The Large Hadron Collider -
status, highlight results and future prospects

- the structure of matter
- LHC, ATLAS and CMS: status and performance
- challenging the Standard Model
- search for physics BSM
- Higgs hunting
- future prospects

S. Bethke
The "Standard Model" of Particle Physics

... is rather simple (und "übersichtlich"): 

<table>
<thead>
<tr>
<th>Elementary Particles</th>
<th>Elementary Forces</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Generation</strong></td>
<td><strong>exchange boson</strong></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Quarks</td>
<td></td>
</tr>
<tr>
<td>u</td>
<td>c</td>
</tr>
<tr>
<td>d</td>
<td>s</td>
</tr>
<tr>
<td>Leptons</td>
<td></td>
</tr>
<tr>
<td>νe</td>
<td>νμ</td>
</tr>
<tr>
<td>e</td>
<td>μ</td>
</tr>
</tbody>
</table>

... as well as anti-particles

... 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

... provides a consistent (yet incomplete) picture of the evolution of the very early universe –> particle cosmology
The “Standard Model” of Particle Physics

- shows no significant discrepancies between data and theory -- however it leaves open fundamental questions

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha^{(s)}_{\text{had}}(m_Z)$</td>
<td>0.02758 $\pm$ 0.00035</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1875 $\pm$ 0.0021</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 $\pm$ 0.0023</td>
</tr>
<tr>
<td>$\sigma_{\text{had}}$ [nb]</td>
<td>41.540 $\pm$ 0.037</td>
</tr>
<tr>
<td>$R_l^0, l$</td>
<td>20.767 $\pm$ 0.025</td>
</tr>
<tr>
<td>$A_{\text{fb}}^{0, l}$</td>
<td>0.01714 $\pm$ 0.00095</td>
</tr>
<tr>
<td>$A_l(P_{l})$</td>
<td>0.1465 $\pm$ 0.0032</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21629 $\pm$ 0.00066</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.1721 $\pm$ 0.0030</td>
</tr>
<tr>
<td>$A_{\text{fb}}^{0, b}$</td>
<td>0.0992 $\pm$ 0.0016</td>
</tr>
<tr>
<td>$A_{\text{fb}}^{0, c}$</td>
<td>0.0707 $\pm$ 0.0035</td>
</tr>
<tr>
<td>$A_{b}$</td>
<td>0.923 $\pm$ 0.020</td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.670 $\pm$ 0.027</td>
</tr>
<tr>
<td>$A_l(SLD)$</td>
<td>0.1513 $\pm$ 0.0021</td>
</tr>
<tr>
<td>$\sin^2\theta_{\text{eff}}^{(Q_{l})}$</td>
<td>0.2324 $\pm$ 0.0012</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>80.399 $\pm$ 0.023</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>2.085 $\pm$ 0.042</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>173.3 $\pm$ 1.1</td>
</tr>
</tbody>
</table>

July 2010
Limitations of the SM:

- **it makes unphysical predictions** at very high energies:
  - at $E > 1 \text{ TeV}$, violates unitarity for some reactions

- **it is incomplete**:
  - too many free parameters (26 masses, couplings ... $\rightarrow$ experiment)
  - symmetry breaking mechanism unclear (Higgs mechanism, masses)

- **it leaves open many fundamental questions**:
  - why are there 3 families of quarks and leptons?
  - why is $(\text{electron charge}) = -(\text{proton charge})$?
  - what happened to the anti-matter in the universe?
  - do forces unify at high energies (GUT)?
  - ....

$\rightarrow$ SM is only an effective theory

$\rightarrow$ there must be physics beyond SM (BSM)
today, there are few but significant signals for BSM physics:

• neutrinos are not massless

• 95% of the mass/energy budget of the universe cannot be explained by SM particles and forces:
  - Dark Matter (23%)
  - Dark Energy (73%)
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
since March 2010, the future has just begun:
the LHC collides protons at 7 TeV c.m.!
The Large Hadron Collider (LHC)

the largest scientific project ever done

- 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
The Large Hadron Collider (LHC)

Proton - Proton collisions at 14 TeV c.m. energy

2835 $\times$ 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
The ATLAS Detector at the **LHC**

- **Length**: 44 m
- **Height**: 22 m
- **Weight**: 7000 t
- **3000 Physicists & Engineers**
  (incl. 1000 Students)
- **178 Institutes**
- **38 Nations**
- **150•10^6** electronic readout channels
- **40 MHz** collision rate
- **10^{14} B/s** raw data flux

Planning & construction 1990 to 2007, operation from 2009, for ~ 15-20 years
LHC: Integrated luminosity until end-of-run 2011 (pp)

LHC Peak luminosity reached:
$ L \sim 3.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ (design: $10^{34}$)

(data statistics 2011: 100x 2010)

Overall ATLAS/CMS data taking efficiency (with full detector on): 95%
pile-up:

- 10-20 collisions per bunch crossing

- detector and electronics have to cope with large data rates

- physics analysis of data has to cope with large backgrounds
Summary of LHC / detector performance:

- LHC delivered an unexpected large amount of high quality data (>5.5. fb-1) in 2011

- LHC reached ~1/3 of the nominal luminosity ($10^{34}$ cm$^{-1}$ s$^{-1}$)

- due to safe operation criteria, LHC can only run only at 50% of the anticipated maximum c.m. energy (14 TeV)

- all particle detectors performed excellently from day one of collision data

- large pile-up rates (15-20 collisions per crossing) and huge data rates challenge data taking and analyses
timeline of CMS physics publications

![Graph showing the timeline of CMS physics publications](image)
hadron jets!
LHC results I: the "rediscovery" of the SM
di-muon invariant mass spectrum

leptons!

$\omega/\rho$, $\phi$, $J/\psi$, $\psi'$, $Y(1S)$, $Y(2S)$, $Z$

$\int L \approx 40 \text{ pb}^{-1}$

$\text{EF\_mu15}$
Summary of main electroweak and top quark cross-section measurements

- Inner error: statistical
- Outer error: total

Good agreement with SM expectations (within present uncertainties)
searches for signals of New Physics (BSM)

missing $E_t$!
Example: search for squarks and gluinos using final states with high $p_T$ jets and large $E_T$ (and NO leptons)

$$M_{\text{eff}} = E_T^{\text{miss}} + \sum |p_T^{\text{jet}}|$$
Example: search for squarks and gluinos using final states with high $p_T$ jets and large $E_T$ (and NO leptons)

• for equal mass gluinos and squarks: exclusion for masses $< O(1 \text{ TeV})$
Results of main searches for New Physics

**SUSY**: mass limits in the range 0.5-1 TeV
(within constrained models)
Search for the (SM) Higgs boson

Higgs production:

... a very rare process!
Search for the (SM) Higgs boson

Higgs decays:
ATLAS: $H \rightarrow ZZ \rightarrow \ell\ell$

- n.b.: good mass resolution, small background, but low statistics at small masses (off-peak Z)!
The LHC Project - status, highlight results and future prospects
S. Bethke, MPP München
MPK Heidelberg, Feb 1, 2012
\[ H \rightarrow \gamma \gamma \]

- n.b.: good mass resolution, but large background
H $\rightarrow$ WW $\rightarrow$ lν lν

- n.b.: limited mass resolution due to missing energy (2 ν‘s !!)
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ATLAS combination of all channels (status: Dec. 2011):

- exclusion of existence of SM Higgs (at least 95% c.l.):
  \[ 112.7 < M_H < 115.5 \text{ GeV}; \ 131 < M_H < 237 \text{ GeV}; \ 251 < M_H < 468 \text{ GeV} \]

- local excess at \( M \sim 126 \text{ GeV} \) (significance: 2.9 std. dev.)
ATLAS single channel results
CMS: $H \rightarrow \gamma \gamma$
CMS: combined SM Higgs analysis
CMS: combined SM Higgs analysis

exclusion: $127 < M_h < 600$ GeV (95% c.l.)
expected: $117 < M_h < 543$ GeV (95% c.l.)

max. local significance: $2.6 \sigma$
incl. look elsewhere (110-145 GeV): $1.9 \sigma$
CMS Preliminary, $\sqrt{s} = 7$ TeV

Combined, $L_{int} = 4.6-4.7$ fb$^{-1}$

95% CL limit on $\sigma/\sigma_{SM}$

Higgs boson mass (GeV/c$^2$)
Summary of physics results:

- SM significantly challenged; still in very (too?) good shape!

- extensive searches for physics BSM without positive result; exclusion of many processes up to and beyond masses of O(1 TeV) → still large phase space region to go ...

- possible signal of „light“ SM Higgs boson at ~125 GeV (in several decay channels, both by ATLAS and CMS); local significance ~$3\sigma$; incl. „look-elsewhere“: ~$2\sigma$
LHC - future planning:

2012:
- collisions at 7 (possibly 8!) TeV
- will reach (~half to total) Design-Luminosity
- expect ~3-times statistics of 2011 (i.e.: ~12-15 fb\(^{-1}\))

\[\rightarrow \text{establishment or exclusion of SM Higgs Boson (5 std.dev.)}\]

2013 / 2014:
- 15-19 months shut-down (installation of final safety systems for highest magnet currents to reach design-energy of 14 TeV)

2014 - 2016:
- full energy (14 TeV) and luminosity \(10^{34} \text{ cm}^{-2} \text{ s}^{-1}\)

from ~ 2020:
- upgrade of LHC (and of detectors) to hl-LHC (luminosity x 5)
... and why do we do all this?

why do we need (such complex and expensive) fundamental research?

in order to understand our World!