physikus particulae --
- ubi es ?
- cui prodes ?
- quo vadis ?
Dimensions and Structure of Matter

- Universe: $10^{26}$ m
- Galaxy: $10^{21}$ m
- Solar System: $10^{13}$ m
- Earth: $10^{7}$ m
- Human: $10^{-6}$ m
- Atom: $10^{-10}$ m
- Atomic Nucleus: $10^{-14}$ m
- Nucleon: $10^{-15}$ m
- Quark; Lepton: $< 10^{-18}$ m
Particle Physics

• ubies
## The "Standard Model" of Particle Physics

<table>
<thead>
<tr>
<th>Elementary Particles</th>
<th>Generation</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quarks</strong></td>
<td></td>
<td>u</td>
<td>d</td>
<td>t</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c</td>
<td>s</td>
<td>b</td>
</tr>
<tr>
<td><strong>Leptons</strong></td>
<td></td>
<td>ν_e</td>
<td>ν_μ</td>
<td>ν_τ</td>
</tr>
<tr>
<td></td>
<td></td>
<td>e</td>
<td>μ</td>
<td>τ</td>
</tr>
</tbody>
</table>

...as well as anti-particles

### Elementary Forces

<table>
<thead>
<tr>
<th>exchange boson</th>
<th>Strong</th>
<th>el.-magn.</th>
<th>Weak</th>
<th>Gravitation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g</td>
<td>γ</td>
<td>W±, Z⁰</td>
<td>G</td>
</tr>
</tbody>
</table>

| relative strength | 1/137 | 10⁻¹⁴ | 10⁻⁴⁰ |

SM describes dynamics of all known particles and forces.

(known matter consists of members of 1ˢᵗ generation)

Theoretical predictions to explain origin of the different masses of particles:

- the HIGGS Boson (unobserved)
CERN / Geneva

LHC: $p$-$p$ collisions from 2009
Some Highlights from LEP & Co:

- resonance line of the $Z^0$ at LEP: there are exactly 3 generations of neutrinos (particles)

- $M_Z = (91.1875 \pm 0.0021) \text{ GeV}$
  (...after correcting for phases of moon and TGV train schedule)

- exp. tests of the Standard Model of particle physics at per-mille level

- limits on the mass of the Higgs-Boson (unobserved, but predicted by theory): $114.1 \text{ GeV} < M_H < 185 \text{ GeV}$

- precision measurement of strength of Strong Force: $\alpha_s$ "runs"; proof of Asymptotic Freedom, of Confinement and therefore, of QCD!

- Nobel Price 2004
### Measurements and Fits of electroweak parameters

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
<th>$O_{\text{meas}}$</th>
<th>$O_{\text{fit}}$</th>
<th>$O_{\text{meas}}/O_{\text{fit}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha^{(5)}_{\text{had}}(m_Z)$</td>
<td>0.02758 ± 0.00035</td>
<td>0.02768</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>91.1874</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>2.4959</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma^0_{\text{had}}$ [nb]</td>
<td>41.540 ± 0.037</td>
<td>41.478</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_l$</td>
<td>20.767 ± 0.025</td>
<td>20.742</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{tb}^0, l$</td>
<td>0.01714 ± 0.00095</td>
<td>0.01645</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_l(P_t)$</td>
<td>0.1465 ± 0.0032</td>
<td>0.1481</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21629 ± 0.00066</td>
<td>0.21579</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{tb}^0, b$</td>
<td>0.0992 ± 0.0016</td>
<td>0.1038</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.1721 ± 0.0030</td>
<td>0.1723</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{tb}^0, c$</td>
<td>0.0707 ± 0.0035</td>
<td>0.0742</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_b$</td>
<td>0.923 ± 0.020</td>
<td>0.935</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.670 ± 0.027</td>
<td>0.668</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_l(SLD)$</td>
<td>0.1513 ± 0.0021</td>
<td>0.1481</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sin^2 \theta_{\text{eff}}^{\text{lep}}(Q_{\text{tb}})$</td>
<td>0.2324 ± 0.0012</td>
<td>0.2314</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>80.399 ± 0.023</td>
<td>80.379</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>2.098 ± 0.048</td>
<td>2.092</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>173.1 ± 1.3</td>
<td>173.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mostly from LEP / SLC; also includes Tevatron: $M_t, M_W$
direct and indirect searches for the Higgs Boson

**direct Higgs searches:** $M_H > 114.1 \text{ GeV/c}^2$; $M_H \notin [158,175]$ (95% CL)

**indirect from radiative corrections:** $M_H < 186 \text{ GeV/c}^2$ (95% CL)
Highlights from ν-physics
Highlights from $\nu$-physics

- Atmospheric neutrinos: oscillation $\nu_\mu \rightarrow \nu_x$
  => neutrinos have (different) masses.

- Solar and reactor neutrinos: oscillation $\nu_e \rightarrow \nu_x$
  => solution to the solar neutrino problem.

Consistent explanation of mass-/flavour-eigenvalues of 3 neutrino families?
(low energy) Precision Experiments

Muon (g-2) Collaboration
the anomalous magnetic moment of the muon (g–2)

Brookhaven alternate gradient synchrotron
The $(g-2)$ value of the negative muon was announced January 8, 2004!

$$a_\mu \ (BNL'01) = 11\ 659\ 214\ (8)(3) \times 10^{-10} \ (0.7\ ppm)$$

$$a_\mu \ (exp) = 11\ 659\ 208\ (6) \times 10^{-10} \ (0.5\ ppm)$$
Supersymmetry: indirect searches

Global fits to world precision ew data

- slightly improved fit quality of SUSY-models
  - however -
  - mostly due to $a_\mu$ measurement (anomalous magnetic moment of $\mu$)

**LEP: $M_Z$**

- $\Gamma_Z$
- $\sigma_{\text{had}}$
- $R_l$
- $A_{FB}^l$
- $R_b$
- $R_c$
- $A_{FB}^b$
- $A_{FB}^c$
- $M_t$
- $\sin^2\theta_{\text{lept}}^{\text{eff}}$
- $M_W^{\text{(LEP)}}$

**SLC: $\sin^2\theta_{\text{lept}}^{\text{eff}}(A_{LR})$**

- $b \rightarrow X_s \gamma$
- $a_\mu^{\text{SUSY}}$

Pulls = (data-theo)/error

- SM: $\chi^2$/d.o.f. = 27.2/16
- MSSM: $\chi^2$/d.o.f. = 16.4/12
- CMSSM: $\chi^2$/d.o.f. = 23.2/16

de Boer & Sander, PLB585 (2004) 276
ubi es ?

so far, no significant signal for physics beyond the Standard Model of Particle Physics!

however, the future has just begun:

high energy operation of the Large Hadron Collider started in March 2010
since March 2010, the LHC collides protons at 7 TeV c.m.!
The Large Hadron Collider (LHC)

Proton – Proton Collisions:

2835 × 2835 bunches
distance: 7.5 m (25 ns)

$10^{11}$ Protons / bunch
Collision rate: 40 million / sec.
Luminosity: $L = 10^{34}$ cm$^{-2}$ sec$^{-1}$

Proton-Proton collisions: $\sim 10^9$ / sec
(about 23 pp-interactions per bunch crossing)

$\sim 1600$ charged particles in detector

high demands on detectors
LHC
the largest scientific project ever attempted

- 30,000 tons of 8.4 Tesla s.c. dipole magnets cooled to 1.9 degrees K by 90 tons of liquid helium

- 40 MHZ collision rate = 1 Terabyte/sec raw data rate from the CMS and ATLAS particle detectors

- 7000 tons (ATLAS) and 12,500 tons (CMS) of high precision particle detector technology

(for comparison: - weight of fully loaded Boeing 747: 200 tons
   - Eiffel tower: 7,300 tons
   - USS John McCain (warship): 8,300 tons)
Higgs & SUSY Searches at the Large Hadron Collider

SM Higgs sensitivity (\(\sim h_0\) in MSSM):

- 10 fb\(^{-1}\) \(\rightarrow\) 1st year at initial Luminosity of \(10^{33}\) s\(^{-1}\) cm\(^{-2}\)
- 100 fb\(^{-1}\) \(\rightarrow\) first 3 years with Luminosity \(\rightarrow\) \(10^{34}\) s\(^{-1}\) cm\(^{-2}\)

Squark and gluino masses in mSUGRA:

- if standard Higgs exists, or if SUSY is realised at \(\sim\) TeV scale, LHC will find it!
Overall data taking efficiency (with full detector on): 95%
Event with 4 pp interactions in the same bunch-crossing
LHC: the re-discovery of the Standard Model

Di-muon resonances

ATLAS Preliminary

Data 2010, $\sqrt{s} = 7$ TeV
$p_T(\mu) = 27 \text{ GeV}$  \hspace{1cm} $\eta(\mu) = 0.7$

$p_T(\mu') = 45 \text{ GeV}$  \hspace{1cm} $\eta(\mu') = 2.2$

$M_{\mu\mu} = 87 \text{ GeV}$

$Z \rightarrow \mu\mu$ candidate in 7 TeV collisions
$\sigma (Z \rightarrow ll) = 0.83 \pm 0.07 \text{ (stat)} \pm 0.06 \text{ (syst)} \pm 0.09 \text{ (lumi)} \text{ nb}$
ATLAS: observed event with hardest jet

$\sqrt{s} = 7$ TeV

$\frac{1}{N} \frac{dN}{dp_T^{\text{jet}}}$ [GeV$^{-1}$]

- Data $\int L dt = 296$ nb$^{-1}$
- PYTHIA
- anti-$k_t$ $R = 0.6$
- $|y^{\text{jet}}| < 2.8$

$p_T^{\text{jet}}$ [GeV]

- $p_T(j_1) = 1120$ GeV
- $p_T(j_2) = 480$ GeV
- $p_T(j_3) = 155$ GeV
- $p_T(j_4) = 95$ GeV

$p_T(j_1) > 1.1$ TeV
Searches for excited quarks: $q^* \to jj$

$0.4 < M (q^*) < 1.29 \text{ TeV}$ excluded at 95% C.L.

Latest published limit:
CDF: $260 < M (q^*) < 870 \text{ GeV}$
• describes the unified electro-weak interaction and the Strong force with gauge invariant quantum field theories;

• is extremely successful in consistently and precisely describing all particle reactions observed to date

• shows no significant discrepancies between data and theorie -- however it leaves open fundamental questions and problems which cannot be answered by the SM.
Particle Physics

• cui prodes
CNN contest (Nov. 2006): „greatest wonders of the modern world“

<table>
<thead>
<tr>
<th>Rank</th>
<th>Description</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>World Wide Web</td>
<td>50%</td>
</tr>
<tr>
<td>2</td>
<td>particle accelerators at CERN</td>
<td>16%</td>
</tr>
<tr>
<td>3</td>
<td>- none -</td>
<td>8%</td>
</tr>
<tr>
<td>4</td>
<td>Dubai</td>
<td>7%</td>
</tr>
<tr>
<td>5</td>
<td>the bionic arm</td>
<td>6%</td>
</tr>
<tr>
<td>6</td>
<td>3-Canyon Dam, China</td>
<td>5%</td>
</tr>
</tbody>
</table>
particle physics

– is knowledge oriented basic research.

– has no direct relation to every-day applications.

– bundles scientific interest world-wide and avoids duplication of projects.

– initiates technological and theoretical developments at the limit of feasibility.

– provides significant spin-off technologies in medical science, engineering, in other natural sciences and culture.

– provides comprehensive scientific education in an international und kompetitive environment.
**Astronomie**

- Entstehung von Protonen und Neutronen
- Positronen verschwinden
- Asymmetry $Q - Q$ L - L

**QUANTENGRAVITATION**

- GROSSE VEREINHEITLICHUNG
- LHC

**UNIVERSUM WIRD TRANSPARENT**

- Bildung von Atomen.
- Entkopplung von Strahlung und Materie.

**ZEIT**

- erste Supernovae
- Entstehung von Sternen und Galaxien

**Temperatur**

- GEGENWART

<table>
<thead>
<tr>
<th>Temperatur</th>
<th>Alter</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7 K</td>
<td>13.7 Milliarden Jahre</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperatur</th>
<th>Alter</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 K</td>
<td>1 Milliarde Jahre</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperatur</th>
<th>Alter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000 K</td>
<td>300 000 Jahre</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th>Alter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{10}K$</td>
<td>1 sec.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperatur</th>
<th>Alter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{15}K$</td>
<td>$10^{-10}$ sec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperatur</th>
<th>Alter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{16}K$</td>
<td>$10^{-15}$ sec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperatur</th>
<th>Alter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{27}K$</td>
<td>$10^{-34}$ sec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperatur</th>
<th>Alter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{31}K$</td>
<td>$10^{-43}$ sec</td>
</tr>
</tbody>
</table>

**Wir sind hier**

- Schwarze Sterne
- Proto-Galaxie

**Teilchenphysik und Kosmologie**

- Teilchenbeschleuniger
Particle Physics

• quo vadis
1. what is the origin of mass?  
   - does the Higgs particle exist?  
   - if not, what is the mechanism of EW symmetry braking?  

2. why are there 3 families of quarks and leptons?  
   why is (electron charge) = -(proton charge)?  

3. where is the anti-matter in the universe?  

4. is there one universal fundamental force?  
   -> GUT  

5. are there unknown forms of matter?  
   - is our world supersymmetric?  
   - what is the origin of Dark Matter and Dark Energy  
     which make up 95% of the universe?  

6. are there hidden extra dimensions?  
   - why is Gravity so much weaker than the other forces?  
   ...
if it's not dark
it doesn't matter
the most *en vogue* candidates to solve (some of) these problems:

- **Supersymmetry (SUSY)**
  - fully compatible with and supported by GUT's
  - offers excellent Dark Matter candidates
  - theory finite and computable up to Planck Mass
  - essential for realisation of string theory
    (including quantum gravity)
  - no SUSY signals seen yet (LEP, Tevatron)
  - (too) many free parameters, large parameter space

- **Extra Space Dimensions**
  - would solve hierarchy problem \(M_{\text{Planck}} \rightarrow O(1 \text{ TeV})\)
  - inspired by string theory: compactified extra dimensions
  - exciting scenarios, but cannot solve many of above problems?
  - large model dependences
there are 2 principle ways to search for physics beyond the Standard Model:

• direct production of new particles in highest energy collisions

• indirect evidence for new phenomena in high precision experiments (through radiative corrections; virtual loops...)

\[ e^+ + e^- \rightarrow Z^0 \rightarrow \tau^+ \tau^- + H \]
Particle Physics Projects

**High Energy Frontier**
- Hadron Collider
  - Tevatron
  - LHC
  - HL-LHC
  - HE-LHC
- Lepton Collider
  - HERA
  - LEP
  - ILC
  - CLIC

**High Precision**
- High energy $E_{cm} \geq M_Z$
  - LEP
- Low energy $E_{cm} < M_Z$
  - ILC

**Neutrino-Beams**
- Long baseline
  - K2K
  - CNGS
  - Fermilab-HERA, Los Alamos
- Short baseline
  - T2K
  - Fermilab-Mini-Boone
  - Fermilab-Soudan

**Non-Accelerator**
- Neutrino mass searches
- Axion searches
- Neutrinoless double-$\beta$-decay searches
- Solar neutrinos
- Neutrinos from reactors
- Neutrinos from space

Legend:
- Brown: completed
- Orange: running / under construction
- Yellow: planned
LHC - further plans:

2010 & 2011:
- continuous collisions at 7 TeV (-> 10 TeV ?); \textit{int. L} \sim 1 \text{ fb}^{-1}
- higher beam currents (when reaching „safe beam conditions“: controlled beam-dump!)
- first sensitivity for „new physics“
- standard model physics (\textit{\sim} comparable with 20 years of Tevatron: top-Quark, ...)

2012:
- 1 year of shut-down (installation of full safety systems high magnet currents)

from 2013:
- full energy (14 TeV) and Luminosity (up to \(10^{34} \text{ cm}^{-2} \text{ s}^{-1}\))

ab ca. 2017:
- upgrade of LHC (and detectors) to „HL-LHC“ (\textit{\sim}10-fold Luminosity)
Expected number of events in ATLAS for 100 pb$^{-1}$ (Fall 2010 ?) after cuts for some representative processes

- $J/\psi \rightarrow \mu \mu$
- $W \rightarrow \mu \nu$
- $Z \rightarrow \mu \mu$
- $t\bar{t} \rightarrow \mu \nu + X$

until end of 2010: about factor 10 more (1 fb$^{-1}$)

expectations until end of 2010:
Super LHC Physics Menu

- Improvements from LHC: triple/quartic gauge couplings, top quark, Z’ & compositeness, but LC can generally do better. (although SLHC will be there first ?)
- Higgs physics:
  - Main strength: wide $m_H$ range coverage for $ttH$ Yukawa coupling and Higgs self-coupling.
  - Improved coupling measurements, but LC will do better.
- SUSY:
  - Main strength: squark, gluino reach: $-> 3$ TeV.
  - Some extended reach of MSSM Higgs not covered by LC.
- Extra dimensions:
  - Improved reach for black-hole production, KK states.
- Strongly coupled vector bosons (if no Higgs):
  - Can have first significant signal (LHC stat. insufficient).
• radiation damage (tracker, electronics)
• increased levels of space charge in detecting media (solid, liquid, gas)
  -> signal degradation, reduced efficiencies and resolutions.
• reduced lifetime of detectors and electronics due to high particle rates
• larger data & background rates to be processed ->
  exceed bandwith -> data loss

Challenge: maintain efficiency, resolution and reliability!
International Linear e+e- Collider

- $E_{cm} = 0.5 \ldots 1.0$ TeV
- super conducting cavities made of pure Niobium ; 31.5 MV/m
- length $\sim 31$ km, plus 2 damping rings with 6 km diameter
- costs: 6.65 Mrd $ plus 13.000 FTE‘s

Estimate 7 years of construction for accelerator and experiments after formal approval
**ILC: Precision!**

Precision of determination of cosmic abundance of Dark Matter and of the mass of DM-particles
**CLIC TWO-BEAM SCHEME**

- **Drive beam**
  - High current
  - Low decelerating field

- **Main beam**
  - Low current
  - High accelerating field

**CLIC TUNNEL CROSS-SECTION**

- 4.5 m diameter
**Open Questions and Future Perspectives of Particle Physics**

S.Bethke, MPP München

String School, Garching, August 2, 2010

---

**CLIC 3 TeV**

- **new parameters**

- **BC2**
  - $e^-$ main linac, 12 GHz, 100 MV/m, 21 km

- **CR1**
  - delay loop

- **CR2**
  - combiner rings

- **IP1**
  - BDS 2.6 km

- **BC2**
  - $e^+$ main linac

- **238 klystrons**
  - 33 MW, 140 $\mu$s

- **drive beam accelerator**
  - 2.4 GeV, 1.3 GHz?

- **decelerator, 17 sectors of 1235 m**

- **47.6 km**

- **Booster linac**
  - 9 GeV, 2.4 GHz

- **BC1**
  - $e^-$ injector, 2.4 GeV
  - $e^-$ DR 360m

- **$e^+$ injector, 2.4 GeV**
  - $e^+$ DR 360m
Neutrino-Factory (CERN-study)
**μ-Collider Complex (CERN-Study)**

- Large muon collider ($\sqrt{s} = 5$ TeV)
- Fast accelerator 2 in LHC tunnel (2.5 TeV)
- Fast accelerator 1 in SPS tunnel (400 GeV)

Higgs factory ($\sqrt{s} = 100$ GeV)

ν factory → Gran Sasso
1. the highest priority is to fully exploit the physics potential of the LHC and centrally organize towards a luminosity upgrade by around 2015 (SLHC).

2. develop the CLIC technology and high performance magnets for future accelerators, and study and develop a high intensity neutrino facility.

3. complement the results of the LHC with measurements at a linear collider within the energy range of 0.5 to 1 TeV, the ILC; coordinated through the Global Design Effort.

4. European participation in a global neutrino programme.

5. Coordinated European strategy for non-accelerator experiments.

update planned for 2011/2012

similar roadmaps exist for U.S., Japan, ...
The End

http://www.mppmu.mpg.de