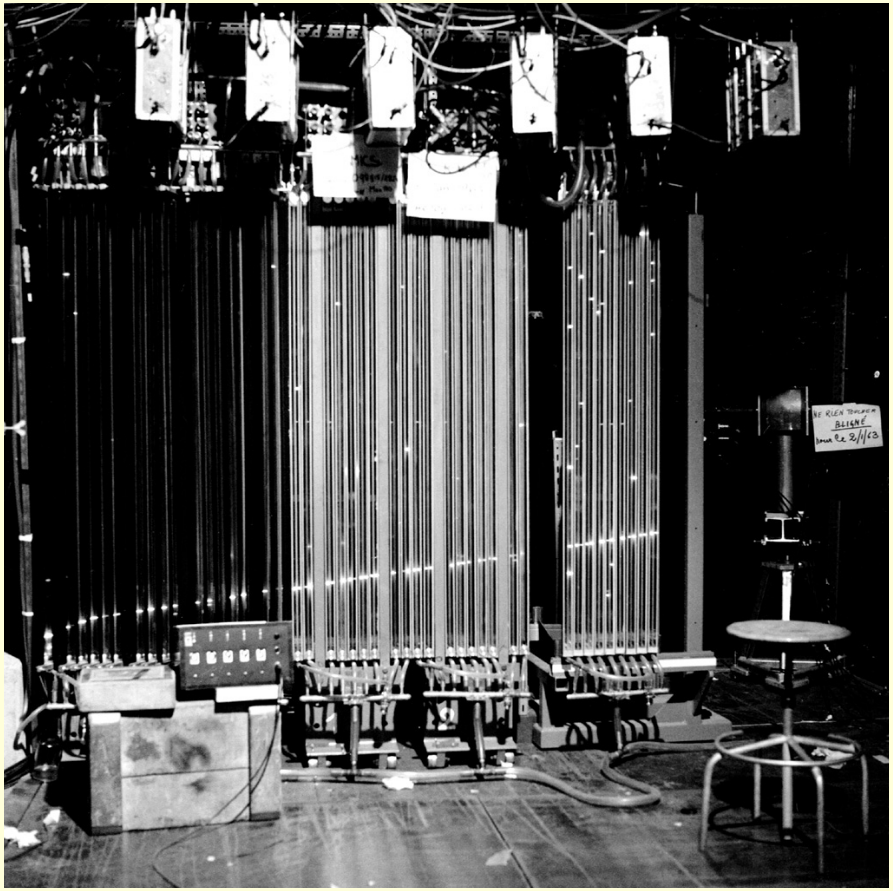
1932 Positron



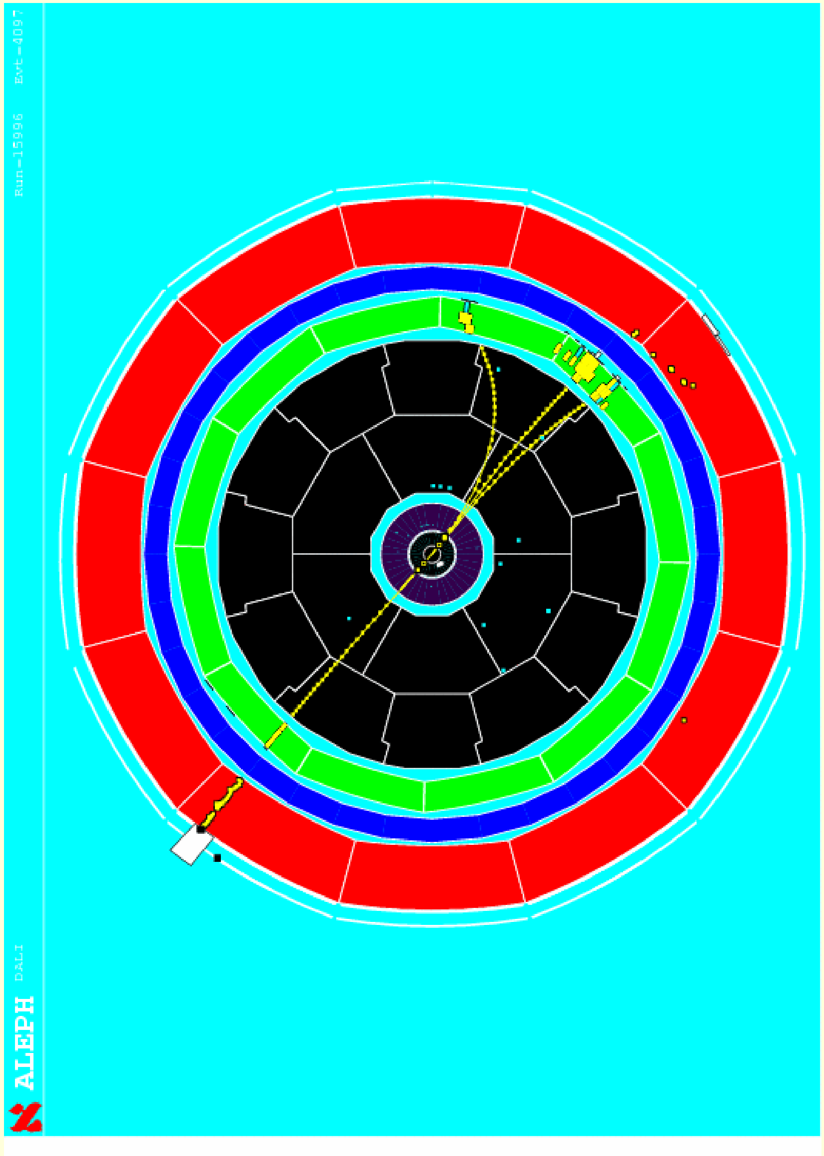

1937 Muon

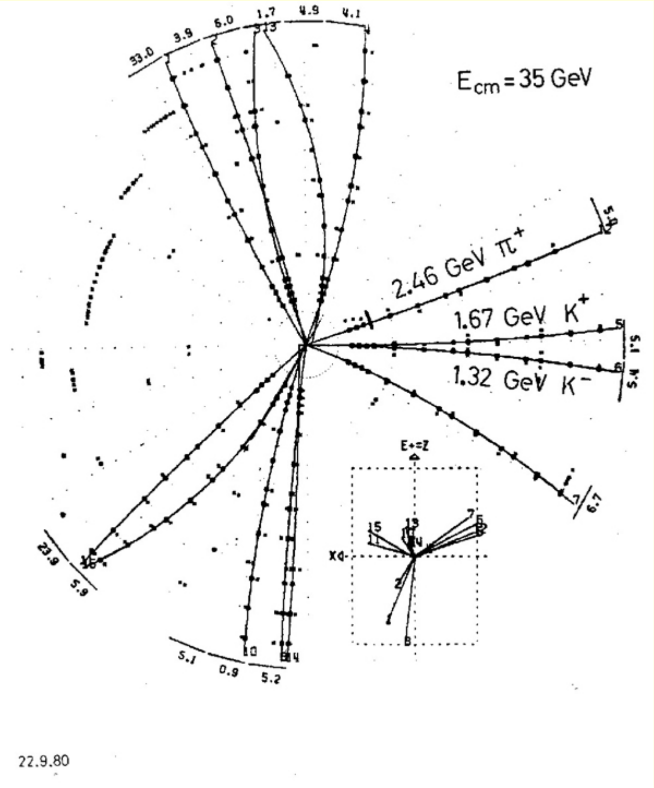


1956 Elektron-Antineutrino



1962 Myon-Neutrino




1979 Gluon

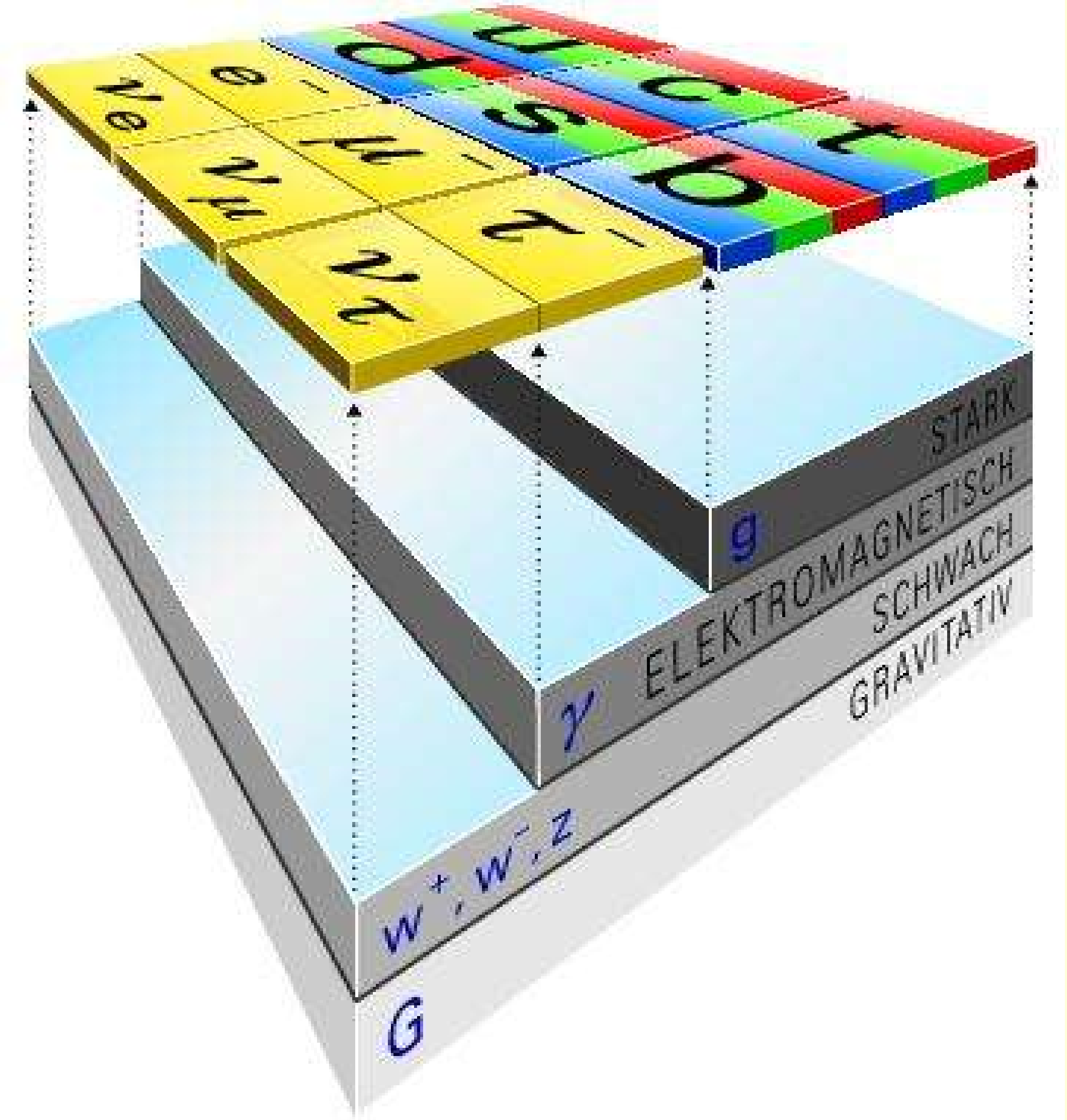
1975 Tau

# Fundamentale Materieteilchen (Fermionen)

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

+ Antiteilchen



STARK
ELEKTROMAGNETISCH
SCHWACH
GRAVITATIV
g
γ
w+, w−, z
G

# Quarks sind farbig

Betrachte
$$R = \frac{\text{Wirkungsquerschnitt} \;\; e^+ e^- \rightarrow \text{Hadronen}}{\text{Wirkungsquerschnitt} \;\; e^+ e^- \rightarrow \text{Muon} - \text{Paare}}$$

$$\sigma \left( e^+ e^- \rightarrow \mu^+ \mu^- \right) \propto \alpha^2 \cdot 1/\text{Energie}^2$$

denn [σ] ist cm²; (h = c = 1 angenommen) ➡

de Broglie-Beziehung λ = h / p ⇒ cm = 1 / Energie

exakt
$$\sigma \left( e^+ e^- \rightarrow \mu^+ \mu^- \right) = \frac{4}{3} \pi \alpha^2 \cdot \frac{1}{s}$$

s - Quadrat der Schwerpunktsenergie

aber $$\alpha = \frac{e^2}{\hbar c}$$

für Quarks ist die Ladung aber $+\frac{2}{3}\,e$ (für u, c, t)

bzw. $-\frac{1}{3}\,e$ (für d, s, b)

also $$\sigma\left(e^+ e^- \rightarrow q\,\bar{q}\right) = \frac{4}{3}\,\pi\,\alpha\,\alpha(q) \cdot \frac{1}{s}$$

damit wird

$$R = \Sigma\,\alpha\left(q\right) = \sum e_q^2 =$$ Summe über die Quarkladungen zum Quadrat,

z.B. falls nur die drei leichten Quarks angeregt werden können.

$$R = \left(+\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 = \frac{2}{3}$$

aber $$R_{\exp} = 2$$

also kommt jedes Quark in drei Typen ( = Farben) vor.

Alternativ

$$\Omega^- = (sss)$$

$$\text{Spin } (\Omega^-) = \frac{3}{2}\,\hbar$$

Pauli-Prinzip → die drei s-Quarks müssen sich in irgendeiner Quantenzahl unterscheiden : Farbe

$$\Omega^- = s_{rot}\; s_{blau}\; s_{grün}$$

Standard Model of

# FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

## FERMIONS

**matter constituents**
**spin = 1/2, 3/2, 5/2, ...**

### Leptons spin = 1/2

| Flavor | Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| $\nu_e$ electron neutrino | $<1\times10^{-8}$ | 0 |
| e electron | 0.000511 | –1 |
| $\nu_\mu$ muon neutrino | <0.0002 | 0 |
| $\mu$ muon | 0.106 | –1 |
| $\nu_\tau$ tau neutrino | <0.02 | 0 |
| $\tau$ tau | 1.7771 | –1 |

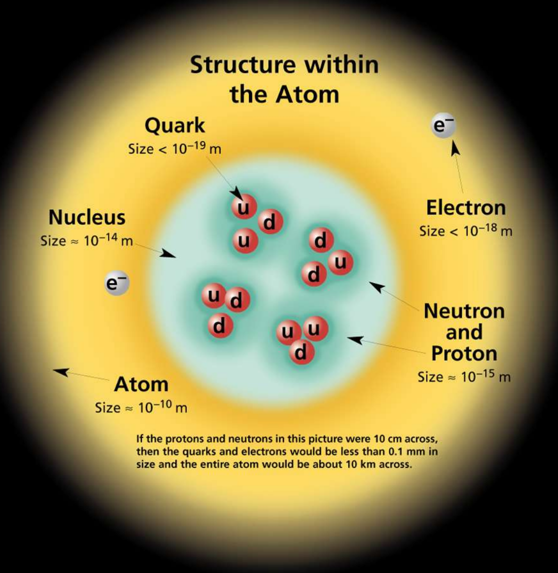
### Quarks spin = 1/2

| Flavor | Approx. Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| u up | 0.003 | 2/3 |
| d down | 0.006 | –1/3 |
| c charm | 1.3 | 2/3 |
| s strange | 0.1 | –1/3 |
| t top | 175 | 2/3 |
| b bottom | 4.3 | –1/3 |

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is $1.60\times10^{-19}$ coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/$c^2$ (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/$c^2$ $= 1.67\times10^{-27}$ kg.




## BOSONS

**force carriers**
**spin = 0, 1, 2, ...**

### Unified Electroweak spin = 1

| Name | Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| $\gamma$ photon | 0 | 0 |
| $W^-$ | 80.4 | –1 |
| $W^+$ | 80.4 | +1 |
| $Z^0$ | 91.187 | 0 |

### Strong (color) spin = 1

| Name | Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| g gluon | 0 | 0 |

**Color Charge**

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

**Quarks Confined in Mesons and Baryons**

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** $qqq$.

**Residual Strong Interaction**

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

## PROPERTIES OF THE INTERACTIONS

| Property \ Interaction | Gravitational | Weak (Electroweak) | Electromagnetic (Electroweak) | Strong: Fundamental | Strong: Residual |
|---|---|---|---|---|---|
| Acts on: | Mass – Energy | Flavor | Electric Charge | Color Charge | See Residual Strong Interaction Note |
| Particles experiencing: | All | Quarks, Leptons | Electrically charged | Quarks, Gluons | Hadrons |
| Particles mediating: | Graviton (not yet observed) | $W^+$ $W^-$ $Z^0$ | $\gamma$ | Gluons | Mesons |
| Strength relative to electromag for two u quarks at: $10^{-18}$ m | $10^{-41}$ | 0.8 | 1 | 25 | Not applicable to quarks |
| Strength relative to electromag for two u quarks at: $3\times10^{-17}$ m | $10^{-41}$ | $10^{-4}$ | 1 | 60 | |
| Strength relative to electromag for two protons in nucleus | $10^{-36}$ | $10^{-7}$ | 1 | Not applicable to hadrons | 20 |

### Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

| Symbol | Name | Quark content | Electric charge | Mass GeV/$c^2$ | Spin |
|---|---|---|---|---|---|
| p | proton | uud | 1 | 0.938 | 1/2 |
| $\bar{p}$ | anti-proton | $\bar{u}\bar{u}\bar{d}$ | –1 | 0.938 | 1/2 |
| n | neutron | udd | 0 | 0.940 | 1/2 |
| $\Lambda$ | lambda | uds | 0 | 1.116 | 1/2 |
| $\Omega^-$ | omega | sss | –1 | 1.672 | 3/2 |

### Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

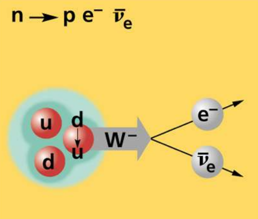
| Symbol | Name | Quark content | Electric charge | Mass GeV/$c^2$ | Spin |
|---|---|---|---|---|---|
| $\pi^+$ | pion | $u\bar{d}$ | +1 | 0.140 | 0 |
| $K^-$ | kaon | $s\bar{u}$ | –1 | 0.494 | 0 |
| $\rho^+$ | rho | $u\bar{d}$ | +1 | 0.770 | 1 |
| $B^0$ | B-zero | $d\bar{b}$ | 0 | 5.279 | 0 |
| $\eta_c$ | eta-c | $c\bar{c}$ | 0 | 2 .980 | 0 |

**Matter and Antimatter**

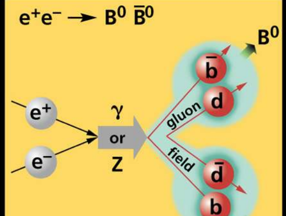
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., $Z^0$, $\gamma$, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

**Figures**

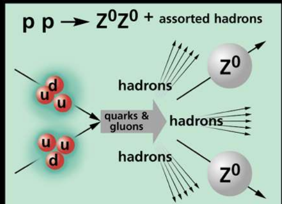
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.




A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.




An electron and positron (antielectron) colliding at high energy can annihilate to produce $B^0$ and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.




Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

**The Particle Adventure**

Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**


**This chart has been made possible by the generous support of:**

U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
**BURLE** INDUSTRIES, INC.

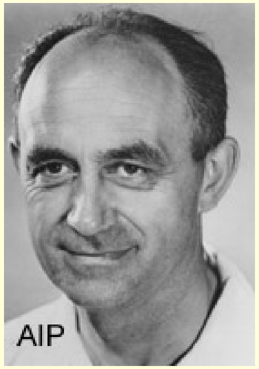


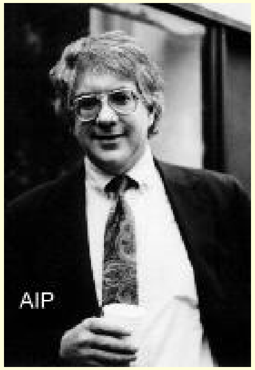

**http://CPEPweb.org**

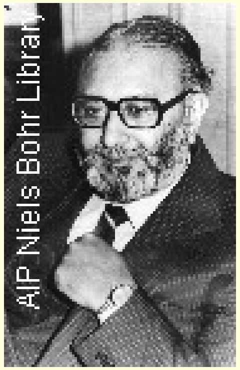
# Kräfte, die die Welt zusammenhalten

Elektrizität
Magnetismus
→ Elektromagnetismus $\gamma$

Elektromagnetismus
Schwache Wechselwirkung
→ elektroschwache Theorie
$W^+$, $W^-$, $Z$




Elektroschwache Theorie

Quantenchromodynamik

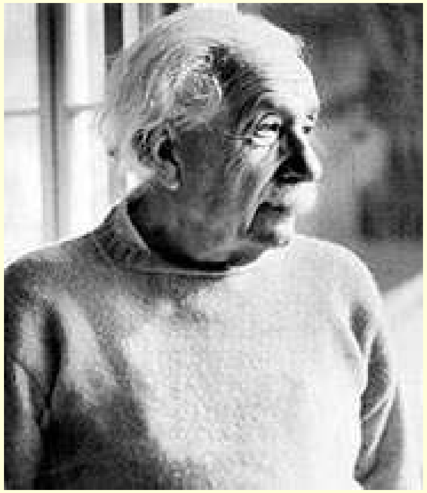
→ GUT



GUT

Gravitation

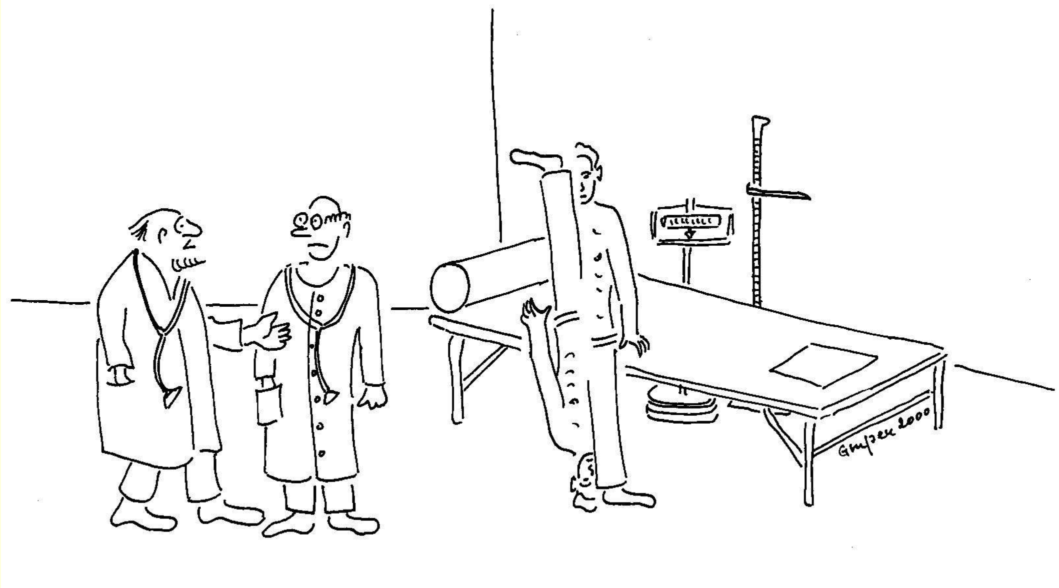
→ Supergravitation, SUSY, Superstringtheorie, TOE

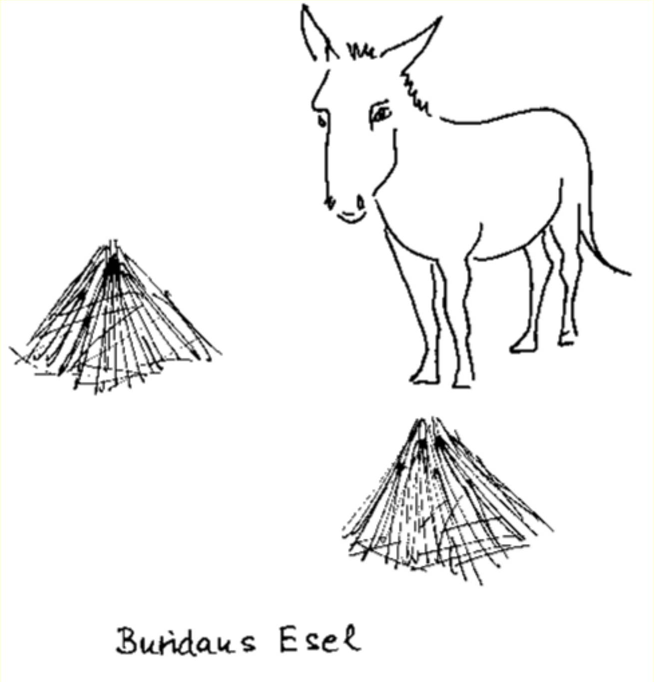


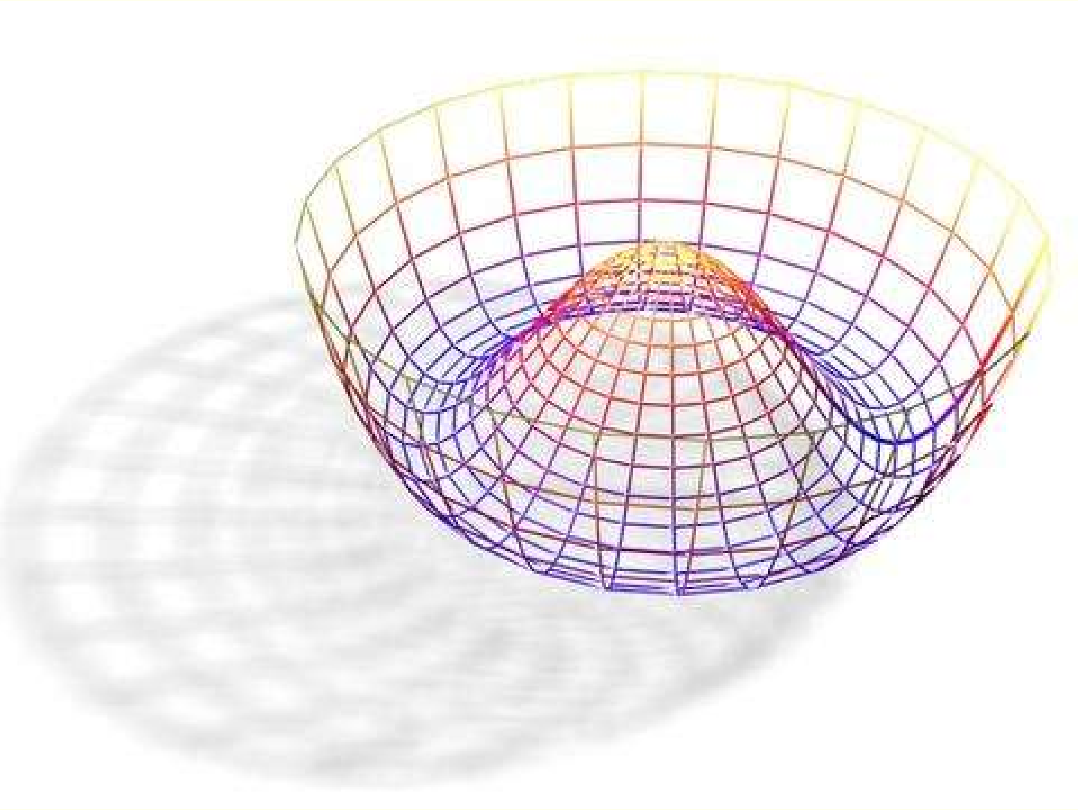
Im Standardmodell sind alle Teilchen masselos

Wer gibt den Teilchen Masse?

→ spontane Symmetriebrechnung



“A severe case of symmetry breaking!”

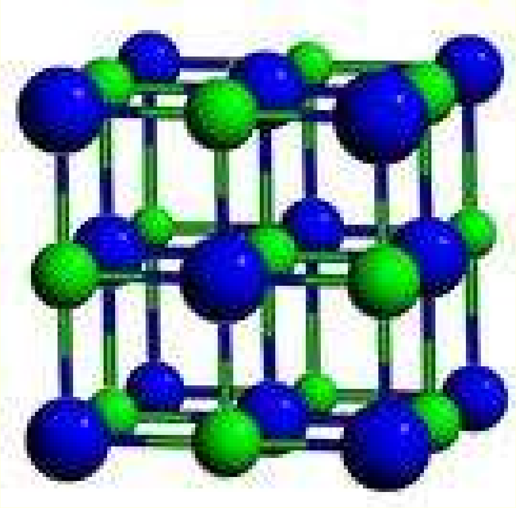


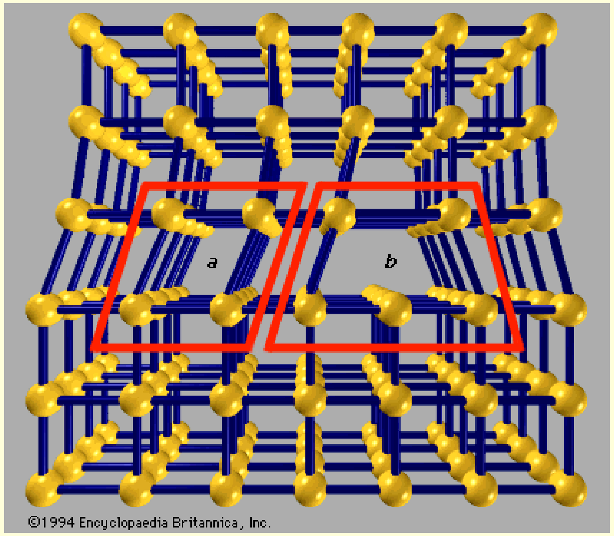


Es gibt verschiedene Higgs-Szenarien:

Im einfachsten Falle:
ein neutrales, skalares Higgsteilchen

# Higgs-Feld-Analogon:

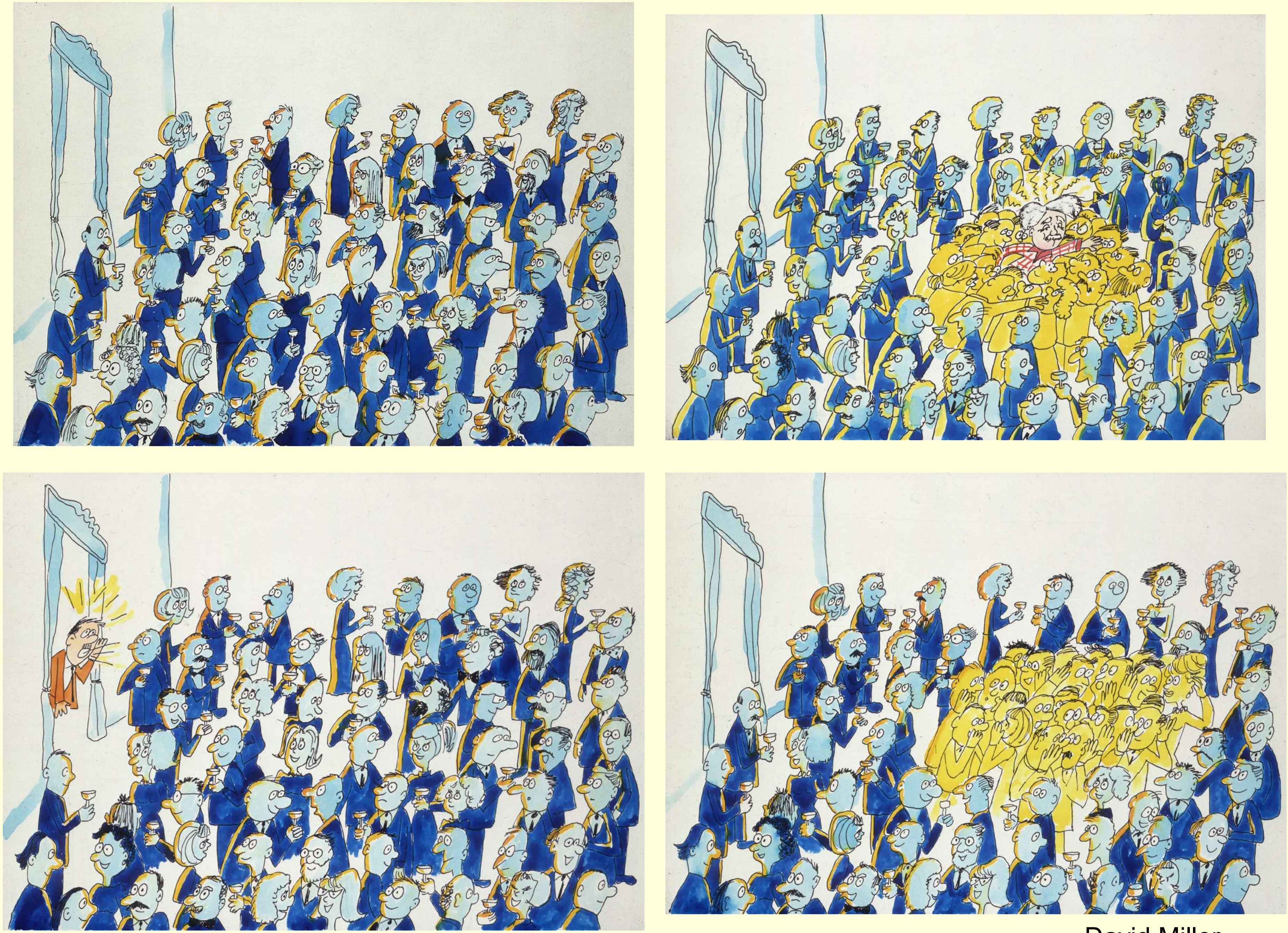





Ein Elektron bewegt sich durch den Kristall.

Es zieht die positiv geladenen Ionen an und erhält eine große effektive Masse.

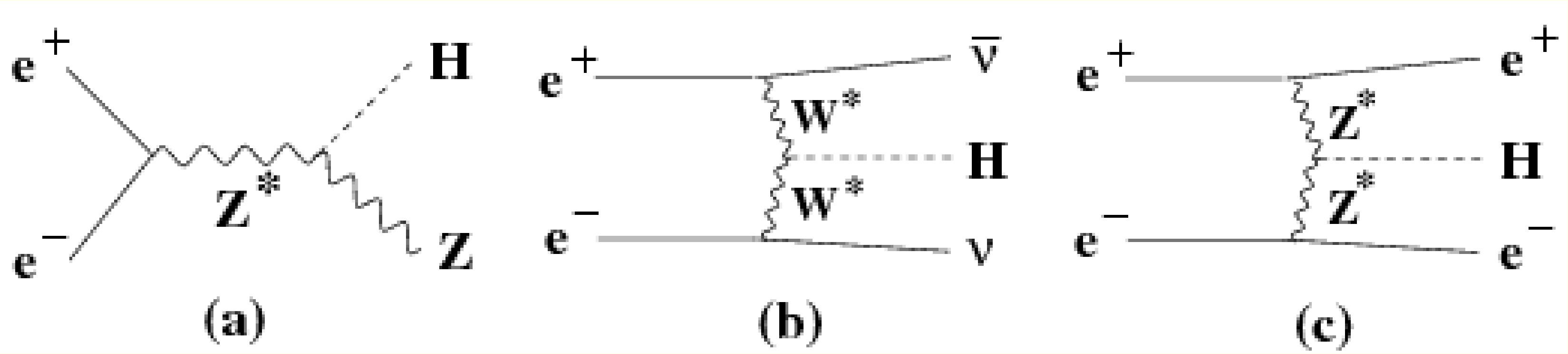
Das Higgsfeld ist ein hypothetisches Gitter, das das Universum erfüllt. Man braucht es z.B., um den W- und Z-Teilchen Masse zu geben.



David Miller

# Higgs-Suche am LEP

Produktionsmechanismus: Higgsstrahlung



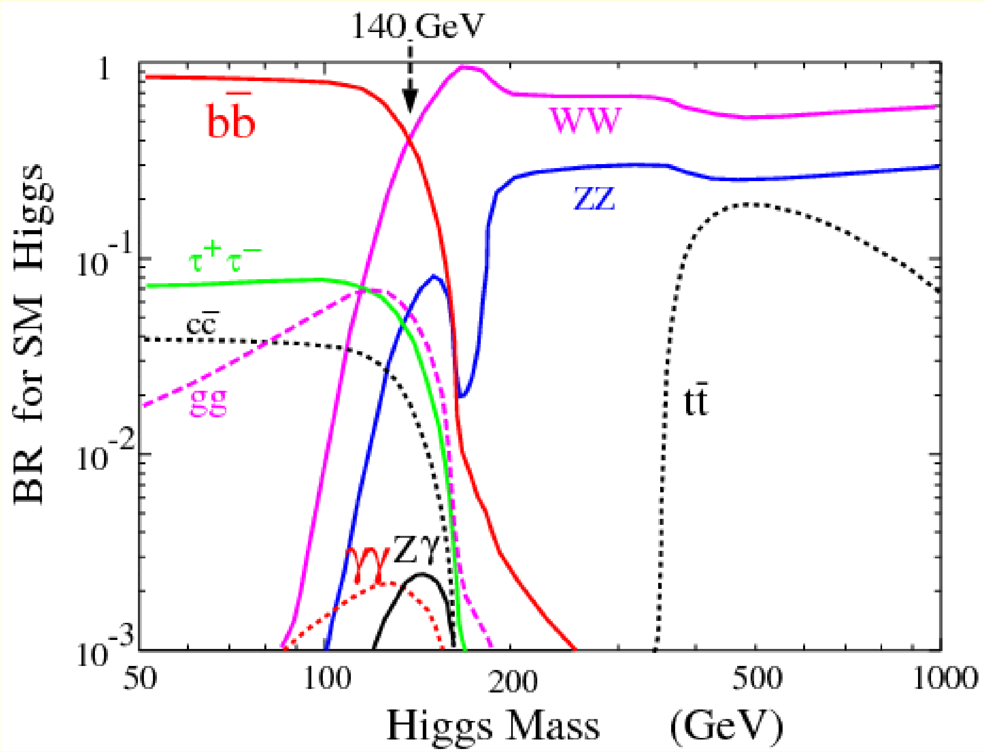

Zerfälle des neutralen Higgs:

$e^+e^- \rightarrow Z\ H$ ➡ vier Jets

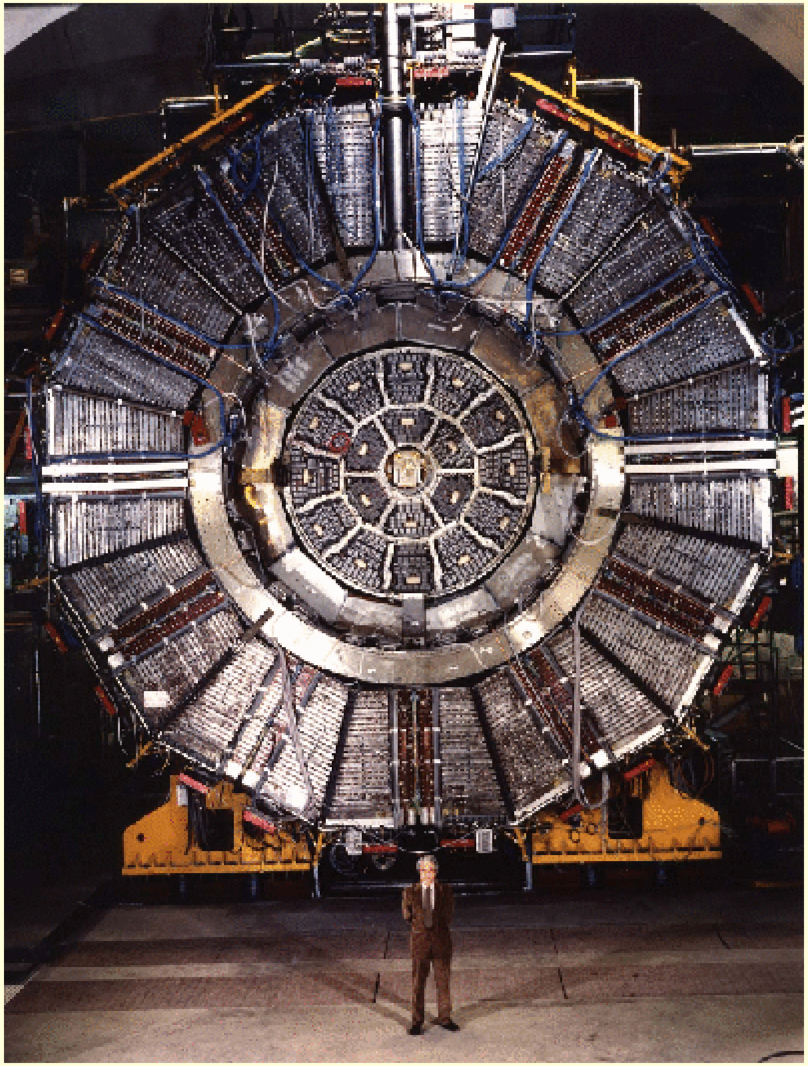
- $Z \rightarrow q\bar{q}$
- $H \rightarrow b\bar{b}$

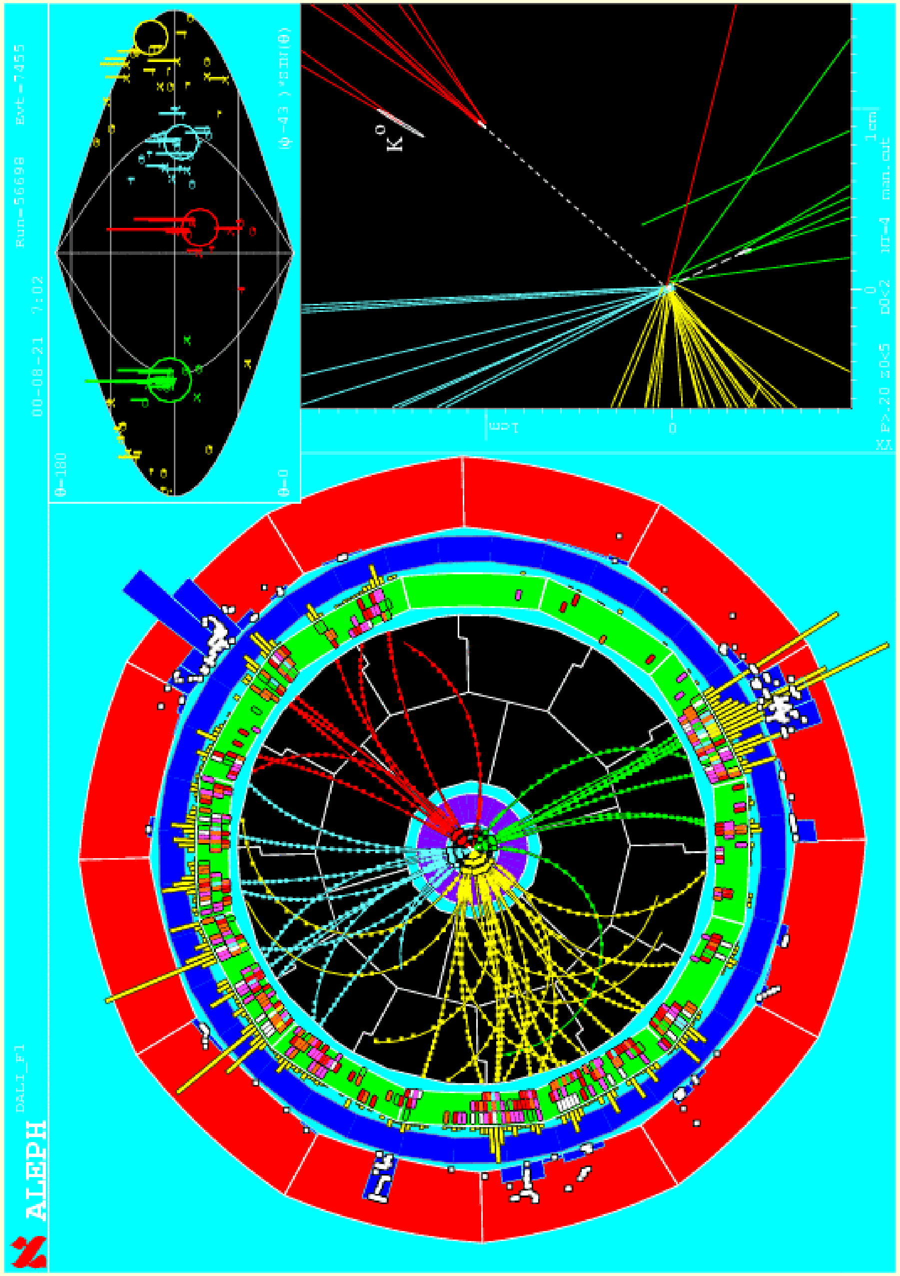
$e^+e^- \rightarrow Z\ H$ ➡ Golden Events

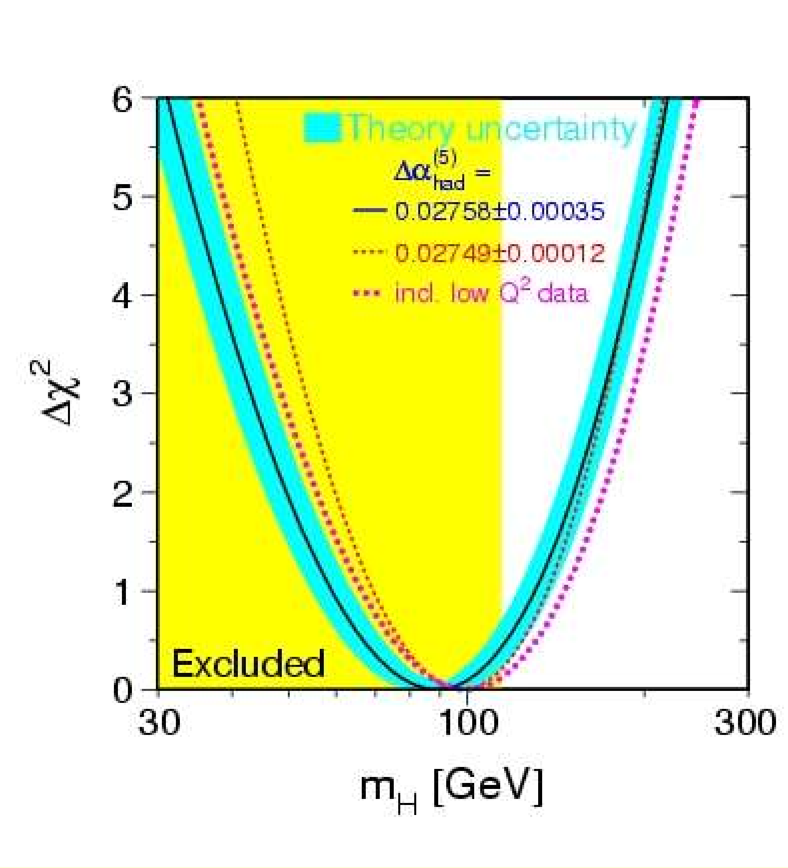
- $Z \rightarrow \mu^+\mu^-$
- $H \rightarrow \mu^+\mu^-$



140 GeV
BR for SM Higgs
Higgs Mass (GeV)
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
50
100
200
500
1000
$b\bar{b}$
WW
ZZ
$\tau^+\tau^-$
$c\bar{c}$
gg
$t\bar{t}$
$\gamma\gamma$
$Z\gamma$


ALEPH


Theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02758±0.00035
0.02749±0.00012
incl. low $Q^2$ data
Excluded
$\Delta\chi^2$
6
5
4
3
2
1
0
30
100
300
$m_H$ [GeV]

# Higgs-Suche am Large Hadron Collider (LHC)

Schwerpunktsenergie 14 TeV

Luminosität L einige $10^{34}$ $cm^{-2}$ $s^{-1}$

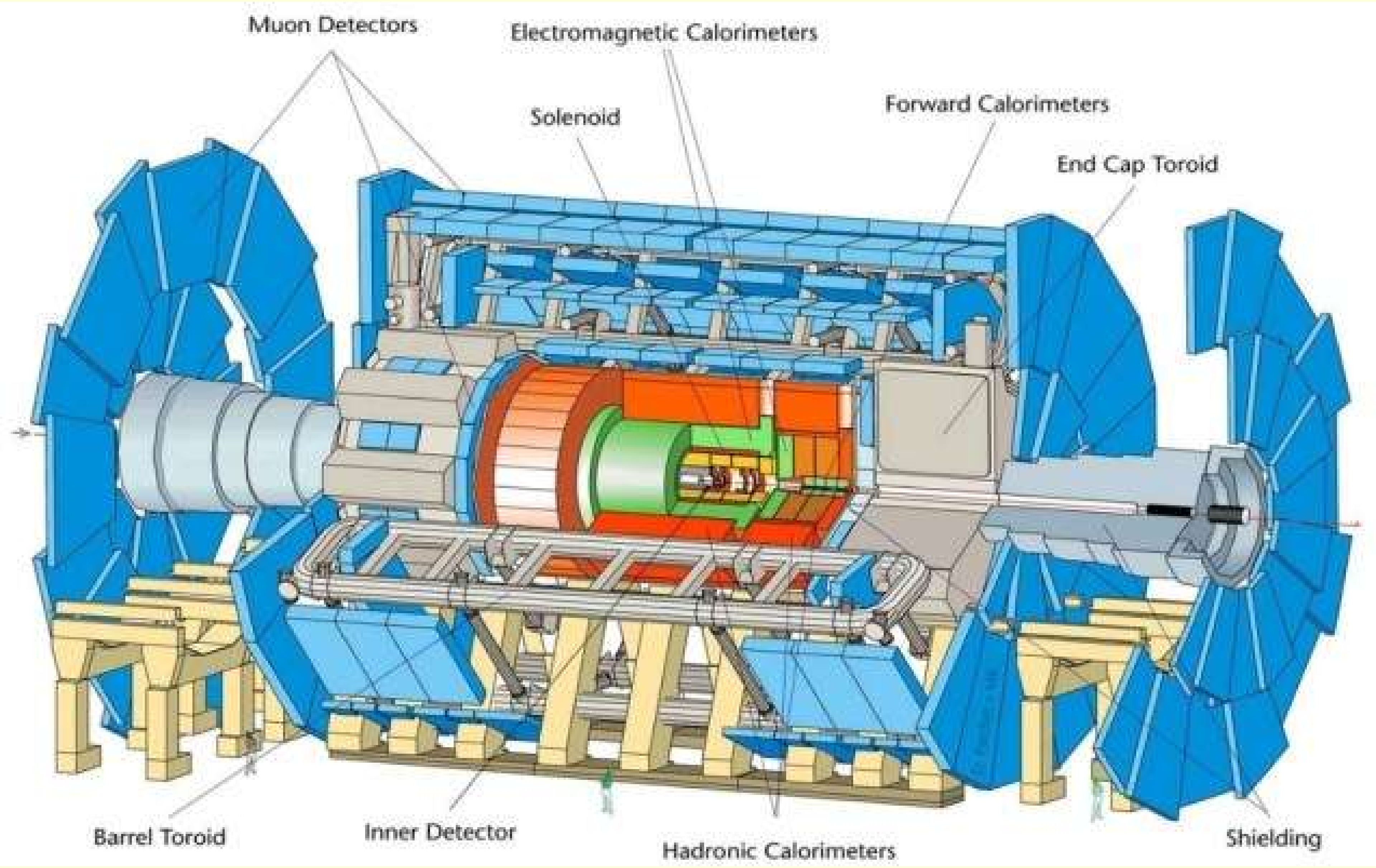
Ereignisrate bei einem Wirkungsquerschnitt $\sigma$

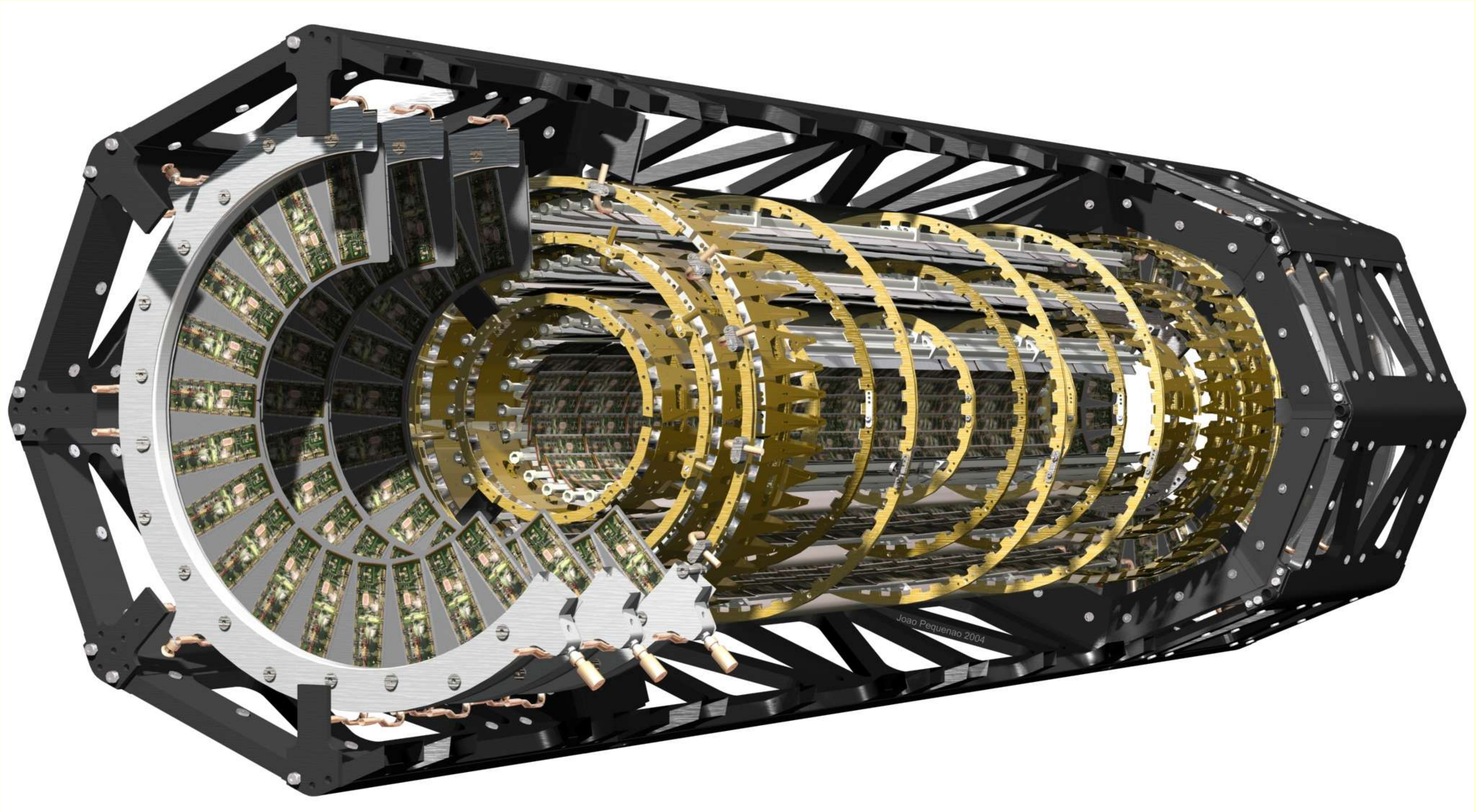
von 10 femtobarn ($10^{-38}$ $cm^{2}$)

Rate $R = L \cdot \sigma = 10^{-4}\ s^{-1} \approx 10/d$

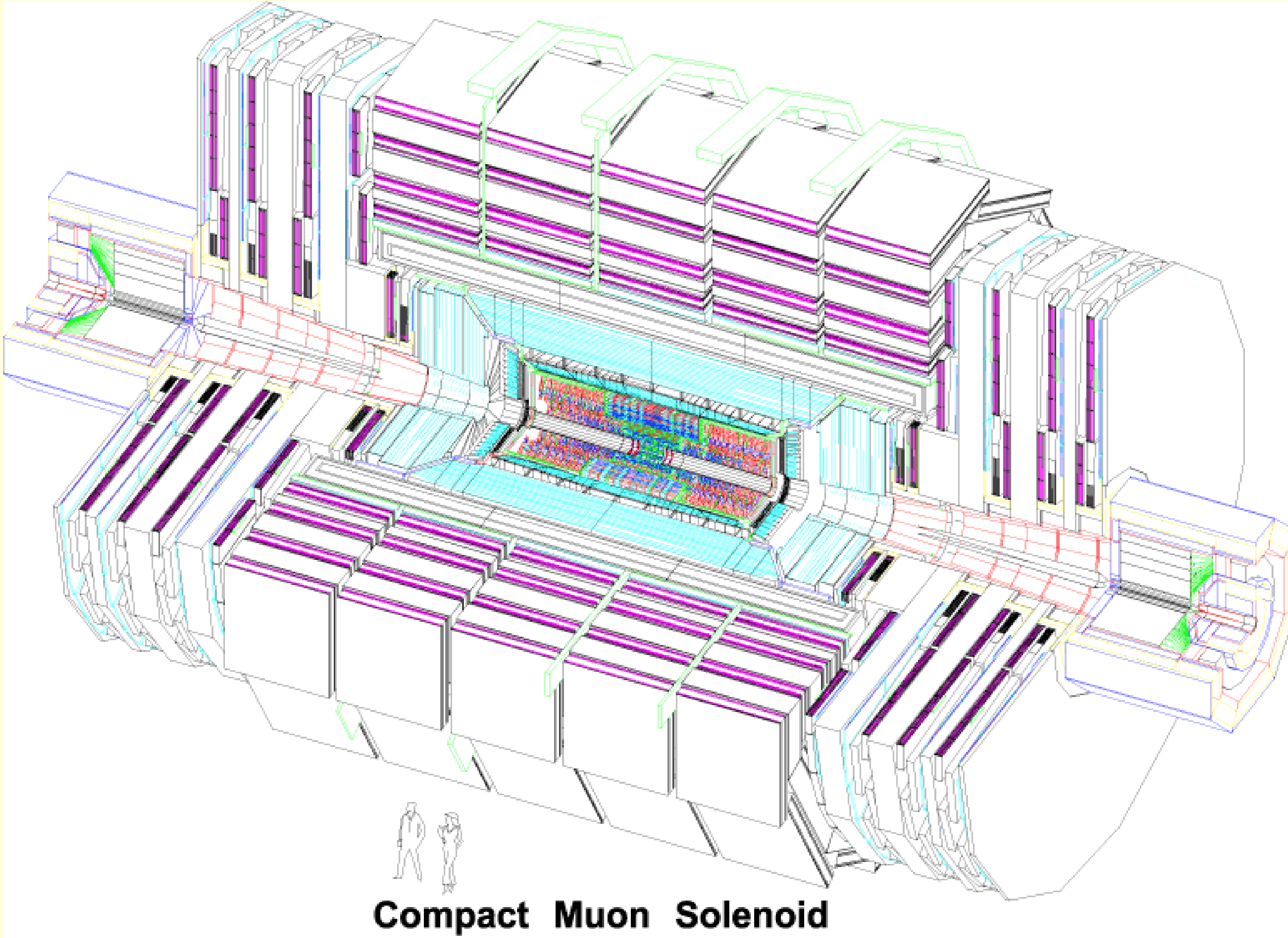
aber: Background ca. 40 MHz !

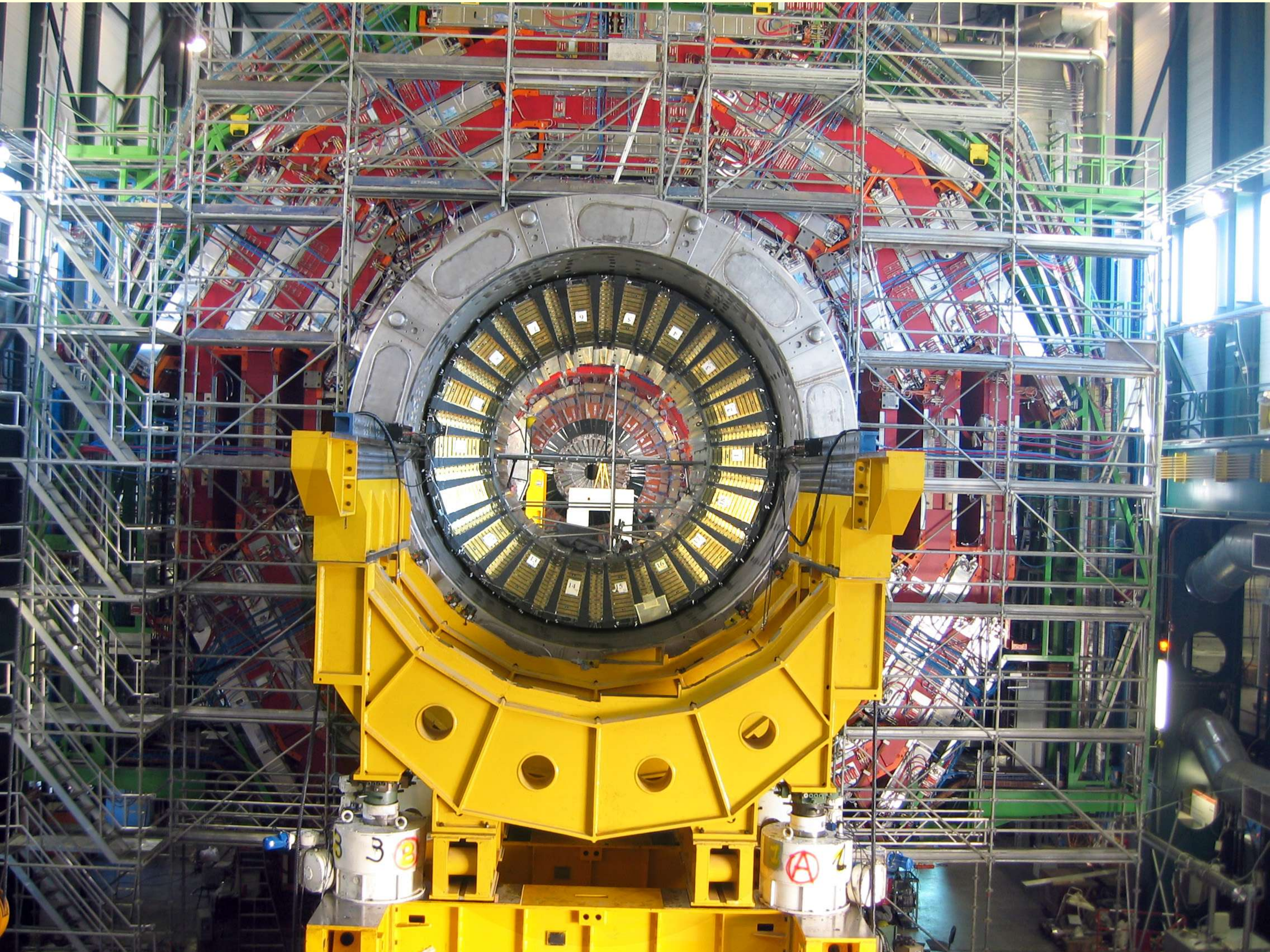

LHC at CERN
France
Switzerland
4.3 km


Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

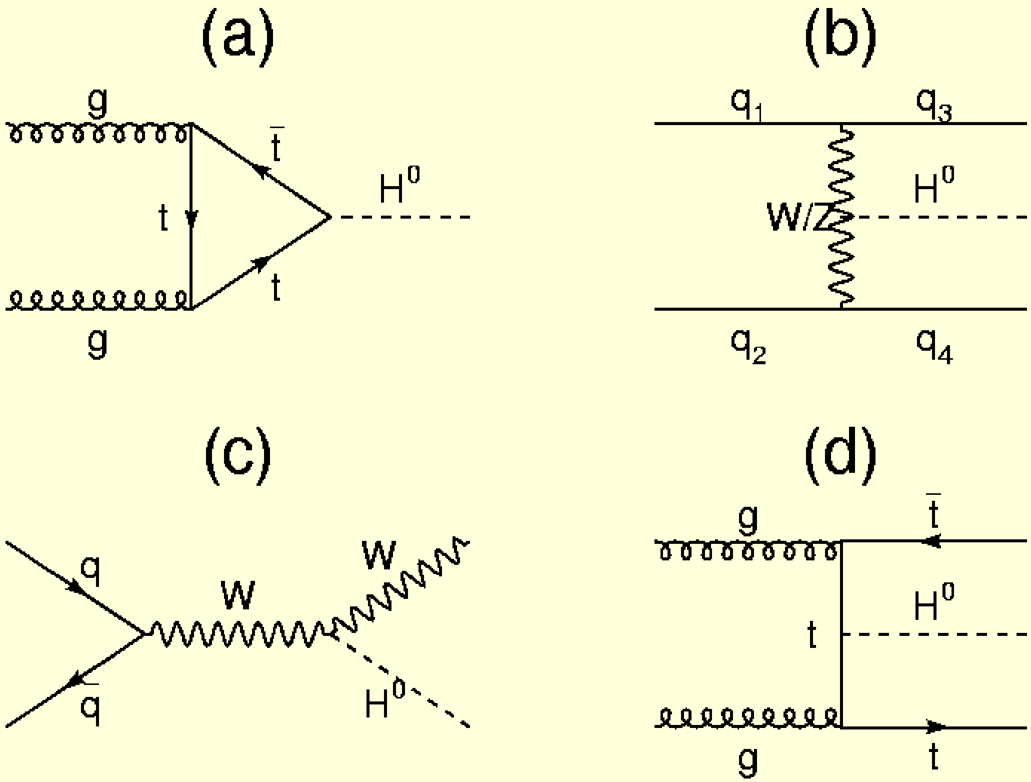


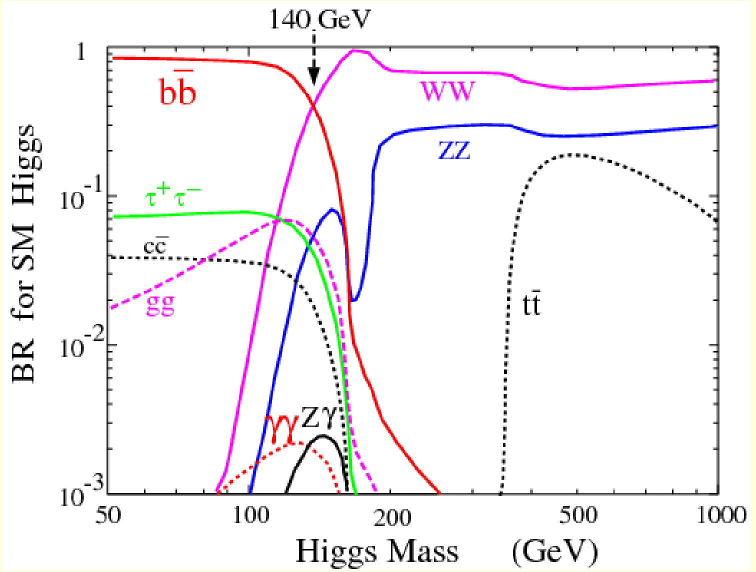

Pixeldetektor ATLAS

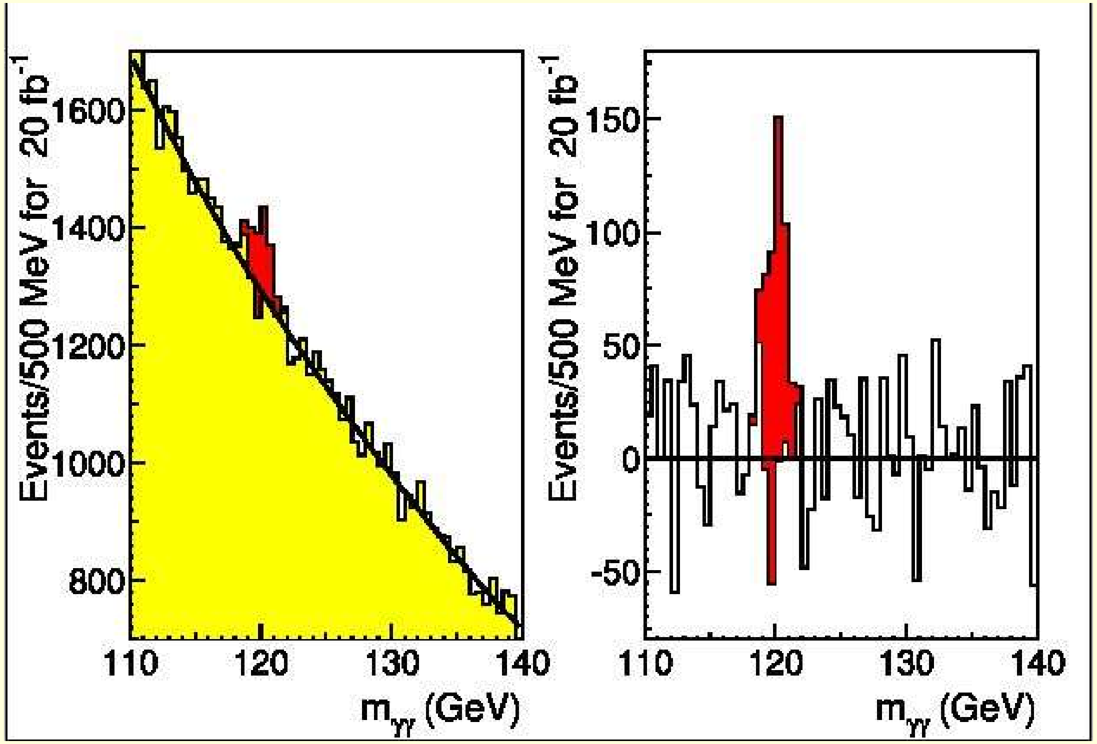

Compact Muon Solenoid



# Higgs-Produktion an Proton-Proton-Speicherringen (LHC und Tevatron)



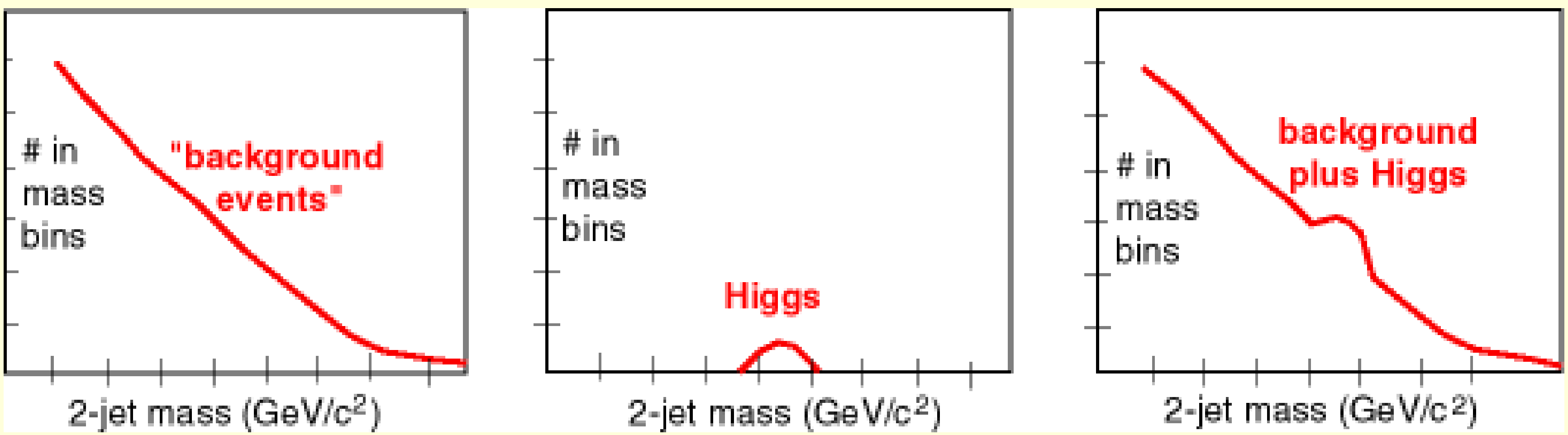






# Entdeckungskanäle:

$$H \rightarrow \gamma\ \gamma$$
$$H \rightarrow \tau^{+}\tau^{-}$$
$$H \rightarrow \text{jet jet}$$

Monte Carlo Simulationen



# Probleme des Standardmodells

- Ursprung der Masse? (kann das Higgs-Szenario lösen?)
- Das Standardmodell enthält 18 freie Parameter
  + 7, wenn man die Neutrinomassen und deren Kopplungen mit einbezieht.
- Mit 25 Parametern kann man vieles beschreiben.
- Warum gibt es drei Teilchengenerationen?
- Das Standardmodell sagt nichts über die Gravitation.
- Die Materiedominanz im Universum kann durch CP-Verletzung nicht erklärt werden.
- Hierarchie-Problem: warum z.B. ist die schwache Kraft $10^{32}$ mal stärker als die Gravitation?

# Ausweg: Supersymmetrie

**Die Theorie der Supersymmetrie wird seit 1970 entwickelt, um einige Probleme des Standardmodells zu lösen;**

z.B. das Problem der Massenskalen:

Warum ist die elektroschwache Skala (100 GeV) von der Planckskala ($10^{19}$ GeV) so sehr verschieden. Bei der Planckskala sollten alle Wechselwirkungen gleich stark sein.

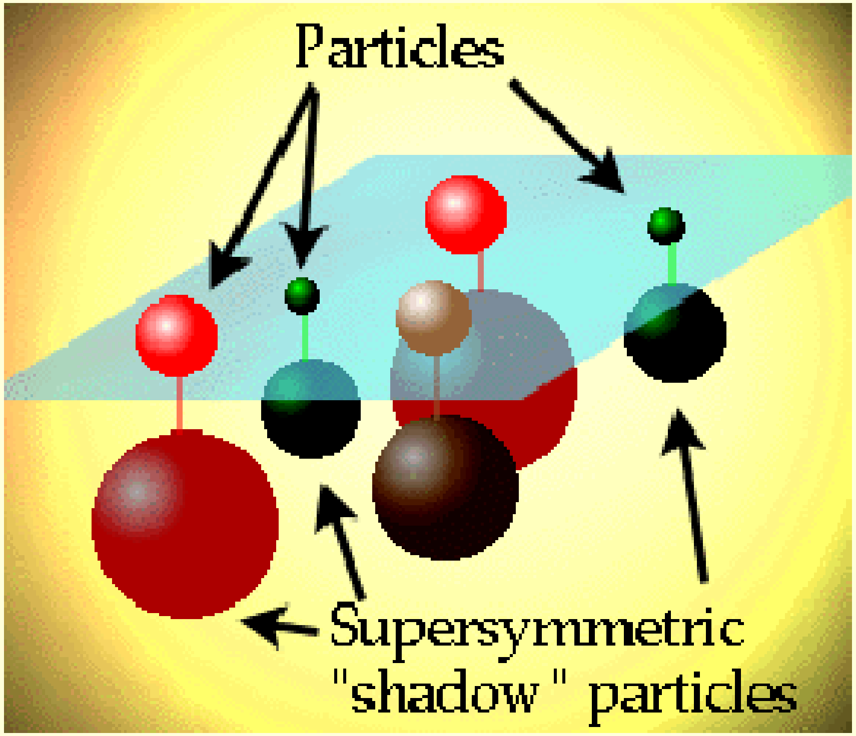
z.B. das Problem der Kopplungskonstanten:

- sie sind nicht wirklich konstant, sondern energieabhängig
- in der Energieevolution treffen sie sich nicht an einem Punkt bei der Planckmasse (wird durch SUSY gelöst).

Im Rahmen der Supersymmetrie wird jedem Fermion ein bosonischer Partner
(squark, selectron, smuon, stau, sneutrino, ...),

und jedem Boson ein fermionischer Partner zugeordnet
(photino, gluino, wino, gravitino, ...)

Da noch keine SUSY-Teilchen entdeckt sind, muss die Supersymmetrie gebrochen sein.



# SUSY

| Standardteilchen (Spin $\frac{1}{2}\hbar$ ) | SUSY-Partner (Spin 0) |
|---|---|
| $e\,,\ \ \mu\,,\ \ \tau$<br>$\nu_e\,,\ \ \nu_\mu\,,\ \ \nu_\tau$<br>$q$ | $\tilde{e}\,,\ \ \tilde{\mu}\,,\ \ \tilde{\tau}$<br>$\tilde{\nu}_e\,,\ \ \tilde{\nu}_\mu\,,\ \ \tilde{\nu}_\tau$<br>$\tilde{q}$ |
| **Austauschteilchen (Spin $1\,\hbar$ )** | **SUSY-Partner (Spin $\frac{1}{2}\hbar$ )** |
| $\gamma$<br>$Z\,,\ \ W^+\,,\ \ W^-$<br>$g$<br>$G\ \ (\text{Spin}\ \ 2\hbar)$ | $\tilde{\gamma}$<br>$\tilde{Z}\,,\ \ \tilde{W}^+\,,\ \ \tilde{W}^-$<br>$\tilde{g}$<br>$\tilde{G}\ \ \left(\text{Spin}\ \ \frac{3}{2}\hbar\right)$ |

Massenskalen $\lesssim$ 1 TeV erwartet

# Kosmologie

Urknall ➡ rapide Ausdehnung (Inflation) ➡ Hubble Expansion

kosmologische Konstante: das Universum gibt wieder Gas

Theorie-Problem:

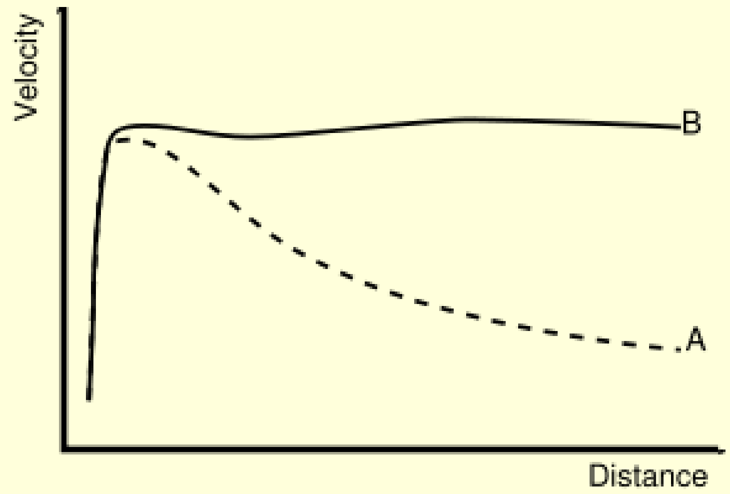
$$\frac{\text{Vakuumenergie der Quantenfeldtheorie}}{\text{kosmologische Konstante } \Lambda} = 10^{120}$$

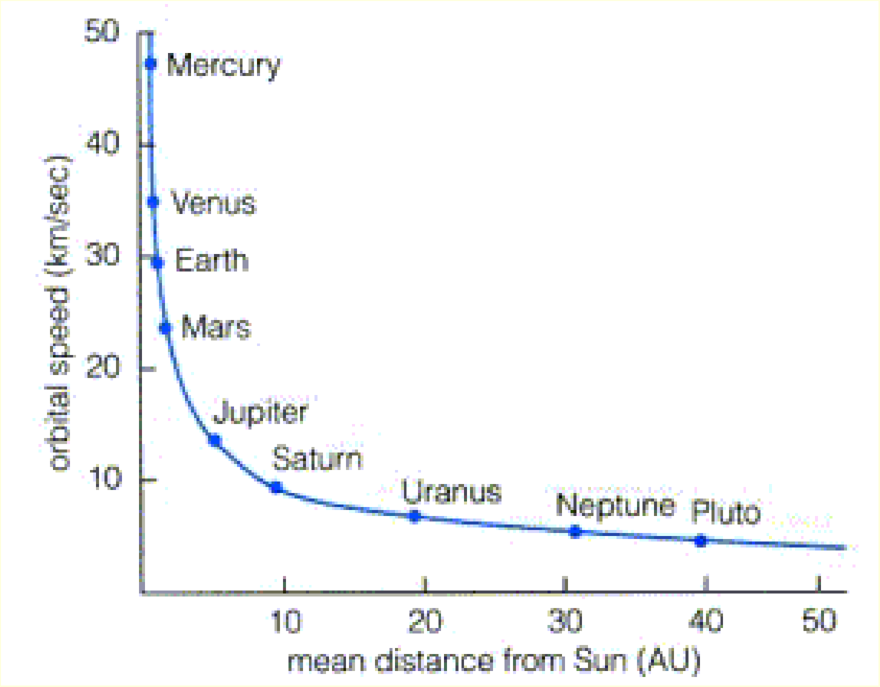
???

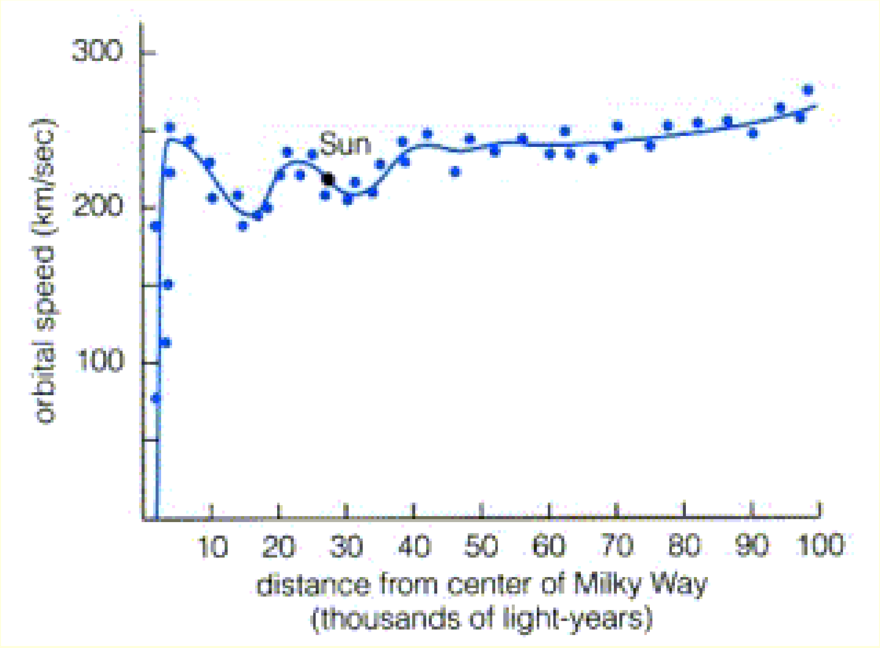
Dunkle Materie:

$$\frac{mv^2}{r} = G \cdot \frac{mM}{r^2} \quad \Rightarrow \quad v \propto \frac{1}{\sqrt{r}}$$

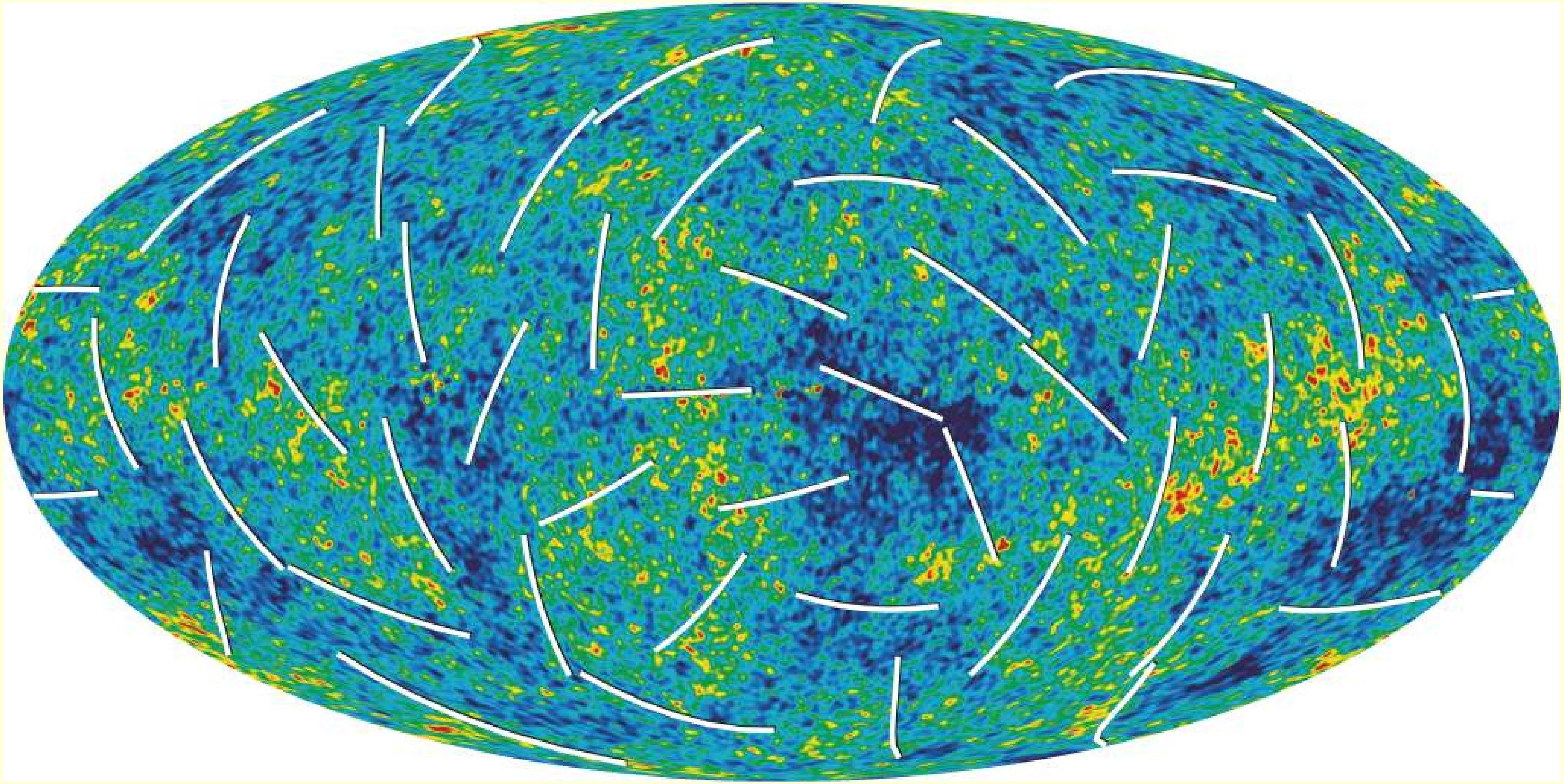
# Rotationsgeschwindigkeiten von Sternen in Galxien

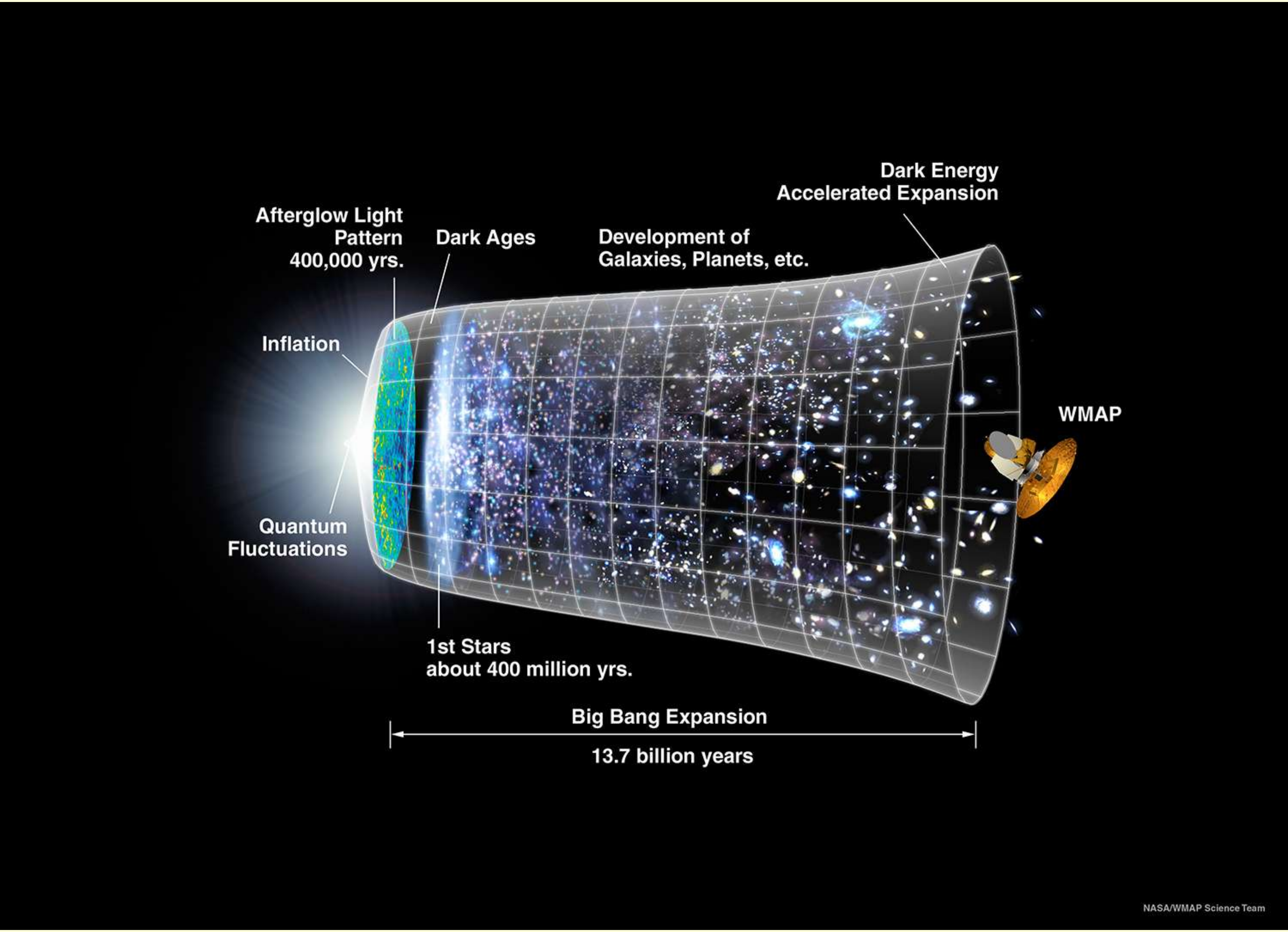


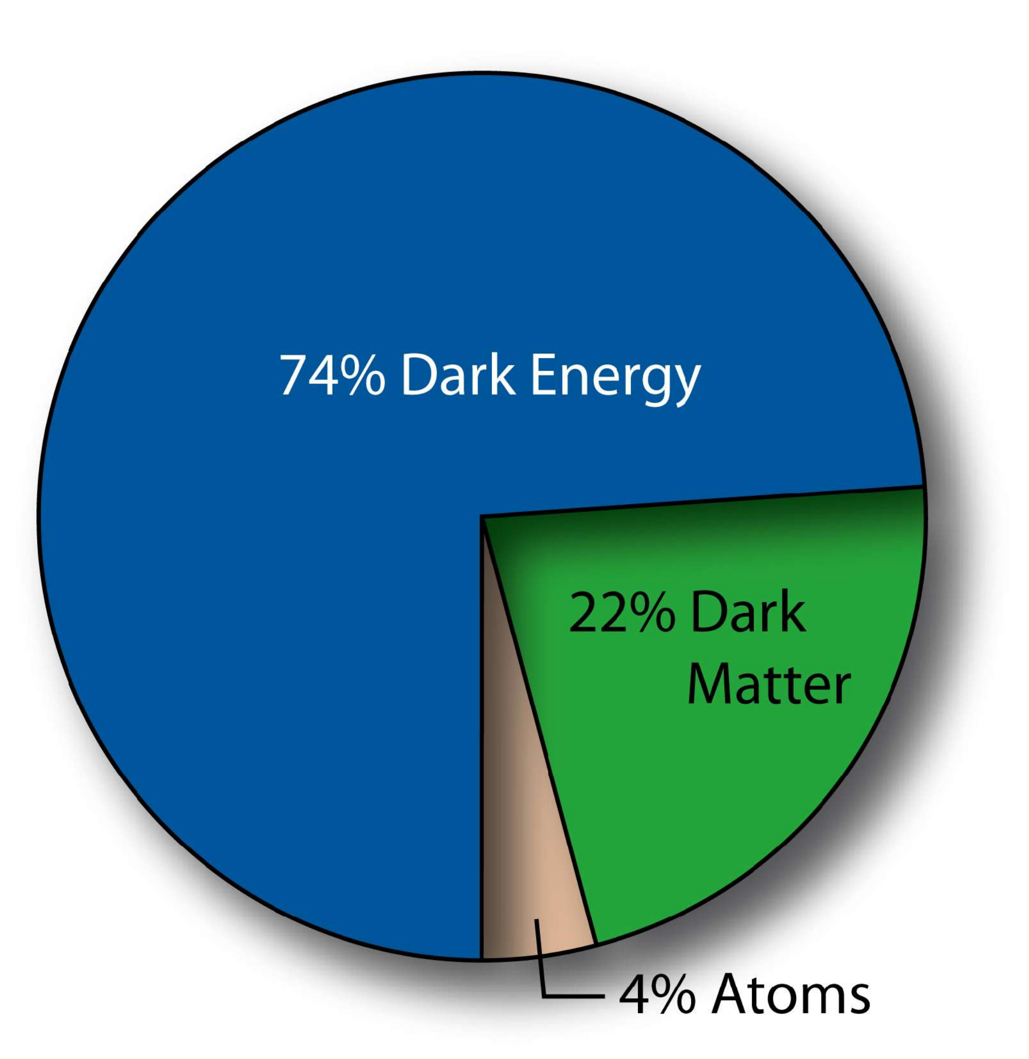



# Wilkinson MAP Daten




Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

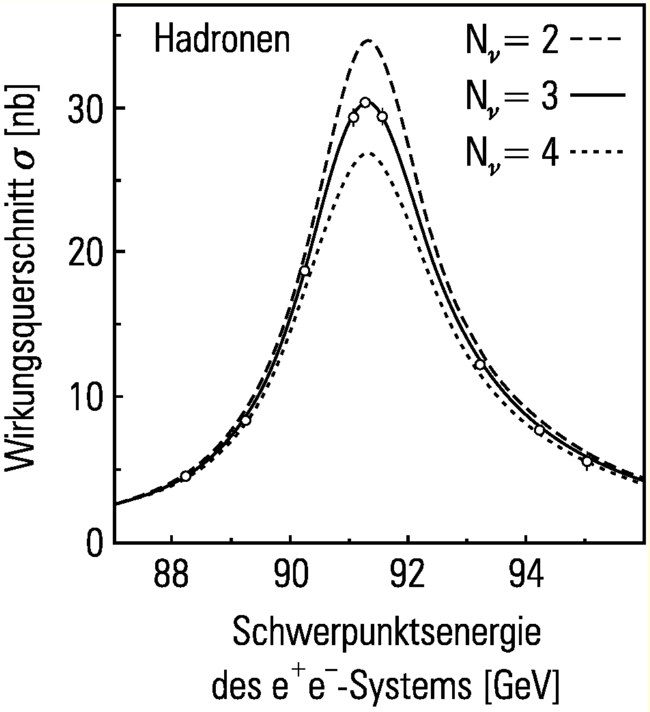



- 22% Dunkle Materie
- 74% Dunkle Energie
- 4% baryonische Materie

- Trotz seiner Schönheit lässt das Standardmodell noch viele Fragen unbeantwortet

# Zusammenfassung und Ausblick

- Das Standardmodell beschreibt die Wechselwirkungen von Quarks und Leptonen mit außerordentlich hoher Präzision
- Offene Fragen:
  - Neutrinomassen
  - Sehr viele freie Parameter
  - Warum drei Generationen?
  - Ist der Higgsmechanismus die Lösung für den Ursprung der Materie
  - Warum sind die Kopplungen so enorm verschieden?
  - Warum haben die Kopplungen die Werte, die sie haben? (kleine Abweichungen würden die Bildung von Sternen, Planeten und Leben nicht ermöglichen).
  - Quantengravitation noch nicht verstanden.



# Lösungansätze

In der Theorie: Supersymmetrie
Supergravitation
Superstringtheorie
TOE

Der LHC sollte folgendes finden:

das neutrale Higgs-Boson oder
den Higgs-Sektor der minimal supersymmetrischen Erweiterung des Standardmodells

Anzeichen von Supersymmetrischen Teilchen
z.B. das stabile
„Leichteste Supersymmetrische Teilchen“

**Die Gemeinde der Elementarteilchenphysiker wartet mit Spannung auf die ersten Resultate vom LHC**