Elementary Particle Physics Research

Achim Geiser, DESY Hamburg
Summer Student Lecture, 21.-22.7.15

Scope of this lecture:

- Introduction to particle physics for non-specialists
  - rather elementary
  - more details -> specialized lectures
  - particle physics in general
  - some emphasis on DESY-related topics

thanks to B. Foster for some of the nicest slides/animations
other sources: www pages of DESY and CERN
What is Particle Physics?

Particle Physics

= science of elementary particles

and their interactions
What is “science”?

Science (from Latin scientia, meaning "knowledge") is a systematic enterprise that builds and organizes knowledge in the form of testable explanations and predictions about the universe.

First large scale scientific experiment: proposal: Galilei 1632
realisation: Pierre Gassendi 1640
French navy Galley with international crew of ~100 people
(fraction of students not reported)

= \textit{breakthrough of inertial theory}

G. Risch
Physik in Unserer Zeit
38 (5) (2007) 249

M. Risch
Physik in Unserer Zeit
38 (5) (2007) 249
What is a „particle“?

- **Classical view:** particles = discrete objects. Energy concentrated into finite space with definite boundaries. Particles exist at a specific location. → Newtonian mechanics

- **Modern view:**
  particles = objects with discrete quantum numbers, e.g. charge, mass, ... not necessarily located at a specific position, (Heisenberg uncertainty principle) can also be represented by wave functions. (Quantum mechanics, particle/wave duality)

Images:
- Isaac Newton (Principia 1687)
- Niels Bohr (Nobel 1922)
- Louis de Broglie (Nobel 1929)
- Werner Heisenberg (Nobel 1932)
- Erwin Schrödinger (Nobel 1933)
What is „elementary“?

Greek: atomos = smallest indivisible part

Dmitry Ivanowitsch Mendeleyev 1868 (elements)

Ernest Rutherford 1911 (nucleus) (Nobel 1908)

Murray Gell-Mann 1962 (quarks) (Nobel 1969)

elementary = no detectable substructure

≤ 0,01 m Kristall
1/10.000.000

10^{-9} m Molekül
1/10

10^{-10} m Atom
1/10.000

10^{-14} m Atomkern
1/10

10^{-15} m Proton
1/1.000

< 10^{-18} m Elektron, Quark
History of basic building blocks of matter

motivation: find smallest possible number

Super-symmetry

Quark and Lepton substructure??

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### Which “interactions”?

<table>
<thead>
<tr>
<th>TYPE</th>
<th>at ~ 1 GeV INTENSITY OF FORCES (DECREASING ORDER)</th>
<th>BINDING PARTICLE (FIELD QUANTUM)</th>
<th>OCCURS IN:</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRONG NUCLEAR FORCE</td>
<td>~ 1</td>
<td>GLUONS (NO MASS)</td>
<td>ATOMIC NUCLEUS</td>
</tr>
<tr>
<td>ELECTRO-MAGNETIC FORCE</td>
<td>~ 10(^{-2})</td>
<td>PHOTONS (NO MASS)</td>
<td>ATOMIC SHELL ELECTROTECHNIQUE</td>
</tr>
<tr>
<td>WEAK NUCLEAR FORCE</td>
<td>~ 10(^{-5})</td>
<td>BOSONS (Z^0, W^+, W^-) (HEAVY)</td>
<td>RADIOACTIVE BETA DESINTEGRATION</td>
</tr>
<tr>
<td>GRAVITATION</td>
<td>~ 10(^{-38})</td>
<td>GRAVITONS (?)</td>
<td>HEAVENLY BODIES</td>
</tr>
</tbody>
</table>

**THE EXCHANGE OF PARTICLES IS RESPONSIBLE FOR THE FORCE**
What we know today

The Standard Model

Quarks
- up
- charm
- top
- down
- strange
- bottom

Leptons
- electron
- muon
- tau
- e-neutrino
- μ-neutrino
- τ-neutrino

Force Carriers
- photon
- gluon
- W boson
- Z boson

Generations of matter
- I
- II
- III

Higgs Boson

Gravity
- the ghost at the feast
The Power of Conservation Laws

- e.g. radioactive neutron decay:
  \[ n \rightarrow p + e^- + \bar{\nu}_e \] not visible

- Pauli 1930:

Wolfgang Pauli
(Nobel 1945)

Neutrino must be present to account for conservation of energy and (angular) momentum
confirmation: neutrino detection

- e.g. reversed reaction:
  \[ \nu_e + n \rightarrow p + e^{-} \]
  extremely rare!
  (absorption length \(\sim 3\) light years Pb)

- first detection: 1956
  Reines and Cowan, neutrinos from nuclear reactor

Conservation laws remain valid down to microscopic scales!
The power of symmetries: Parity

Parity = Mirror Symmetry

- Will physical processes look the same when viewed through a mirror?

- In everyday day life: violation of parity symmetry is common
  "natural": our heart is on the left
  "spontaneous": cars drive on the right
  (on the continent)

- What about basic interactions?
- Electromagnetic and strong interactions conserve parity!

Eugene Wigner
(Nobel 1963)
The power of symmetries: Parity

Lee & Yang 1956: weak interactions violate Parity
experimentally verified by Wu et al. 1957:

consequence:

neutrinos are always lefthanded!
(antineutrinos righthanded)
The Power of Quantum Numbers

- 1948: discovery of muon
  - same quantum numbers as electron, except mass

muon decay: \( \mu^- \rightarrow \nu_\mu \ e^- \ \bar{\nu}_e \)

conservation of
- electric charge: \(-1\ \ 0\ \ -1\ \ 0\)
- lepton number: \(1\ \ 1\ \ 1\ \ -1\)
- “muon number”: \(1\ \ 1\ \ 0\ \ 0\)

\( \nu_\mu \neq \nu_e \) (1955)
\( \nu_\mu \neq \nu_e \) (1962)

Lepton number is conserved

There is a distinct neutrino for each charged lepton
The Power of Precision

- Precision measurements of shape and height of $Z^0$ resonance at LEP I (CERN 1990's)

number of (light) neutrino flavours = 3

$e^+e^- \rightarrow Z^0$

There seem to be exactly three lepton + quark families!

Why???
Can we “see” particles?

we can!
A typical particle physics detector

see e.g. ARGUS near DESY entrance
Why do we need colliders?

- Early discoveries in cosmic rays, but need controlled conditions.

\[ m = \frac{E}{c^2} \]

- Need high energy to discover new heavy particles.

- Colliders = microscopes (later)
The HERA ep Collider and Experiments

Data taking stopped summer 2007. Data analysis ongoing until 2014 and beyond.

\[ E_e = 27.6\text{GeV}, E_p = 920\text{GeV} \]
\[ \sqrt{s} = 2\sqrt{E_e E_p} = 319\text{GeV} \Leftrightarrow E_e^f = 54.1\text{TeV} \]

polarisation: \[ P(e) = -0.5...0...+0.5 \]

\[ L_{\text{spec}} \approx 4...16\cdot10^{29}\text{ cm}^{-2}\text{s}^{-1}\text{mA}^{-2} \]

\[ I_e = 20...50\text{mA}, I_p = 60...100\text{mA} \]
Particle Physics = People
Strong Interactions: Quarks and Colour

- strong force in nuclear interactions
  - „exchange of massive pions“ between nucleons
  - = residual Van der Waals-like interaction

- modern view:
  (Quantum Chromo-Dynamics, QCD)
  - exchange of massless gluons between quark constituents

  „similar“ to electromagnetism
  (Quantum Electro-Dynamics, QED)
The Quark Model (1964)

arrange quarks (known at that time) into flavour-triplet

\[ \Rightarrow SU(3)_{\text{flavour}} \text{ symmetry} \]

treat all known hadrons (protons, neutrons, pions, ...) as objects composed of two or three such quarks (antiquarks)

\[
\begin{align*}
Q = -1/3 & \quad \text{d} \\
Q = 2/3 & \quad \text{u} \\
S = 0 & \quad \text{s}
\end{align*}
\]
The Quark Model

baryons = qqq

mesons = q̅q
Colour

Quark model very successful, but seems to violate quantum numbers (Fermi statistics), e.g. \( |\Delta^{++}\rangle = |uuu\rangle |\uparrow\uparrow\uparrow\rangle \)

=> introduce new degree of freedom:

3 colours -> \( SU(3)_{\text{colour}} \)

qqq = q\bar{q} = \text{white!}
Screening of Electric Charge

- Electric charge polarises vacuum $\rightarrow$ virtual electron positron pairs
- Positrons partially screen electron charge
- Effective charge/force
  - Decreases at large distances/low energy (screening)
  - Increases at small distance/large energy

(Sin-Itoro, Julian, Richard P. Tomonaga, Schwinger, Feynman (Nobel 1965))
Anti-Screening of Colour Charge!

quark-antiquark pairs $\rightarrow$ screening gluons carry colour $\rightarrow$ gg pairs $\rightarrow$ anti-screening!

\[
\frac{1}{r^2} \sim E^2, \quad Q^2
\]

asymptotic freedom

Confinement

(Nobel 2004)
Comparison QED / QCD

**Electromagnetism**

**QED**
- 1 kind of charge (q)
- force mediated by photons
- photons are neutral
- $\alpha$ is nearly constant

**QCD**
- 3 kinds of charge (r, g, b)
- force mediated by gluons
- gluons are charged (e.g. $rg$, $bb$, $gb$)
- $\alpha_s$ strongly depends on distance

**Strong Interactions**

**Confinement limit:**

- The underlying theories are formally almost identical!
The effective potential for $q\bar{q}$ interactions

\[ V(r) \approx -4 \frac{\alpha_s}{3} \frac{1}{r} + k \cdot r \]

asymptotic freedom

confinement

lattice gauge calculation

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Heavy Quark Spectroscopy

Positronium = bound e⁺e⁻ system

Charmonium = bound system of c̅c quark pair

\[
\begin{align*}
\text{D} & \rightarrow \Psi(4.04) \rightarrow \Psi(3.77) \\
\text{DD} & \rightarrow \Psi'(3.096) \\
& \rightarrow \eta_c' \rightarrow \chi_0 \rightarrow \eta_c
\end{align*}
\]

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calculation of proton mass in QCD

from lattice gauge theory:

spontaneous breakdown of “chiral symmetry” (left-right-symmetry) yields QCD “vacuum” expectation value

⇒ proton mass,
⇒ mass of the visible part of the universe!

Yoichiro Nambu
(Nobel 2008)
**How to detect Quarks and Gluons?**

### Jets!

Example of the hadron production in $e^+e^-$ annihilation in the JADE detector at the PETRA $e^+e^-$ collider at DESY, Germany.

- **Jets**
- **hadrons**

\[ e^+ \; q \; e^- \]

- **CMS energy 30 GeV.**
- **Lines of crosses - reconstructed trajectories in drift chambers (gas ionisation detectors).**
- **Photons - dotted lines - detected by lead-glass Cerenkov counters.**
- **Two opposite jets.**

Georges Charpak (Nobel 1992)
Discovery of the Gluon (1979)

PETRA at DESY: look for

\[ e^+ e^- \rightarrow q \bar{q} + g + \alpha_s \]

Björn Wiik  Paul Söding

Günter Wolf  Sau Lan Wu

(TASSO event picture 1979)

E_{cm} = 35 \text{ GeV}

2.46 GeV \pi^+

1.67 GeV K^+

1.32 GeV K^-

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Jets in ep and pp interactions

H1 inclusive jet photoproduction

H1 data $Q^2 \leq 0.01 \text{ GeV}^2$ ($\times R_F$)
H1 data $Q^2 \leq 1 \text{ GeV}^2$

NLO (1+ $\delta_{\text{hadr.}}$)
NLO
GRV, CTEQ5M

incl. $k_T$ algor. (D=1)

$-1 \leq \eta^{\text{jet}} \leq 2.5$

$164 \leq W_{\gamma p} \leq 242 \text{ GeV}$

NLO (1+ $\delta_{\text{hadr.}}$)
LO (1+ $\delta_{\text{hadr.}}$)

H1 data

CMS \quad L = 34 \text{ pb}^{-1}
\sqrt{s} = 7 \text{ TeV}

\begin{itemize}
  \item $|y|<0.5$ (×3125)
  \item $0.5 \leq |y|<1$ (×625)
  \item $1 \leq |y|<1.5$ (×125)
  \item $1.5 \leq |y|<2$ (×25)
  \item $2 \leq |y|<2.5$ (×5)
  \item $2.5 \leq |y|<3$
\end{itemize}

NLO⊗NP
(PDF4LHC)

Exp. uncertainty

Anti-$k_T$ $R=0.5$

QCD works!

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Running strong coupling "constant" $\alpha_s$

e.g. from jet production at $e^+e^-$, ep, and pp at DESY, Fermilab and CERN

\[ \alpha_s(Q) \]

\[ \alpha_s(M_Z) = 0.1171 \pm 0.0075 \text{ (3-jet mass)} \]

\[ \alpha_s(M_Z) = 0.1185 \pm 0.0006 \text{ (World average)} \]
How to determine the „size“ of a particle?

microscope:
low resolution -> small instrument
high resolution -> large instrument

resolution ~ $10^{-18}$ m = 1/1000 of size of a proton

HERA = giant electron microscope
How to resolve the structure of an object?

e.g. X-rays (Hasylab, FLASH, PETRA III, XFEL)  \( E \sim \text{keV} \)

\[ \quad \rightarrow \text{structure of a biomolecule} \]

Ada Yonath (Nobel 2009)
Resolve the structure of the proton

- $E \sim \text{MeV}$
  - resolve whole proton

- static quark model, valence quarks
  - $(m \sim 350 \text{ MeV})$

- $E \sim m_p \sim 1 \text{GeV}$
  - resolve valence quarks and their motion

- $E \gg 1 \text{GeV}$
  - resolve quark and gluon “sea”
At higher and higher resolutions, the quarks emit gluons, which also emit gluons, which emit quarks, which…….

Heisenberg’s UP allows gluons, and $q\bar{q}$ pairs to be produced for a very short time.

- Low $Q^2$ (large $\lambda$)
- Medium $Q^2$ (medium $\lambda$)
- Large $Q^2$ (short $\lambda$)

At highest $Q^2$, $\lambda \sim 1/Q \sim 10^{-18}$ m

no quark compositeness found (so far)
Deep Inelastic $ep$ Scattering at HERA

Diagram showing the interaction of an electron (e) with a proton (p) resulting in a scattered positron (scattered positron) and a remnant proton (p remnant).
Deep Inelastic Scattering (DIS)

Neutral Current

\[ s = (l + p)^2 \]

2 degrees of freedom at fixed cms energy

\[ Q^2 = -(l - l')^2 \]

boson virtuality (resolution scale)

\[ x = \frac{Q^2}{2p \cdot q} \]

fractional momentum of struck quark (in QPM)

Parton distribution functions (PDF) in pQCD

\[ F_2^{em}(x, Q^2) = x \sum_i e_i^2 [q_i(x, Q^2) + \bar{q}_i(x, Q^2)] \]

\( q_i \) – probability to find quark with flavour \( i \) in proton
The Proton Structure

structure functions  quark and gluon densities

Amanda Cooper-Sarkar
(Chadwick medal 2015)
**Kinematic regions: HERA vs. LHC**

- **Proton structure** measured directly for a large part of the LHC phase space.

- **QCD evolution** successful.
  
  \[ Q^2/\text{GeV}^2 \]

- Safely extrapolate to higher \( Q^2 \).

---

**Input to measurements at LHC**
Example: Higgs cross section at LHC

**H \rightarrow \gamma\gamma in ATLAS**

Knowledge of gluon and quark distributions essential
Intermediate summary

- Particle physics: Symmetries and conservation laws are important
- many exciting results at DESY, CERN and elsewhere!
- HERA closed down, but particle physics at DESY alive and well
- tomorrow: weak interactions, Higgs, (neutrinos), cosmology, future of particle physics
Weak Interactions

The Theory of GLASHOW, SALAM and WEINBERG ~ 1959-1968

(Nobel 1979)

Theory of the unified weak and electromagnetic interaction, transmitted by exchange of “intermediate vector bosons”

mass generated by Higgs field
Discovery of the W and Z (1983)

- To produce the heavy W and Z bosons (m ~ 80-90 GeV) need high energy collider!
- 1978-80: conversion of SPS proton accelerator at CERN into proton-antiproton collider
  challenge: make antiproton beam!
- success!
  -> first W and Z produced 1982/83

Carlo Rubbia
Simon van der Meer

(Nobel 1984)
Now millions of events ...
yesterday’s signal is today’s background and tomorrow’s calibration
Three Boson Coupling @ LEP

W/Z bosons carry electroweak charge (like colour for gluons) -> measure rate of W pair production at LEP II

W/Z bosons carry electroweak charge (like colour for gluons) -> measure rate of W pair production at LEP II
Electroweak Physics at HERA

Neutral Current (NC) interactions

Charged Current (CC) interactions
Weak interactions are "left-handed"

- Lefthanded electrons interact (CC)
  \[ \sigma^{e^\pm p}_{polCC} = (1 \pm P_e) \cdot \sigma^{e^\pm p}_{unpolCC} \]

- Righthanded electrons do not!

- Cross section linearly proportional to polarization

\[ \sigma^{e^\pm p} = \sigma^{e^\pm p}_{unpolCC} \]

It works!
Electroweak Unification

**H1 and ZEUS**

Strength of weak and electromagnetic forces become similar at scale $Q^2 \sim M_W^2$

\[
\frac{d^2\sigma_{NC}}{dQ^2 \, dx} \sim \alpha^2 \frac{1}{Q^4} \frac{1}{x} \Phi_{NC}(x, Q^2)
\]

\[
\frac{d^2\sigma_{CC}}{dQ^2 \, dx} \sim G_F^2 \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \frac{1}{x} \Phi_{CC}(x, Q^2)
\]
The Quest for Unification of Forces

Maxwell's equations

- Electric
- Magnetic
- Weak
- Gravity

Electroweak Unification

Grand Unified Theories?

Superstring Theories?

Big Bang

LHC
$\alpha_s$ running and Grand Unification

with SUSY (see later):

$\alpha_s = 0.1186 \pm 0.003$

$\alpha_s(M_Z) = 0.1171 \pm 0.0075$ (3-jet mass)

$\alpha_s(M_Z) = 0.1185 \pm 0.0006$ (World average)

hep-ph/0407067 B.Allanach ... P.Zerwas
Antimatter

relativistic Schrödinger equation (Dirac equation)
two solutions:
one with positive, one with negative energy
Dirac: interpret negative solution as 1932 antielectrons (positrons) found in conversion of energy into matter
1995 antihydrogen consisting of antiprotons and positrons produced at CERN

In principle: antiworld can be built from antimatter
In practice: produced only in accelerators and in cosmic rays

Why???
Pair Production

e.g. $\gamma \rightarrow e^+ + e^-$

Equal amounts of matter and antimatter are produced when radiation is converted to matter.
Annihilation

\[ e^+ + e^- \rightarrow 2hf \]

Antimatter can be produced. It annihilates with matter to produce radiation.
As far as we can see in universe, no large-scale antimatter. -> need CP violation!
The Matter Antimatter Puzzle

Early Universe

-> particles, anti-particles and photons in thermal equilibrium
- colliding, annihilating, being re-created etc.

Slight difference in fundamental interactions between matter and antimatter ("CP violation")?
-> matter slightly more likely to survive

Ratio of baryons (e.g. p, n) to photons today tells us about this asymmetry - it is about 1:10^9
Like weak interaction, symmetric under CP (at first sight!)
Can there be small deviations from this symmetry?
CP violation in B meson decays

First B decays

Second B decays \( (B^0) \)

\[ e^+ \rightarrow e^- \]

Decay length \( \sim 1/4 \text{ mm} \)

\[ t \]

\[ t_2 \]

\[ B^0_d \text{ (or } \bar{B}^0_d \text{)} \]

Asymmetry \( (t) \) = \[ \frac{B^0 - B^0}{B^0 + B^0} \]

Simply count decays as function of \( t \)!
CP violation in B meson decays

Example: measurement from BaBar at SLAC
(also Belle at KEK)
B and anti-B are indeed different
(also found earlier for K decays: )

Weak Interactions violate CP!

James W. Cronin Val L. Fitch
(Nobel 1980)

M. Kobayashi T. Maskawa
(Nobel 2008)

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DESY contribution to the antimatter puzzle?

- CP violation measured so far not strong enough to explain matter-antimatter asymmetry
- Way out: CP violation in neutrino oscillations and/or strong lepton number asymmetry in early universe.
- Standard Model predicts baryon and lepton number violation through so-called „sphaleron“ process: converts 3 leptons into 3 baryons!
- Rare process at very high energy -> not observable so far
- Related process: QCD „instantons“
- In principle observable at HERA or LHC
- Still searching ...
The Mystery of Mass

- $u$ (up)
- $d$ (down)
- $\nu_e$ (e-neutrino)
- $e$ (electron)
- $c$ (charm)
- $s$ (strange)
- $\nu_\mu$ (\(\mu\)-neutrino)
- $\mu$ (muon)
- $b$ (bottom)
- $\nu_\tau$ (\(\tau\)-neutrino)
- $\tau$ (tau)
The Mass (BEH) Mechanism

P. Higgs et al. (1964-66,71)
Brout, Englert, Guralnik, Hagen, Kibble, ...

many subvariants
which is right?

source: viXra blog

Peter Higgs
François Englert
(Nobel 2013)

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Fermion Mass from Higgs field?

very brilliant scientist (fermion) works with speed of light!

room = vacuum
people = Higgs vacuum expectation value

"massless"
Fermion Mass from Higgs field?

scientist becomes famous!
enters room with people
Fermion Mass from Higgs field?

people cluster around him hamper his movement/working speed
\rightarrow he becomes “massive”!

Why are some fermions so much more famous than others?
How much do Neutrinos weigh?

from the lightest ...

Standard Model has $m_\nu = 0$

$\rightarrow$ evidence for $m_\nu \neq 0$

forces

extension of Standard Model

Why ???

this year no special neutrino lecture, sorry
The quest for the top quark

Electroweak precision measurements at LEP/CERN sensitive to top quark mass and Higgs mass (indirect effects)

... to the heaviest

\[ \propto \left( \frac{M_t}{M_W} \right)^2, \ln \left( \frac{M_h}{M_W} \right) \]

\[ \rightarrow M_t \sim 170 \text{ GeV} \]
The Tevatron (Fermilab)

data taking ended in 2011
analysis still ongoing
Top quark discovery (Fermilab 1995)

Top quark actually found where expected!

Tevatron at Fermilab (CDF + D0)

measured mass value: (PDG12)

\[ M_{\text{top}} = 173.5 \pm 1.0 \text{ GeV/c}^2 \]
Precision @ LEP and Higgs

Insert measured top mass into precision measurements at LEP -> now sensitive to Higgs mass

$m_H < 182 \text{ GeV at 95\% CL}$

LEP direct lower limit:

$m_H > 114 \text{ GeV at 95\% CL}$
**Precision @ LEP and Higgs at LHC**

**and there it is!**

\[ H \rightarrow ZZ^* \rightarrow 4 \text{ leptons} \]

**CMS preliminary**

L=5.1 and 19.6 fb\(^{-1}\) at \( \sqrt{s} = 7\text{ TeV} \) and 8 TeV

- data
- 2\(\ell\)2\(\nu\) \(7\text{ TeV}, 8\text{ TeV}\)
- 4\(\ell\) \(7\text{ TeV}, 8\text{ TeV}\)
- 4\(e\) \(7\text{ TeV}, 8\text{ TeV}\)

\(m_H = 126\text{ GeV}\)
for their leadership role in the scientific endeavour that led to the discovery of the new Higgs-like particle by the ATLAS and CMS collaborations at CERN’s Large Hadron Collider.

Peter Jenni, ATLAS
Tejinder Singh Virdee, CMS
Lyn Evans, LHC
Fabiola Gianotti, ATLAS
Joe Incandela, CMS

Michel Della Negra, CMS
Guido Tonelli, CMS
Higgs production at LHC

measure as many as possible to check Higgs properties
The LHC Project

Just restarted @ 13 TeV

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The DESY CMS group

- Installation & Commissioning
- Computing
- Tracking, Tracker upgrade
- Beam Condition Monitor
- Forward detectors (CASTOR)
- Data Quality Monitoring
  building 1a, first floor

- Physics
  - Standard Model
  - Forward Physics
  - Top + Higgs
  - Supersymmetry
The DESY ATLAS group

- Trigger
- Computing
- Lumi monitor (ALFA)
- sLHC upgrade

Physics:
- Standard Model
- Top quarks
- Supersymmetry
- Higgs
Supersymmetry

- A way to solve theoretical problems with Unification of Forces: **Supersymmetry**
- For each existing particle, introduce similar particle, with spin different by 1/2 unit
Supersymmetry

- double number of particles:

  Standard-Teilchen

  SUSY-Teilchen

- not seen at LEP, HERA, Tevatron ... -> must be heavy!
- (still) hope to see them at LHC!
To include gravity in unification of forces, need Superstrings (Supersymmetric strings)
Superstring interaction
Extra Dimensions?

- Superstrings require more than 3+1 dimensions
- Additional “extra” dimensions -> “curled up”
  - could be as large as a mm (?)
extra dimensions -> micro black holes?

extremely short-lived - no indications so far
The case for an e+e- Linear Collider

Historically, hadron (proton) and electron colliders have yielded great symbiosis:

- hadron colliders:
  discoveries at highest energies
- electron colliders:
  discoveries and precision measurements
- latest example:
  Tevatron/LEP (top), now Higgs at LHC

=> International Linear Collider!
“NEW DIRECTIONS IN SCIENCE ARE LAUNCHED BY NEW TOOLS MUCH MORE OFTEN THAN BY NEW CONCEPTS. THE EFFECT OF A CONCEPT-DRIVEN REVOLUTION IS TO EXPLAIN OLD THINGS IN NEW WAYS. THE EFFECT OF A TOOL-DRIVEN REVOLUTION IS TO DISCOVER NEW THINGS THAT HAVE TO BE EXPLAINED.”

Freeman Dyson, Imagined Worlds

The ILC Technical Design Report released (June 2013)
Hosting in Japan being discussed
Example: Higgs Physics at the ILC

Gauge couplings

Yukawa couplings

Self coupling

Top-Yukawa coupling

all measurable with high precision!
Cosmology

Direct link between Particle Physics and Cosmology

increasing energy
-> going further backwards in time in the universe
-> getting closer to the Big Bang
Inflation ceases, expansion continues. Grand Unification breaks. Strong and electroweak forces become distinguishable.

Grand unification era

Electroweak era

Quarks combine to make protons and neutrons

Nuclei are formed

Protons and neutrons combine to form helium nuclei

The Universe becomes transparent and fills with light

Galaxies begin to form

Galaxy formation

1000 M years

You!
Elementary Particle Physics is exciting!

- We already know a lot, but many open issues.

- Exciting new insights expected for the coming decade!

Join the Fun!