#### The Relativistic Quantum World

#### A lecture series on Relativity Theory and Quantum Mechanics

and the second se

Marcel Merk

HCb

**CERN** Prévessin



CMS



ATL.

LIC

#### University of Maastricht, Sept 16 – Oct 14, 2020

#### The Relativistic Quantum World

Relativity	<u>Sept 16:</u> Lecture 1: The Principle of Relativity and the Speed of Light Lecture 2: Time Dilation and Lorentz Contraction
	<u>Sept 23:</u> Lecture 3: The Lorentz Transformation and Paradoxes Lecture 4: General Relativity and Gravitational Waves
Quantum Mechanics	<u>Sept 30:</u> Lecture 5: The Early Quantum Theory Lecture 6: Feynman's Double Slit Experiment
	<u>Oct 7:</u> Lecture 7: The Delayed Choice and Schrodinger's Cat Lecture 8: Quantum Reality and the EPR Paradox
Standard Model	<u>Oct 14:</u> Lecture 9: The Standard Model and Antimatter Lecture 10: The Large Hadron Collider

Lecture notes, written for this course, are available: <u>www.nikhef.nl/~i93/Teaching/</u> Prerequisite for the course: High school level mathematics.

#### Lecture 10

#### The Large Hadron Collider

# Hunting the Higgs at the LHC

Pieke Dassen: art



# Hunting the Higgs at the LHC

### **CERN:** *the LHC Large Hadron Colldir*

ISSE

FRANC

CMS

LHCb-

LHC 27 km

100

**CERN** Prévessin

ATLAS

SPS\_7 km

CERN Mevrin

ALIC

## The LHC

Beam energy equal to that of a TGV at full speed.





## CERN: the LHC



#### CERN: *The LHC*

#### Tunnel of 27 km, 100 meter deep underground



## **The Atlas Experiment**

## **The Atlas Experiment**



#### **The Atlas Experiment**

Largest photo camera in the world

- 45m x 25 m
- 2500 physicists

80 MegaPixel camera: 40.000.000 pic's per second

## The Atlas Experiment under construction

## The Atlas Experiment under constructio

### The Atlas muon detector



## Atlas: side-view







# **Discovery of Higgs boson**



# **Discovery of Higgs boson**



## November 20, 2009



#### **Collisions of Particles**



#### All possibilities of Nature will be produced



#### All possibilities of Nature will be produced





#### **Collecting data and testing the theory**











 $Higgs \rightarrow \gamma \gamma ?$ 



CMS Experiment at the LHC, CERN Data recorded: 2012-May-13 20:08:14.621490 GMT Run/Event: 194108 / 564224000

HIGGS->

Atlas:









#### Announcement Higgs discovery









#### **Nobel prize in Physics 2013**



Francois Englert

Peter Higgs

#### The Standard Model

"The formula"

"Elementary quanta of Nature"

2



The 'Higgs' field  $\phi$ 



#### Higgs Field / and Particle //

- Higgs field is uniform, hard to see
- Higgs boson particle is "wave" of the field
- Mass results from interaction of matter particles with the Higgs field

#### • Compare:

- A photon is a quantum of electromagnetic field
- Water wave





## July 4, 2012: The Vacuum






Muon,  $\mu$ Spin  $\frac{1}{2}$ Charge -1 Lifetime 2.2  $\mu$ s Mass 106 MeV

μ

1937

Tau, τ Spin ½ Charge –1 Lifetime 290 fs Mass 1777 MeV

1975



#### Hence...



# Antimatter research at the LHC

b

 $V_{\tau}$ 

S

d

Ve

Why do particles come in three generations?

Antiquarks



# Antimatter research at the LHC

Why do particles come in three generations?

# How did antimatter disappear in the Big Bang?



# What's the story with the asymmetrie between matter and antimatter?







# **Back to the LHC**



#### LHC: from Atlas to the LHCb experiment



23 sep 2010 Run 79646

Quarks

U C

ds

b

19:49:24 Event 143858637

Compare millions of particle and antiparticle decays... ...and look at differences between matter and antimatter!

# B-meson particles: Asymmetry between matter and antimatter

B ( $\overline{b}d$ ) particle decays to K<sup>+</sup>( $\overline{s}u$ ) and  $\pi^-(\overline{u}d)$  particle anti-B (bd̄) particle decays to  $K^{-}(s\overline{u})$  and  $\pi^{+}(ud\overline{d})$  particle



- But left and right not the same decay rate!
- Only happens in rare decays in which quarks of all 3 generations are involved.
- Exactly as predicted in the Standard Model!

# B-meson particles: Asymmetry between matter and antimatter



• The laws of nature for matter en anti-matter turn out to be clearly not 100% mirror-symmetric !

# Are we ready now?



# How did antimatter disappear in the Big Bang?



# Standard Model explanation not enough!



BIG BANG SCAL



**Present Day Acceleration** 

Big Bang

Inflation

**Recent developments: New forces or particles?** 

Expansion

#### **Precision** test of the Standard Model Quarks **B-mesons:** particles with a b-quark С up top Forces S photon Z bosot Higgs boson e electron electron neutrino muon neutrino ons

# **Enter Penguins**

#### John Ellis loses a game of darts...









#### Penguins in the Big Bang theory...

 $BR(t-wb) = \frac{\Gamma(t-wb)}{\Gamma(t-wb)}$ t-Wb \_ 1 Ves /2 | Ves |2 + | Ves |2 + | Ves |2 ~ (0. 9945)2 (0.0074)\* (0.044)\* (0.7745)\* = 97.827. but F.C.N.C ... 4.5.6 taze t- Kc t-You t + Zn Galas .... ULAM = - Sn G23 - C12 = 53 5,30 ...

55

# **Penguins & Lepton Universality?**

Are the three generations of particles truly identical?



*The quantum penguin test* 





## Lepton Universality?

#### Measure the processes:



## A new fundamental force in nature?



Three experiments observe a small hint:
→ A new line in the fundamental theory?!
→ More investigations are in progress!

# How did antimatter disappear in the Big Bang?



# New step in understanding of the Big Bang?





"After the discovery of 'antimatter' and 'dark matter', we have just confirmed the existence of 'doesn't matter', which does not have any influence on the Universe whatsoever."

#### Astronomy

?

?

#### Particle-Physics

<u>Current status:</u> With LHC in search of a fundamental theory for particles in the Big Bang.

Higgs particle en field Matter – antimatter asymmetry Is there another force of nature? Are 3 copies of particles a natural necessity?

# Towards the future: "Circles and Triangles" Particle-colliders: physics of the Big Bang...



(1)



## Gravitation-detectors: listening to the Big Bang...





# The Relativistic Quantum World

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#### In conclusion:

CMS

- Relativity and quantum mechanics give us a counterintuitive view of nature.
- The relativistic quantum world is the environment of fundamental particles under high energy conditions.
  It is all about fundamental physics of the Big Bang.





LIC

#### Thank you for joining these lectures!

### X-tra slides

# **Unsolved Puzzles**

Trying to understand Big Bang Are there more particles or forces?

# **Big Bang**

**Present Day Acceleration** 

**Big Bang** 

Inflation

Expansion

time

# **Higgs field appeared during Big Bang**



# 1) How did antimatter disappear in the Big Bang?

# Standard Model cannot explain it



# 2) Higgs mystery: Vacuum stability

#### **Higgs Potential**



#### Zoom out very far:



#### Can vacuum "tunnel away"?



#### Our universe in Standard Model:



## 2) Higgs mystery: Vacuum stability



# Is the vacuum actually stable?<sup>d Model:</sup>





# 3) Why is the Higgs particle so light?

Higgs gives quantum mechanically mass to:

- Matter Particles, W and Z force particles
- Also to itself  $\rightarrow$  Higgs should be *very massive*!



The existence of supersymmetric particles would explain the relatively low mass of the Higgs boson.


#### **Personal Research Focus**



Why are there three generations of particles and where is the antimatter? Does the Higgs particle/field perhaps play an even more fundamental role?

# Applications



#### Elementary particle physics: why?

#### Questions that occupied humanity for 2000 years:

- > What are the building blocks of matter ?
- > Which forces interact between these particles ?



Demokritos atom



Newton forces



Maxwell

electromagnetism



Einstein various...



- Might lead to surprises,
  - Sometimes even useful...
  - But by definition unpredictable



"Continuous applied research to candles would have never resulted in the invention of electric light."





- Might lead to surprises,
  - Sometimes even useful...
  - But by definition unpredictable



"Quantum mechanics and research on atoms of crucial importance for transistors."





- Might lead to surprises,
  - Sometimes even useful...
  - But by definition unpredictable



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SH = TATAS - 29 TASTA =- T, T, S, +2 T, S(y "T, A)

#### $\mathfrak{K}_{p}^{-*}\mathcal{T}_{r,n}^{A}) = \frac{1}{2} S \Big[ \mathfrak{J}_{n}^{n} \mathfrak{J}_{n}^{A} \Big( \frac{2\mathfrak{g}_{nd}}{2\mathfrak{x}_{n}} + \frac{2\mathfrak{g}_{nd}}{2\mathfrak{x}_{n}} - \frac{2\mathfrak{g}_{n}}{2\mathfrak{x}_{n}} \Big) \Big]$ un die annden Klammen lavorgehenden

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"Without relativitytheory GPS is wrong by ~ 10 km/day!"



- Fundamental research
  - Leads to useful spin-off
    - Medical applications
    - Internet
    - Training of researchers in our society (Philips, ASML, etc, etc)

WW







- People are curious
- Part of humanity
  - What is the use of art? religion?



#### • Expensive ?

- Total cost LHC: 6 billion
- Cost for NL: 50 million / year

#### To compare, see budget Ministery of OCW:



Cern	31 miljoen	
ESA	32 miljoen	
Genomics	36 miljoen	
Kon. Bibliotheek	45 miljoen	
TNO	192 miljoen	
Stichting AAP	10 miljoen	
Monumentenzorg	70 miljoen	
Film	20 miljoen	
Archeologie	10 miljoen	(Top-sports: 28 million)

#### **CERN:** *the member states*



#### Member States (Dates of Accession)



## The "God Particle"?

Leon Lederman's book:

"The God Particle: If the universe Is the Answer, What Is the Question?" (The publisher did not like the titel "The *goddamn* particle:...")

![](_page_83_Picture_3.jpeg)