Concepts for Experiments at Future Colliders

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Organization

- Lecture over two semesters.
- Time in the winter semester: Mondays from 10:00 to 11:30.
  Room: PH II 127
  Language: English.
- Media: Copies of my slides or my notes on the blackboard will be provided at the beginning of each lecture. An electronic copy will be available on https://indico.mpp.mpg.de/event/10551/.
- Oral examination: Individual dates to be agreed at the end of the semester.

Literature

Text books about particle detectors

K. Kleinknecht, *Detektoren f”ur Teilchenstrahlung*, Teubner 1992.

W. R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, Springer 1993.

H. Kolanoski, N. Wermes, *Teilchendetektoren, Grundlagen und Anwendungen*, ISBN 978-3-662-45349-0.

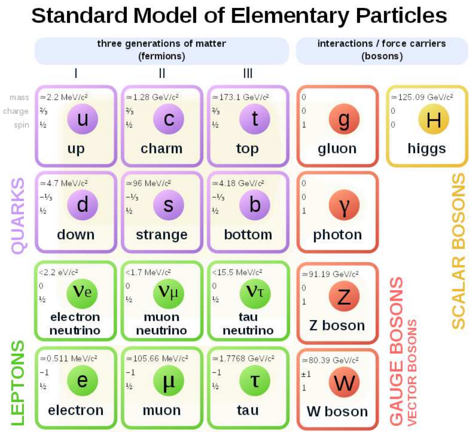
Statistical methods

F. James, *Statistical Methods in Experimental Physics (2Nd Edition)*, ISBN-13: 978-9812705273. FCC webpage: https://fcc.web.cern.ch/

Introduction

Standard modell of particle physics

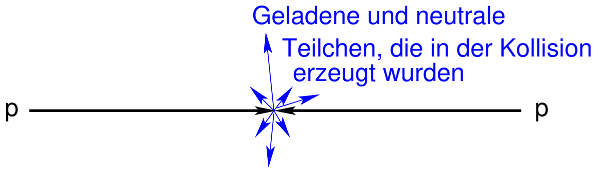
- Below a scale of 10^{-10} m, matter is not continuously distributed, but discrete and consists of particles.
- Particle content of the Standard Model of the strong and electroweak interactions:



The Standard Model has been confirmed with impressive precision at colliders.

A selection of experimental tests of the Standard Model will be presented on the next slides.

Topology of a e^+e^-/pp collision event



Final state particles which can be created in a collision

Leptons

- Neutrinos: stable, only weakly charged. $\Rightarrow$ No interaction leading to a measurable electronic signal in the detector.
- Electrons: stable, electrically charged. $\Rightarrow$ Elektronic signals in the detector components.
- Muons: unstable, but, because they are ultrarelativistic, so longlived in the laboratory system that they do not decay inside the detector; electrically charged. $\Rightarrow$ Elektronic signals in the detector components.
- τ leptons: unstable. $\Rightarrow$ Detectable only via their decay products.

Topology of a e^+e^-/pp collision event

Further final state particles which can be created in a collision

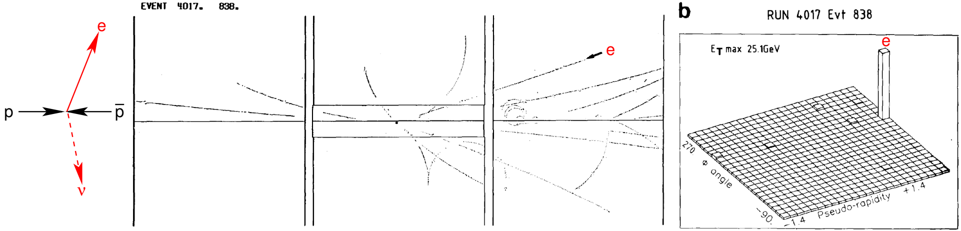
Hadrons

- Intially, quarks and gluons are created in the primary collisions. These are invisible due to the quark confinement, but the create so-called "hadron jets" which are detectable.
- Special role of two types of quarks:
  b quarks build longlived b hadrons which makes it possible to identify jets as b quark jets via the detection of the decay vertex of a b hadron.
  t quarks are so shortlived that they cannot build hadrons. They can be detected via their decay $t \to Wb$.

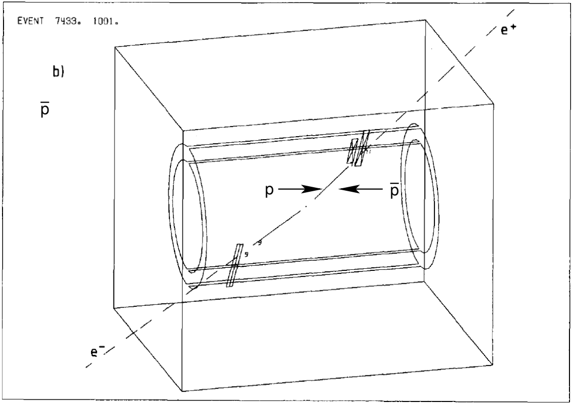
Photons

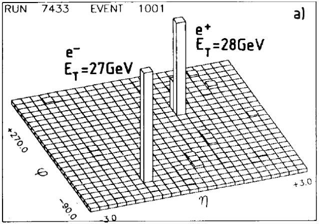
Photons are stable. They are electrically neutral, but can create electromagnetic showers in matter. These showers can be detected.

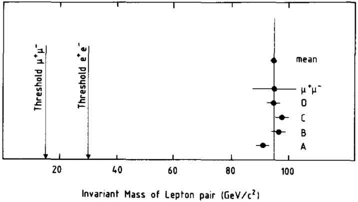
- Upgrade of the Super Proton Synchrotron (SPS) at CERN to the Super Proton Antiproton Synchroton ($Sp\bar{p}S$) operating as a $p\bar{p}$ collider with 540 GeV centre-of-mass energy.
- Discovery of the W boson by the UA1 experiment in 1983 (https://doi.org/10.1016/0370-2693(83)91177-2).
  Event candidate:



- Discovery of a Z boson half a year later (https://doi.org/10.1016/0370-2693(83)90188-0).
  Event candidate:

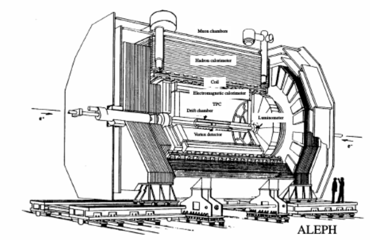


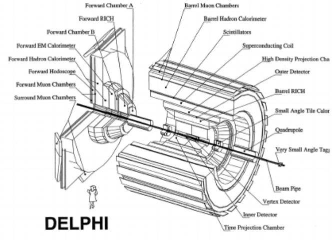


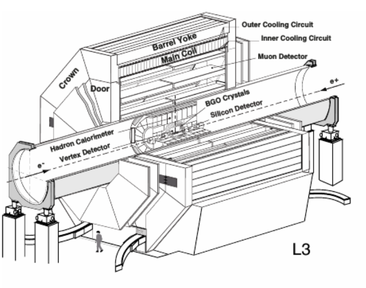


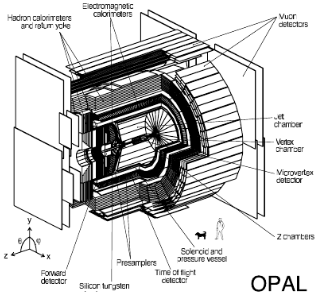
Precision measurements at the Z and W poles at LEP

- Large Electron-Positron Collider (LEP) for the precise measurements of the properties of the W and Z bosons from 1989 to 2000.
- 4 experiments af LEP:







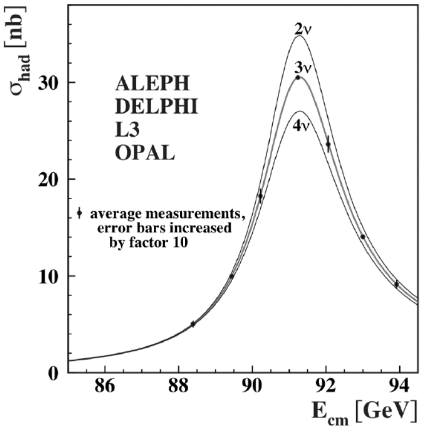


Measurement of the number of neutrino families at LEP

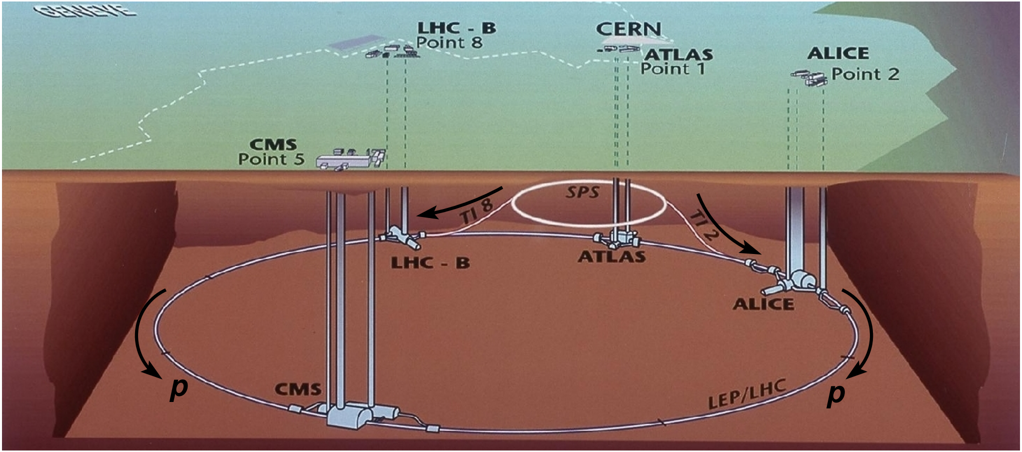
- Hadronic cross section at the Z pole:

$$\sigma(e^+e^- \to jj) = \sigma^0_{had} = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}.$$

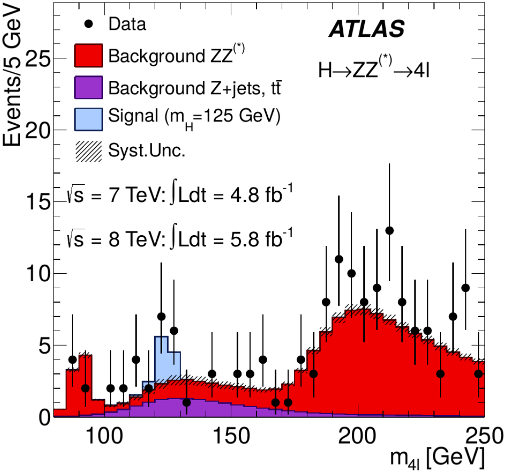
- PrecisionPhys. Rept. 427, 257-454 (2006):



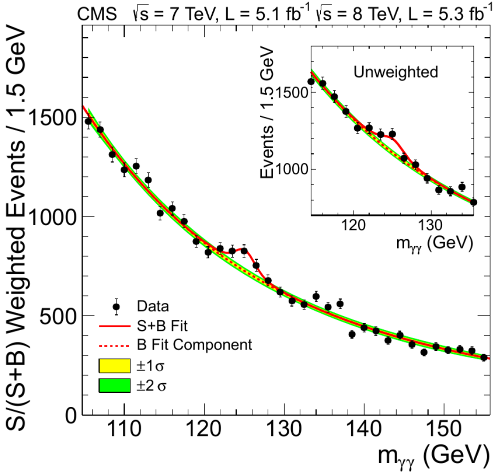
Current experiments at the Large Hadron Collider (LHC)



Discovery by the ATLAS and CMS experiments



10.1016/j.physletb.2012.08.021



Limitations of the Standard Model

Experimental evidence for the imcompleteness of the Standard Model

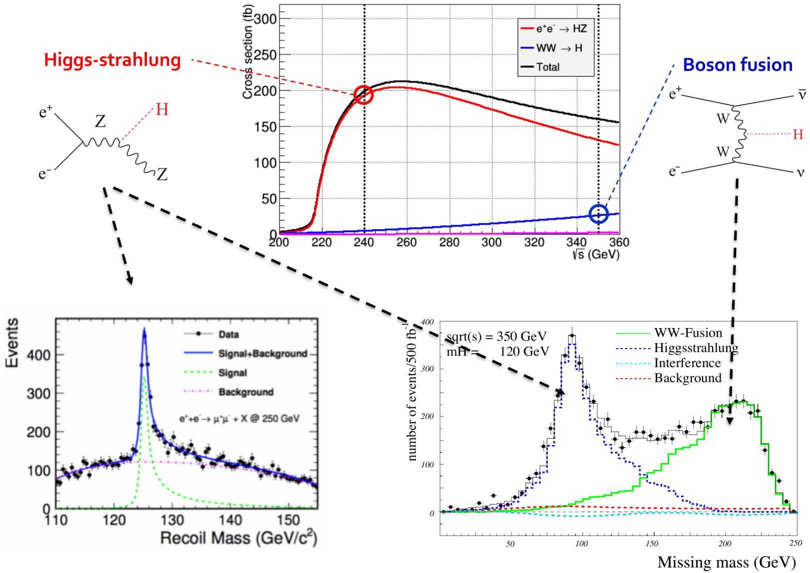
- Existance of non-vanishing neutrino masses because of the observation of neutrino oscillations.
- Existance of non-baryonic dark matter in our universe.
- Baryon number and CP violation required for the baryogenesis in the early universe.

In order to find the correct extension of the Standard Model, additional (concrete) experimental evidence are needed. An important source are experiments at existing (LHC) and future colliders:

- HL-LHC: Upgrade of the LHC to the High-Luminosity LHC (2026-2028).
- Midterm and longterm projects:
  - FCC-ee (Future Circular Collider): e^+e^- collider in a new tunnel of 80 km circumference for the electroweak precision measurement, the precision Higgs boson physics measurements, and searches for beyond Standard Model physics processes.
  - FCC-hh (Future Circular Collider): pp collider with 100 TeV centre-of-mass energy in the FCC-ee tunnel with strong dipole magnets.

A first glance at the FCC-ee project

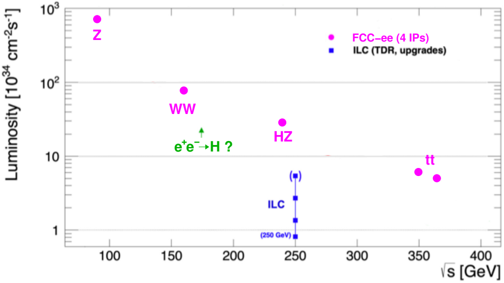
Higgs boson production at an e^+e^- Higgs factory



FCC-ee as Higgs factory plus EW and top factory

Higgs factory programme

- $2 \cdot 10^6$ HZ events (similar to the HL-LHC, but higher purity and selectrion efficiency) and 125,000 W^+W^- events.
- Precise measurements of Higgs couplings to fermions and bosons.
- Sensitivity to Higgs self-coupling at 2-4 σ level via loop diagrams.
- Unique opportunity to measure the electron coupling in $e^+e^- \to H$ at $\sqrt{s} = 125$ GeV.



By changing the centre-of-mass energy of the collider the FCC-ee can also be operated as an electroweak and top quark factory.

- $\sim 100,000$ Z/s (1 Z/s at LEP).
- $\sim 10,000$ Ws/h (20,000 Ws in 5 years at LEP).
- $\sim 1,500$ top quarks/d.

Outline of the lecture

Winter semester

1. Interaction of particles with matter.
2. Particle identification.
3. Concepts for exeperiments at future colliders.
4. Detectors for experiments at future colliders.

Summer semester

1. Basic principles of read-out electronics for particle detectors.
2. Methods of statistical data analysis.
3. Reconstruction of collision events.
4. Trigger concepts for future collider experiments.