The Large Hadron Collider: Shedding Light on the Dark Universe

Particle Physics and the Early Universe

The Large Hadron Collider (LHC)

The LHC and the Dark Universe

R.-D. Heuer, CERN

Berlin, July 12, 2010
Particle Physics at accelerators

Explore the innermost structure of matter:

- Which are the fundamental constituents of matter?
- Which forces interact between them?

Investigating the Structure of Matter

Understanding the Early Universe
Vision

- Revolutionary advances in understanding the microcosm
- Connect microcosm with early Universe

Particle Physics at the **Energy Frontier** with highest collision energies ever will change our view of the universe
matter particles

electron neutrino
\( \nu_e \)
electron
\( e \)
up quark
\( u \)
down quark
\( d \)
charmed quark
\( c \)
strange quark
\( s \)
bottom quark
\( b \)
top quark
\( t \)
muon neutrino
\( \nu_\mu \)
muon
\( \mu \)
tau neutrino
\( \nu_\tau \)
tau
\( \tau \)

plus corresponding antiparticles
Electron-Positron Collider LEP:

\[ e^+e^- \rightarrow Z^0 \rightarrow f\bar{f} \]
where \( f = q, l, \nu \)

\( \sigma_Z \) and \( \Gamma_Z \) depend on number of (light) neutrinos

number of families:

\[ N = 2.984 \pm 0.008 \]
Matter (Stars <=> living organisms) consists of
3 families of Quarks and Leptons

Matter around us: only 1 of the 3 families
Matter at high energies:
‘democratic’, all 3 families present

→ Situation fraction of seconds after the creation of the Universe
→ Study of Matter at High Energies
    knowledge about Early Universe
Forces

Gravitation
(acts on mass, energy)

Electromagnetic Force
(acts on el. charge)

Weak Force
(acts on leptons, quarks)

Strong Force
(acts on quarks)
Force Carriers = Gauge Bosons

- **Graviton**
- **Photon**
- **W^+/−, Z^0**
- **Gluon**
# The Forces in Nature

<table>
<thead>
<tr>
<th>Type</th>
<th>rel. Strength</th>
<th>Force Carrier</th>
<th>acts on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong Force</td>
<td>1</td>
<td>Gluon $g$, $m = 0$</td>
<td>Quarks, Nuclei</td>
</tr>
<tr>
<td>Electro-magnet.</td>
<td>~ 1/137</td>
<td>Photon $\gamma$, $m = 0$</td>
<td>Electric Charge Atoms, Chemistry</td>
</tr>
<tr>
<td>Weak Force</td>
<td>~ $10^{-14}$</td>
<td>W, Z Bosons, $m = 80, 91$ GeV</td>
<td>Leptons, Quarks Radioactive Decays ($\beta$-decay)</td>
</tr>
<tr>
<td>Gravitation</td>
<td>~ $10^{-40}$</td>
<td>Graviton $\gamma$, $m = 0$</td>
<td>Mass, Energy</td>
</tr>
</tbody>
</table>

Force Carriers (Bosons) mediate the forces
Structure of Matter II

4 fundamental **forces** act between **Matter Particles** through the exchange of **Gauge Bosons** (Gluon, W und Z, Photon, Graviton)

Within our Energy regime:
- resp. strengths of forces very different

At high Energies:
- all forces of same strength \(\rightarrow\) one force?

\(\rightarrow\) Situation fraction of seconds after creation of the Universe

\(\rightarrow\) Study of the forces of Nature knowledge about Early Universe
The physical world is composed of Quarks and Leptons interacting via force carriers (Gauge Bosons).

Last entries: top-quark 1995
tau-neutrino 2000

What have we learned the last 40 years or Status of the Standard Model
Past few decades

“Discovery” of Standard Model

through synergy of

hadron - hadron colliders (e.g. Tevatron)
lepton - hadron colliders (HERA)
lepton - lepton colliders (e.g. LEP)
Standard Model of Particle Physics

Mathematical formalism describing all interactions mediated through weak, electromagnetic and strong forces

Test of predictions with very high precision

experimental validation
down to $\sim 10^{-18}$ m
or up to $\mathcal{O}(100 \text{ GeV})$
Test of the SM at the Level of Quantum Fluctuations

indirect determination of the top mass

prediction of the range for the Higgs mass

possible due to
- precision measurements
- known higher order electroweak corrections

$\propto \left( \frac{M_t}{M_W} \right)^2 \ln \left( \frac{M_h}{M_W} \right)$
Status recent Summer Conferences

**Standard Model Analysis**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
<th>$I_{\text{meas}}^0$</th>
<th>$I_{\text{fit}}^0$</th>
<th>$I_{\text{meas}}^1$</th>
<th>$I_{\text{fit}}^1$</th>
<th>$I_{\text{meas}}^2$</th>
<th>$I_{\text{fit}}^2$</th>
<th>$I_{\text{meas}}^3$</th>
<th>$I_{\text{fit}}^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha_{\text{had}}^{(5)}(m_2)$</td>
<td>0.02758 ± 0.00035</td>
<td>0.02768</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>91.1875</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>2.4957</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_{\text{had}}^0$ [nb]</td>
<td>41.540 ± 0.037</td>
<td>41.477</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_l$</td>
<td>20.767 ± 0.025</td>
<td>20.744</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{1}^{0,l}$</td>
<td>0.01714 ± 0.00095</td>
<td>0.01645</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{1}(P_{t})$</td>
<td>0.1465 ± 0.0032</td>
<td>0.1481</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21629 ± 0.00066</td>
<td>0.21586</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.1721 ± 0.0030</td>
<td>0.1722</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{fb}^{0,b}$</td>
<td>0.0992 ± 0.0016</td>
<td>0.1038</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{fb}^{0,c}$</td>
<td>0.0707 ± 0.0035</td>
<td>0.0742</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></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>
<td></td>
<td></td>
<td></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>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{b}(\text{SLD})$</td>
<td>0.1513 ± 0.0021</td>
<td>0.1481</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sin^2\theta_{\text{eff}}^\text{lep}(Q_{fb})$</td>
<td>0.2324 ± 0.0012</td>
<td>0.2314</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>80.398 ± 0.025</td>
<td>80.374</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>2.140 ± 0.060</td>
<td>2.091</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>170.9 ± 1.8</td>
<td>171.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fit to 17 high-$Q^2$ observables plus $\Delta \alpha_{\text{had}}$:

$\chi^2/\text{ndof} = 18.2/13$ (15.1%)

Largest $\chi^2$ contribution:

$A_{1}(\text{SLD})$ vs. $A_{fb}^{b}(\text{LEP})$

Without this point, the fit is too good!

A$_{fb}^{b}$ has largest pull: 2.9σ!

Decided in favour of isomeron theory!

however . . .

. . . one piece missing within Standard Model
What is the origin of mass of elementary particles?

Possible solution:
Mass = property of particles with energy $E$ to move with velocity $v/c = (1 - m^2/E^2)^{1/2}$

- introduction of a scalar field (Higgs-Field)
  particles acquire mass through interaction with this Higgs-Field
  Self interaction $\rightarrow$ Higgs-Particle

Nobel Prize 2008 to Nambu $\rightarrow$ „foundation“ for Higgs et al.
THE missing cornerstone of the Standard Model

What is the origin of mass of elementary particles?

Possible solution:
Mass = property of particles with energy $E$ to move with velocity $v/c = (1-m^2/E^2)^{1/2}$

$\Rightarrow$ introduction of a scalar field (Higgs-Field)
particles acquire mass through interaction with this Higgs-Field
Self interaction $\rightarrow$ Higgs-Particle

Higgs-Particle = last missing cornerstone within SM

but:
Does the Higgs-Particle exist at all??

named after Peter Higgs
Key Questions of Particle Physics

- origin of mass/matter or origin of electroweak symmetry breaking
- unification of forces
- fundamental symmetry of forces and matter
- unification of quantum physics and general relativity
- number of space/time dimensions
- what is dark matter
- what is dark energy

→ with the Large Hadron Collider at the Terascale now entering the ’Dark Universe’
The Large Hadron Collider: Shedding Light on the Dark Universe

Particle Physics and the Early Universe

The Large Hadron Collider (LHC)

The LHC and the Dark Universe
The Large Hadron Collider (LHC) at CERN

- Largest scientific instrument ever built, 27km of circumference
- 10,000 people involved in its design and construction
- Collides protons to reproduce conditions at the birth of the Universe...
  ...40 million times a second
The most empty place in the solar system......

In order for particles to circulate in the LHC, a vacuum similar to that in interstellar space is needed.

The pressures in the vacuum tubes of the LHC are below those on the surface of the moon.
One of the most coldest places in the Universe...

With a temperature of -271 C, or 1.9 K above absolute zero, the LHC is colder than outer space.
One of the **hottest** places in the galaxy...

The collision of two proton beams generates temperatures 1000 million times larger than those at the centre of the Sun, but in a much more confined space.
Proton-Proton Collisions at the LHC

- 2835 + 2835 proton bunches separated by 7.5 m
  $\rightarrow$ collisions every 25 ns $= 40 \text{ MHz crossing rate}$

- $10^{11}$ protons per bunch

- at $10^{34}/\text{cm}^2/\text{s}$
  $\approx 35 \text{ pp interactions per crossing pile-up}$

- $\rightarrow \approx 10^9 \text{ pp interactions per second} !!!$

- in each collision
  $\approx 1600 \text{ charged particles produced}$

enormous challenge for the detectors
To select and record the signals from the 600 million proton collisions every second, huge detectors have been built to measure the particles traces to an extraordinary precision.
Hector Berlioz, “Les Troyens”, opera in five acts
Valencia, Palau de les Arts Reina Sofia, 31 October -12 November 2009
Basic processes at LHC

Proton 1 $p_1$  

Proton 2 $p_2$  

$f_a(x_1, Q^2)$  

$f_b(x_2, Q^2)$  

$q$  

$q'$  

Jet  

Jet

$$d\sigma(p_1 p_2 \rightarrow c d) = \int_0^1 dx_1 dx_2 \sum_{a,b} t_B(x_1, Q^2) t_B(x_2, Q^2) d\sigma^{ab \rightarrow cd}$$
Basic processes at LHC

Proton 2 $p_2$

$g$

$f_b(x_2, Q^2)$

$W/Z$

Proton 1 $p_1$

$g$

$f_a(x_1, Q^2)$

$W/Z$
“Well known” processes. Don’t need to keep all of them ...

New Physics!! We want to keep!!
The LHC data

- 40 million events (pictures) per second
- Select (on the fly) the ~200 interesting events per second to write on tape
- “Reconstruct” data and convert for analysis: “physics data” \(\rightarrow\) the grid...

<table>
<thead>
<tr>
<th>(x4 experiments x15 years)</th>
<th>Per event</th>
<th>Per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw data</td>
<td>1.6 MB</td>
<td>3200 TB</td>
</tr>
<tr>
<td>Reconstructed data</td>
<td>1.0 MB</td>
<td>2000 TB</td>
</tr>
<tr>
<td>Physics data</td>
<td>0.1 MB</td>
<td>200 TB</td>
</tr>
</tbody>
</table>

- Concorde (15 km)
- Balloon (30 km)
- CD stack with 1 year LHC data! (~ 20 km)
- Mt. Blanc (4.8 km)
Enter a New Era in Fundamental Science

Start-up of the Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever, is the most exciting turning point in particle physics.

Exploration of a new energy frontier

CMS

ALICE

plus three smaller experiments

TOTEM

LHCf

MoEDAL

ATLAS

LHCb
First Collisions at LHC on 23 November 2009 at $E_{CM} = 900$ GeV

Chronology of a fantastic escalation of events:

**2009**
- 20 November: first beams circulating in the LHC
- 23 November: first collisions at $\sqrt{s} = 900$ GeV
- 8, 14, 16 December: few hours of collisions at $\sqrt{s} = 2.36$ TeV (the world record !)
- 16 December: end of first run
- 16 December- 26 February: technical stop

**2010**
- 27 February: machine operation started again
- 19 March: first (single) beams ramped up to 3.5 TeV
- 30 March: first collisions at $3.5+3.5$ TeV

... after more than a year of repairs and improvements
First paper (submitted 28/11)

- $dN_{ch}/d\eta$ for $|\eta| < 0.5$
- $dN_{ch}/d\eta$ vs $\eta$

2010

- 30 March: first collisions at 3.5TeV/beam
- 19 April: order of magnitude increase in luminosity
  - doubling the number of particles/bunch
  - $\beta^*$ from 11 to 2m (4b/beam) $L \sim 2 \times 10^{28}$.
  - Beam lifetimes of $\sim 1000$ hours
- 22 May another order of magnitude:
  - 13 bunches in each beam ($L \sim 3 \times 10^{29}$)
- 26 May: Design intensity bunches were brought into collision at 3.5TeV/beam.
status today:
more than 100/nb delivered to the experiments

LHC works beautifully
Ready for b physics (and b-tagging in general)

Two b-jets candidate
J/ψ Effective Lifetime

A total of 4000 $J/\psi \rightarrow \mu\mu$ decays reconstructed

Proper lifetime distribution shows clear evidence for $J/\psi$ produced in B decays

Solid prospects to measure production cross-sections for prompt $J/\psi$ and $b\bar{b}$ at $\sqrt{s} = 7$ TeV
After pre-selection:

-- $W \rightarrow e \nu$:
  loose $e^\pm$, $E_T > 20$ GeV

-- $W \rightarrow \mu \nu$:
  $p_T(\mu) > 15$ GeV
  $|\Delta p_T(ID-MS)| < 15$ GeV
  $|Z_{\mu-Z_{\text{vtx}}}| < 1$ cm

MC: normalised to data (total number of events)

Observed events: 57

After all cuts but $E_T^{\text{miss}}$ and $m_T$

Final candidates inspected in detail $\rightarrow$ timing, lepton reconstruction quality, event topology ...
Event selection:
- Two electrons with $E_T > 20$ GeV
- Monte Carlo: Event count normalized to integrated luminosity

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

Monte Carlo: cross section normalized to $17 \text{nb}^{-1}$ integrated luminosity

CMS Preliminary 2010, $\sqrt{s} = 7$ TeV

$\int L \cdot dt = 0.0523 \text{ pb}^{-1}$

- $Z \rightarrow ee$
- QCD
- Electroweak
- $t\bar{t}$

# of candidate = 18
# of expected signal = 19
# of expected background = 0.8

$Z \rightarrow ee$ candidate

52 $\text{nb}^{-1}$
Charged Particle Multiplicities at $\sqrt{s}=0.9, 7$ TeV

Monte Carlo underestimates the track multiplicity seen in ATLAS.

ALICE+CMS
Performance of Missing Transverse Energy (0.3nb⁻¹)

Understanding of high ETmiss tails is crucial for NP

Hopefully very low rate of new physics events sitting in these tails

Test ETmiss up to 250 GeV of transverse energy

time stability within 3%

Event cleaning: find jets from noise burst or photons from cosmic muon bremsstrahlung.

\[ E_T^{\text{miss}} = - \sum E_{\text{cell}} \text{ (vector sum)} \]

Due to large granularity of calorimeter, use only cells belonging to 3D calorimeter "topo" cluster 4 \( \sigma / 2 \sigma \) algorithm

Excellent agreement between data and MC at this early stage

More advanced computation of ETmiss including electrons, muons, taus, jets and their proper calibration under way
LHC Experiments Summary

- So far, so good....
- Experiments tracking nicely the machine evolution, eagerly awaiting more data
- Computing infrastructure supports magnificently the swift data analysis
- Experiments are re-discovering the Standard Model (only top quark missing.....)
- …exciting times!
The Science

We are poised to tackle some of the most profound questions in physics:

- Newton’s unfinished business… what is mass?
- Nature’s favouritism… why is there no more antimatter?
- The secrets of the Big Bang… what was matter like within the first second of the Universe’s life?
- Science’s little embarrassment… what is 96% of the Universe made of?
ready to enter the Dark Universe
Dark Matter

Astronomers & astrophysicists over the next two decades using powerful new telescopes will tell us how dark matter has shaped the stars and galaxies we see in the night sky.

Only particle accelerators can produce dark matter in the laboratory and understand exactly what it is.

Composed of a single kind of particle or more rich and varied (as the visible world)?

LHC may be the perfect machine to study dark matter.
The favoured candidate:

Supersymmetrie

Die bekannte Welt

Eine neue Welt?
Supersymmetry

- unifies matter with forces for each particle a supersymmetric partner (sparticle) of opposite statistics is introduced.
- allows to unify strong and electroweak forces
  \[
  \sin^2 \theta^\text{SUSY}_W = 0.2335(17) \\
  \sin^2 \theta^\text{exp}_W = 0.2315(2)
  \]
- provides link to string theories
- provides Dark Matter candidate (stable Lightest Supersymmetric Particle)
Mass spectra depend on choice of models and parameters...

Supersymmetry

Energy range of the LHC
Supersymmetry: A New Symmetry in Nature

Candidate Particles for Dark Matter
⇒ Produce Dark Matter in the lab

SUSY particle production at the LH

3 isolated leptons
+ 2 b-jets
+ 4 jets
+ $E_T^{miss}$
Searching for SUSY

Key:
- missing energy
- missing momentum

Vital:
- well understood detectors
Search for SUSY at LHC Start-up

- Due to their high production cross-sections, squarks and gluinos can be produced in large numbers even at modest luminosities.

- Potential for discovery of SUSY is sizeable even at LHC start-up.

→ First light in the Dark Universe (?)
Is dark matter linked to the Lightest Supersymmetric Particle?

Accel. and sat. data (WMAP and Planck): complementary views of dark matter.

WMAP/Planck: sensitive to total density of dark matter.

LHC/LC: identify DM particle, measures its mass;

Together they establish the nature of dark matter.

Neutralinos is not the full story
LHC results should allow, together with dedicated dark matter searches, first discoveries in the dark universe: around 73% of the Universe is in some mysterious “dark energy”. It is evenly spread, as if it were an intrinsic property of space. It exerts negative pressure.

Challenge: get first hints about the world of dark energy in the laboratory.
The Higgs is Different!

All the matter particles are spin-1/2 fermions.
All the force carriers are spin-1 bosons.

Higgs particles are spin-0 bosons (scalars).
The Higgs is neither matter nor force.
The Higgs is just different.
This would be the first fundamental scalar ever discovered.

The Higgs field is thought to fill the entire universe.
Could it give some handle of dark energy (scalar field)?

Many modern theories predict other scalar particles like the Higgs.
Why, after all, should the Higgs be the only one of its kind?

LHC can search for and study new scalars with precision.
Status of search for Higgs-Boson

Time evolution of experimental limits on the Higgs boson mass

If the Higgs-Boson exists it will be found at the LHC

$M_H$ between 114 and ~200 GeV
Search for the Higgs Boson

**LEP:**
- $H \rightarrow bb$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow W^+W^-$
- $H \rightarrow ZZ$

**LHC:**
- $H \rightarrow bb$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow W^+W^-$
- $H \rightarrow ZZ$

- enormous QCD bkgd
- low $m_H$ (BR $\approx 10^{-3}$)
- medium $m_H$
- high $m_H$

$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ \rightarrow 4\mu$ (golden channel)
SM Higgs Reach

**Needed $\sqrt{s} dt (fb^{-1})$ per experiment**

(at 14 TeV)

- $\leq 1$ fb$^{-1}$ for 98% C.L. exclusion
- $\leq 5$ fb$^{-1}$ for 5$\sigma$ discovery over full allowed mass range

Most difficult part is $M_h \sim 115$ GeV

Early discovery already possible with 1 fb$^{-1}$

$H \rightarrow WW^{(*)} \rightarrow 2l$

With 1 fb$^{-1}$ of understood data:

- Potential to exclude almost all $m_h$ values
- Potential to discover higgs with $m_h \sim 165$ GeV

LHC will give us an answer!

but it will take time...
In conclusion (G. Altarelli, LP09)

Is it possible that the LHC does not find the Higgs particle?

Yes, it is possible, but then must find something else

Is it possible that the LHC finds the Higgs particle but no other new physics (pure and simple SM)?

Yes, it is technically possible but it is not natural

Is it possible that the LHC finds neither the Higgs nor new physics?
LHC results will allow to study the Higgs mechanism in detail and to reveal the character of the Higgs boson.

This would be the first investigation of a scalar field.

This could be the very first step to understanding Dark Energy.
Past decades saw precision studies of 5% of our Universe → Discovery of the Standard Model

The LHC is delivering data

We are just at the beginning of exploring 95% of the Universe
Past decades saw precision studies of 5 % of our Universe → Discovery of the Standard Model

The LHC will soon deliver data

We are just at the beginning of exploring 95 % of the Universe

the future is bright in the Dark Universe