Physics at the LHC experiments

Summer School Lectures
DESY Zeuthen, August 25th-26th
2008

Marcello Barisonzi
Slides by Christiane Risler
Outline of the lecture

1. **Introduction to hadron colliders and pp physics**
   Overview of collider physics, LHC

2. **standard model physics at LHC** (and Tevatron)
   QCD Jets, top and W/Z physics and precision measurements

3. **searches**
   for the Higgs boson and new physics beyond the standard model

4. **ATLAS and CMS**
   how detectors work
Outline of part 1

1. The standard model of particle physics
2. Hadron Colliders: LHC
3. Some more details on pp physics and what to expect at LHC
4. LHC experiments ATLAS and CMS
1. The standard model of particle physics: short introduction, its success and its limitations
Building blocks of matter

quarks and leptons in three generations
The Standard Model of Particle Physics

**building blocks of matter**

quarks and leptons in three generations

**and forces**

electromagnetic, weak
strong force
mediated by exchange of gauge bosons

- photon $\gamma$ $m=0$
- gluon $g$ $m=0$
- $W,Z$-boson $m_W = 80.4$, $m_Z = 91$ GeV
Origin of mass in the standard model
so far particles massless

• electron and top mass
  \( m_e = 0.5 \text{ MeV} \)  \( m_t = 171.2 \text{ GeV} \)

• gauge Boson masses
  \( \gamma, g \)  \( m = 0 \)
  \( W, Z \)  \( m_W = 80.4, m_Z = 91 \text{ GeV} \)

Higgs mechanism: (Peter Higgs, 1964)
  masses of W and Z boson
  quark and lepton masses
  via coupling to the Higgs boson

mass of Higgs boson = free parameter
  constraints
  114.4 GeV (exp.) < \( m_H \) < \(~1 \text{ TeV} \) (theory)
Success of the Standard Model

**electro weak theory**
Glashow, Salam, Weinberg, 1974
SU(2) × U(1)
Higgs mechanism
prediction of neutral weak currents and massive weak gauge bosons

experimental confirmation:
Gargamelle and UA1, UA2

charm quark, top (heavier and found much later...)

**theory of strong interactions QCD**  SU(3)\(_C\)
also formulated in 1974
describes data over large energy range

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Pull</th>
<th>Pull</th>
<th>Pull</th>
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</thead>
<tbody>
<tr>
<td>( m_\gamma ) [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>.05</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_\gamma ) [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>-.42</td>
<td></td>
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<tr>
<td>( \sigma_{\text{hadr}} ) [nb]</td>
<td>41.540 ± 0.037</td>
<td>1.62</td>
<td></td>
</tr>
<tr>
<td>( R_\gamma )</td>
<td>20.767 ± 0.025</td>
<td>1.07</td>
<td></td>
</tr>
<tr>
<td>( A_\beta^{0,1} )</td>
<td>0.01714 ± 0.00095</td>
<td>.75</td>
<td></td>
</tr>
<tr>
<td>( A_\beta )</td>
<td>0.1498 ± 0.0048</td>
<td>.38</td>
<td></td>
</tr>
<tr>
<td>( A_\gamma )</td>
<td>0.1439 ± 0.0042</td>
<td>-.97</td>
<td></td>
</tr>
<tr>
<td>( \sin^2\theta_{\text{eff}} )</td>
<td>0.2321 ± 0.0010</td>
<td>.70</td>
<td></td>
</tr>
<tr>
<td>( m_W ) [GeV]</td>
<td>80.427 ± 0.046</td>
<td>.55</td>
<td></td>
</tr>
<tr>
<td>( R_\beta )</td>
<td>0.21653 ± 0.00069</td>
<td>1.09</td>
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<tr>
<td>( R_\gamma )</td>
<td>0.1709 ± 0.0034</td>
<td>-.40</td>
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</tr>
<tr>
<td>( A_\beta^{0,1} )</td>
<td>0.0990 ± 0.0020</td>
<td>-2.38</td>
<td></td>
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<tr>
<td>( A_\beta^{0,1,0} )</td>
<td>0.0689 ± 0.0035</td>
<td>-1.51</td>
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<tr>
<td>( A_\beta )</td>
<td>0.922 ± 0.023</td>
<td>-.56</td>
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<tr>
<td>( A_\gamma )</td>
<td>0.631 ± 0.028</td>
<td>-1.43</td>
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</tr>
<tr>
<td>( \sin^2\theta_{\text{eff}} )</td>
<td>0.23099 ± 0.00026</td>
<td>-1.61</td>
<td></td>
</tr>
<tr>
<td>( \sin^2\theta_W )</td>
<td>0.2255 ± 0.0021</td>
<td>1.20</td>
<td></td>
</tr>
<tr>
<td>( m_W ) [GeV]</td>
<td>80.452 ± 0.062</td>
<td>.81</td>
<td></td>
</tr>
<tr>
<td>( m_t ) [GeV]</td>
<td>174.3 ± 5.1</td>
<td>-.01</td>
<td></td>
</tr>
<tr>
<td>( \Delta \alpha_\text{had}(m_\gamma) )</td>
<td>0.02804 ± 0.00065</td>
<td>-.29</td>
<td></td>
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</tbody>
</table>

e+e- colliders (LEP, SLC), Tevatron (pp), HERA(ep),... energy range up to ~100 GeV with high precision SM consistent with all experimental data!
However, ...
The Standard Model: Open Questions

- **Origin of mass in the standard model?**
  does the Higgs boson exist, what is its mass?

- **Unification of forces?**
Unification of Forces?

- unification of electric and magnetic forces: Maxwell
- standard model unifies electro-magnetic and weak forces

Can electroweak and strong force (and even gravity) be unified at some higher scale = grand unification scale GUT?

All forces described by one unified theory with SM as low energy approximation
more symmetry (broken), more fundamental theory...

Possible in supersymmetric theories:
The Standard Model: Open Questions

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  More fundamental theory where forces are unified at higher scale?
The Standard Model: Open Questions

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- **Hierarchy Problem?**
  Why is the electro weak scale $\sim 100$ GeV $<<$ Planck scale $10^{19}$? 
  In other words: Why is gravity so weak?

- **Finetuning Problem**
  Radiative corrections to the Higgs mass quadratically diverge, 
  cancellation possible only with extreme fine tuning of parameters

- **Dark Matter?**
Dark Matter

Does not emit or reflect electromagnetic radiation, undetected

Where do we know it exists?

- motion of galaxies
- gravitational lensing
- cluster formation in cosmic microwave background

E.g. SUSY could provide candidates for dark matter

![Cosmic microwave background](image)
The Standard Model: Open Questions

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cancellation possible only with extreme fine tuning of parameters

- **Dark Matter?**
  what is it?

- **Flavor or generation problem**
  why three generations?
  origin of CP violation? why no strong CP violation
  neutrino masses and mixing
Possible Answers from LHC

How could LHC give answers to these questions?

- search for the Higgs Boson
- Test of standard model at highest energies – find deviations?
- search for supersymmetric particles?
  elegant, unifies forces, helps with fine tuning and hierarchy problem, provides dark matter candidate
- ..and of course any other physics beyond the standard model

new machine to find new physics:
LHC - answer on new physics at few TeV scale!
2. Hadron colliders
LHC @ CERN
Why hadrons?

e^+e^-

Collide compound objects, hadrons in initial state: hadron collisions more complex!

pp

7 TeV 7 TeV
Why hadrons?

**e^+e^-**

LEP event (higgs candidate 4 jet event)

\[ e^+e^- \rightarrow ZH \rightarrow bb \, qq \]

- no hadrons in initial state
- “clean” environment
- \( \sqrt{s} = 2E_{\text{beam}} \)

**pp**

simulated Higgs -> \( \mu\mu\mu\mu \) event in CMS

- hadron collisions more complex...
- \( \sqrt{s} \) of hard interaction of constituents \( \neq 2E_{\text{beam}} \)
- overlap with soft hadronic interactions
Advantage of hadron beams

wanted: highest energies
but losses due to synchrotron radiation
electrodynamics: accelerated charges radiate
ring accelerators: x-rays via bremsstrahlung

Energy loss per term: \[-\Delta E \approx \frac{4\pi e^2}{3R} \left( \frac{E}{mc^2} \right)^4\]

how to reduce \(\Delta E\)?
reduce \(E\)? no!
increase \(R\)? done!
increase \(m\)!

Ratio of \(e/p\):
\[\frac{\Delta E(e)}{\Delta E(p)} = \left( \frac{m_p}{m_e} \right)^4 \approx 10^{13}\]

future
- pp ring accelerator LHC
- \(e^+e^-\) linear accelerator ILC (R&D, planning phase)
energy of electron and hadron colliders

History of $\sqrt{s}$

higher center of mass energies at hadron colliders

constituent cms!
Hadron Colliders and Detectors

- Tevatron (CDF, DO)
  - 1987-2007
  - 2 TeV

- SPS (UA1, UA2...)
  - 1981-1990
  - 0.6 TeV

- CERN

- LHC (Atlas, CMS, LHC-B)
  - 2007-2020
  - 14 TeV

Marcello Barisonzi  marcello.barisonzi@desy.de  LHC experiments  August 25-26 2008  21
LHC

From LEP to LHC

Superconducting magnets

Compact Muon Solenoid

ATLAS

PS

SPS

ALICE

LHC-B

27 Km

CMS
proton-proton accelerator
in the LEP tunnel = 27 km
beam energies 7 TeV
four **experiments**: ATLAS, CMS (pp physics)  
LHC-B (physics of b quarks in pp)  
ALICE (Pb-Pb collisions)
Superconducting dipole magnets
1232 magnets, 15 m long
magnetic field 8.3 Tesla
temperature 1.9 K

Accelerator units
8 superconducting structures
gradient 5 MV/m
some LHC parameters

SC magnets  1235,  15m,  8.33 Tesla
beam energy  7 TeV

bunches/beam  2835
particles/bunch  1.15 \cdot 10^{11}
bunch spacing  25 ns

Lumi initial phase (1-2yr)  $10^{33}$ cm$^{-2}$ s$^{-1}$
Lumi design  $10^{34}$ cm$^{-2}$ s$^{-1}$

1 year \sim 10^{7} s running
integrated Lumi $10 - 100$ fb$^{-1}$/ year

for comparison:
design Tevatron Run II (2001 – now):
   \[ L = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \]
LHC design 50 x larger!
Start up scenario

now : beam commissioning in part of the ring, seen by LHCb!

Sep 2008: Beams in whole ring

Oct 2008: first interactions at 10 TeV
used for calibration and commissioning of experiments
October 21st is the official inauguration

Dec 2008: End of first run

2009 : Commissioning for 14 TeV
Beam halo at LHCb
Proton antiproton collider
exp.: CDF and D0

1992 – 1996 RunI
\( \sqrt{s} = 1.8 \) TeV
L = 125 pb\(^{-1}\)

1996 – 2001 upgrade of accelerator and detectors

since 2001 RunII
\( \sqrt{s} = 1.96 \) TeV

2001 - 2006
Run IIa  L = 1.2 fb\(^{-1}\)

2006 – 2009
Run IIb  L = 5-8 fb\(^{-1}\)
3. physics at hadron colliders
Definition of variables: $p_T$ and $\eta$

- **transverse momentum $p_T$:** momentum perpendicular to the beam axis

- **pseudorapidity $\eta$:**

  rapidity
  
  $$y = \frac{1}{2} \ln \frac{E + p_L}{E - P_L}$$

  massless particles (mass unknown) use **pseudorapidity** instead:
  
  $$\eta = -\ln \tan \theta / 2$$

  $\Delta \eta = 1$
  
  1 unit in pseudorapidity
  
  same number of charged particles
  
  $<n> \sim 7$ (for min bias events)
pp collisions

collide complex objects

interaction of partons in the proton
quarks and gluons (a,b)

hard subprocess
\[ a+b \rightarrow c+d \]

final state:
hadrons and jets
proton remnants X
pp colliders: QCD machines

Quarks and gluons interact strongly

**what was special about QCD?**

- high \( Q^2 \)
- long distance interactions
- low \( \alpha_s \)
- high \( \alpha_s \)

**Feynman diagrams for qq, qg, gg interactions:**

- Perturbative QCD
  - \( \text{expansion in orders in } \alpha_S \)

- Asymptotic confinement freedom

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**Running coupling**

Asymptotic freedom

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2004 Nobel Prize in Physics

David J. Gross

H. David Politzer

Frank Wilczek

For the discovery of asymptotic freedom in the theory of strong interactions
**pp collisions**

**long distance interactions**
- $\alpha_s$ large
- inside the proton
- formation of hadrons from partons
- pert. QCD not applicable

**short distance interactions**
- high momentum transfer and small $\alpha_s$
  - **hard subprocess**
  - outgoing (hard) partons
    - parton shower
    - $\rightarrow$ jets of partons
  - partons form hadrons
    - $\rightarrow$ jets of hadrons
pp collisions

**long distance interactions**
- \( \alpha_s \) large
- inside the proton
- formation of hadrons from partons
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**short distance interactions**
- high momentum transfer
- and small \( \alpha_s \)
- **hard subprocess**

outgoing (hard) partons
parton shower
--> jets of partons

partons form hadrons
--> jets of hadrons

pdfs

fragmentation
Hard subprocess

Proton momenta \( p_A = p_B = p = 7 \text{TeV} \)

momentum of partons in proton

\[ x_a \cdot p \quad x_b \cdot p \]

\( x = \) longitudinal momentum fraction

center of mass energy

of pp collision: \( \sqrt{s} = 2E_{\text{beam}} \)

of hard subprocess:

\[ \hat{s} = x_1 x_2 2p_A p_B = x_1 x_2 s \]

\[ \sqrt{\hat{s}} = <x> \sqrt{s} \]

which \( x \) needed to produce masses \( M \)?

<table>
<thead>
<tr>
<th>( M )</th>
<th>( &lt;x&gt; )</th>
<th>LHC</th>
<th>Tevatron</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 GeV</td>
<td>( \sim 0.007 )</td>
<td>( \sim 0.05 )</td>
<td></td>
</tr>
<tr>
<td>5 TeV</td>
<td>( \sim 0.36 )</td>
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</tbody>
</table>

what is probability to find parton with momentum fraction \( x \) in the proton?
What is probability to find parton with momentum fraction $x$ in the proton?

Probe structure of the proton deep inelastic ep scattering

HERA ep collider DESY, HH $e$ 27.5 GeV $p$ 920 GeV

QCD: structure depends on $x$, $Q^2$ probability is given by pdfs
Parton density functions

measure structure functions $F_2(x,Q^2)$...

total ep cross section $\rightarrow F_2$

$F_2(x) = \frac{F_2(x)}{F_2(0)}$

...extract pdfs for valence (up, down), sea quarks and gluons

fit of parameterised pdfs to $F_2$ data

$= test$ of QCD, extract pdfs

$Q^2 = 10 \text{ GeV}^2$
Cross section calculation

\[ \sigma = \sum_{a,b} dx_a dx_b f_a(x, Q^2) f_b(x, Q^2) \hat{\sigma}_{ab}(x_a, x_b) \]

- sum over initial partons \(a, b\)
- parton density functions \(f_{a,b}(x, Q^2)\)
  - non-perturbative, universal
- partonic hard scattering cross section \(\hat{\sigma}_{ab}(x_a, x_b)\)
  - calculable in pert. QCD

Long distance parton (pdfs) and short distance interaction (hard subprocess) factorise!
from partons to jets: fragmentation

at large momentum transfer: quarks act as free (asymptotic freedom) however: **no free quarks observed**, but jets of color less hadrons before QCD: puzzling ...

String-model

hard parton from subprocess creates **parton shower** =

- gluon radiation
- quark-antiquark pairs (pert)!

At each splitting: $E$ smaller --> $\alpha_s$ increased

non perturbative process: hadronisation
e.g. Lund String model

jets of hadrons
formation of jets

non-perturbative process

string-model

jet (to be defined)
**Minimum-bias events**

**Inelastic pp scattering cross section** (70 mb = very large) dominated by

*long distance interaction between pp with low momentum transfer*
  * final state very little pT, very large pL
  * pt of charged tracks ~ 500 MeV
  * # charged particles dN/dη ~ 7

so-called **minimum-bias events**

*why this name?* Trigger on... almost nothing = minimum bias

*why interesting?*

**Underlying event** = everything but what I'm interested in
  e.g. everything except the hard subprocess

min.-bias events = part of underlying event, Lumi dependent pile-up

**all interesting events come along with underlying min-bias events!**
Pile up of min-bias events

2835x2835 proton bunches
separation 7.5 m (25 ns)
$10^{11}$ protons/bunch

bunch crossing rate: 40 MHz
Lumi (design): $10^{34}$ cm$^{-2}$ s$^{-1}$

$\sim 10^9$ pp collisions / s and
$10^9 / 40 \cdot 10^6$

$\sim 25$ pp interactions/bc = pile up!

Simulated event in CMS

$h \rightarrow \mu\mu\mu\mu$
Pile up of min-bias events

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Simulated event in CMS
$h \rightarrow \mu\mu\mu\mu$
with min-bias pile up events
Cross sections and rates

Rates for design $L=10^{34}$ cm$^{-2}$ s$^{-1}$

inelastic pp interactions : $10^9$ Hz
(total total cross section)

- $b\bar{b}$ pairs $5 \cdot 10^6$ Hz
- $t\bar{t}$ pairs 8 Hz
- $W \to e\nu$ 150 Hz
- $Z \to ee$ 15 Hz
- Higgs (150 GeV) 0.2 Hz
- gluinos, squarks (1 TeV) 0.03 Hz

most cross sections 7-9 or more orders smaller than total cross section!
Typical signatures

The signatures we look for are characterised by...

- Leptons and photons at high $p_T$
  - initial state $pp$: no leptons, no $p_T$
  - high $p_T$ leptons in final state:
    - decay of heavy particles
    - signature of interesting physics

- $b$ quarks, tau leptons from decays
  - long lived particles, decay vertex reconstruction

- missing Energy $\rightarrow E_{\text{miss}}$
  - Higgs, $W$ decays involve neutrinos
  - many SUSY and other BSM scenarios

  - missing Energy
  - measure missing transverse $E$

  why not $E_{\text{L}}$ miss?
• **Hadron colliders** play an important role in particle physics discovery but also precision measurements

• **LHC will open up TeV energy range**
  new particles with 3-5 TeV mass could be produced and hopefully detected

• **typical signatures** include high pT objects, leptons and photons and often missing (transverse) energy

• **challenges at LHC**
  huge interaction rates and large QCD background pile up

**requires detectors and electronics**
  fast, high granularity, radiation hard
  ... let's have a look at them!