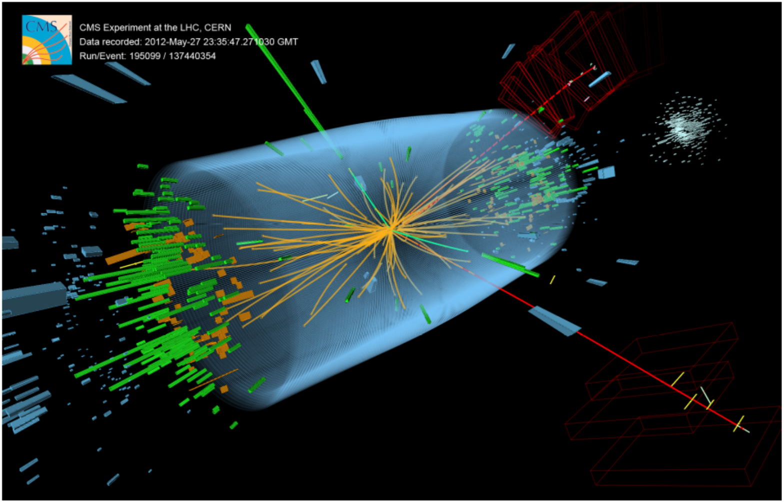
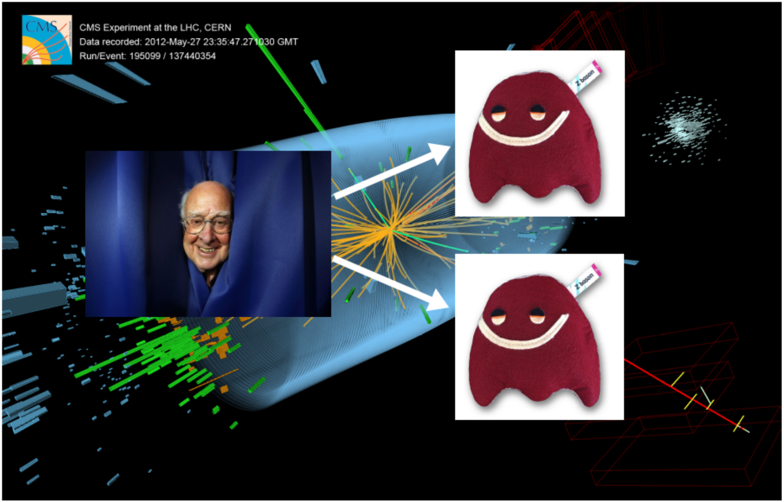
Teilchenphysik 2 — W/Z/Higgs an Collidern

Sommersemester 2019

Matthias Schröder und Roger Wolf | Vorlesung 1

INSTITUT FÜR EXPERIMENTELLE TEILCHENPHYSIK (ETP)


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
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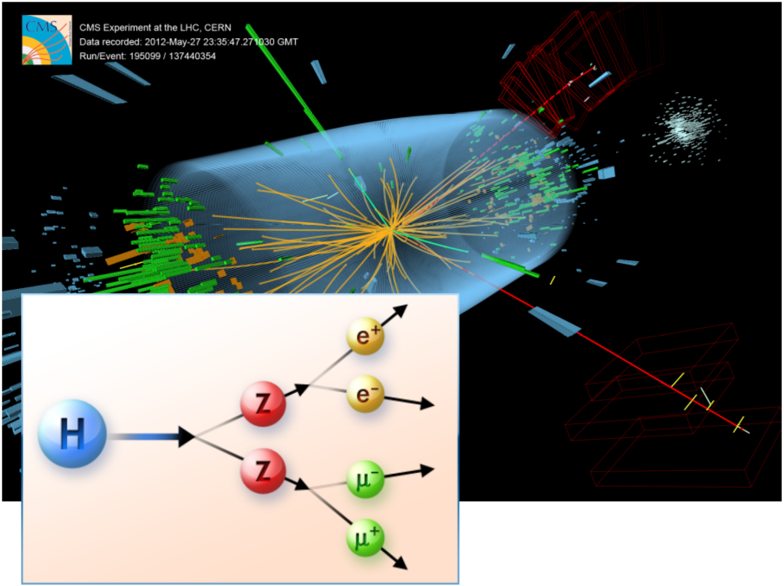
Z boson
Z boson


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354
H
Z
Z
e+
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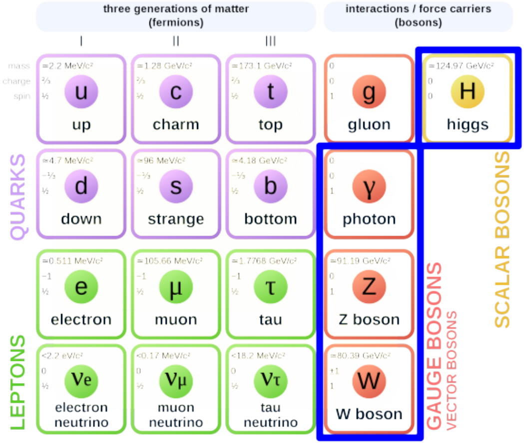
Electroweak Sector of the Standard Model



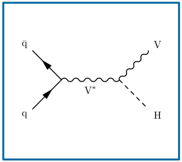
+ new physics beyond the Standard Model?

Programme of this Lecture

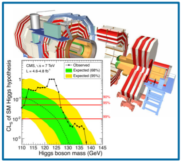
Basics of electroweak theory

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

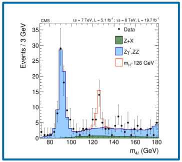
From theory to observables



Experimental techniques



Results and open questions



Organisatorisches

Teilchenphysik 2: W/Z/Higgs an Collidern

- Dozenten
  - Dr. Matthias Schröder (ETP)
    - E-Mail: matthias.schroeder@kit.edu
    - Campus Nord, Bau 401, Raum 406, Tel.: 0721-608-23819
    - Sprechstunde: immer nach Vereinbarung
  - Priv. Doz. Dr. Roger Wolf (ETP)
    - E-Mail: roger.wolf@kit.edu
    - Campus Süd, Bau 30.23, Raum 9-20, Tel.: 0721-608-43591
    - Sprechstunde: Mittwochs 15:30–17:00 oder nach Vereinbarung
- Tutor
  - Sebastian Wieland (ETP)
    - E-Mail: sebastian.wieland@kit.edu
    - Campus Nord, Bau 401, Raum 418, Tel.: 0721-608-24173

Materialien

- Materialien auf ILIAS: `https://ilias.studium.kit.edu/goto.php?target=crs_956216&client_id=produktiv`
- Vorlesungsfolien, Übungsblätter, Ankündigungen, …

Magazin » Organisationseinheiten » Fakultät für Physik » SS 2019 » Teilchenphysik II - W, Z, Higgs an Collidern

Teilchenphysik II - W, Z, Higgs an Collidern

Inhalt Info Einstellungen Mitglieder Lernfortschritt Metadaten Export Rechte Voransicht als Mitglied aktivieren

Zeigen Verwalten Sortierung Seite gestalten

Neues Objekt hinzufügen

Teilchenphysik II - W/Z/Higgs an Collidern

Herzlich willkommen auf der ILIAS-Seite zur Lehrveranstaltung *Teilchenphysik II - W/Z/Higgs an Collidern* des Masterstudiengangs Physik am KIT im Sommersemester 2019.

Die Vorlesung behandelt die theoretischen und experimentellen Grundlagen der Physik der W-, Z- und Higgs-Bosonen sowie die wichtigsten dazugehörigen Messungen an Collidern. Sie baut dabei auf die in der einführenden Veranstaltung *Teilchenphysik I* vermittelten Kenntnisse auf und vertieft diese in einem aktuellen Spezialgebiet der experimentellen Teilchenphysik. Es werden folgende Themen behandelt: Elektroschwacher Sektor und Higgs-Mechanismus im Standardmodell der Teilchenphysik, Berechnung von W/Z/Higgs-Produktionsprozessen, experimentelle Techniken und Methoden der statistischen Datenanalyse, historische Entwicklung und wichtige Experimente, aktuelle Messungen am Large Hadron Collider, Higgs-Sektoren in hypothetischen Modellen neuer Physik, gegenwärtiger Kenntnisstand und Ausblick auf zukünftige Experimente.

In den praktischen Übungen werden die theoretischen Grundlagen vertieft sowie moderne Techniken der statistischen Datenanalyse erlernt und auf einfache Problemstellungen aus der W/Z/Higgs-Physik angewendet. Physikalische Problemstellungen werden in Teamarbeit gelöst und Präsentationstechniken geübt. Ferner werden themenbezogene Originalveröffentlichungen der Teilchenphysik analysiert.

Vorlesungen (Lehrveranstaltungsnummer 4022161) und Praktische Übungen (Lehrveranstaltungsnummer 4022162)

Dozenten: Dr. Matthias Schröder (matthias.schroeder@kit.edu), PD Dr. Roger Wolf (roger.wolf@kit.edu)
Tutor: Sebastian Wieland (sebastian.wieland@kit.edu)

Vorlesungen und Übungen werden flexibel, abhängig vom Kursinhalt durchgeführt. Die genaue Aufteilung wird in der ersten Vorlesung bekannt gegeben. Termine:

- mittwochs, 14:00-15:30 in Geb. 30.22, Physik-Hörsaal Nr. 4 (Kl. HS B)
- Termin nach Absprache in erster VL

Erste Vorlesung: Mittwoch, 24. April, 14:00-15:30 (Kl. HS B, Geb. 30.22)

INHALT

Vorlesungsmaterial
Hier finden Sie Material zur Vorlesung

Übungen
Hier finden Sie Material zur den Übungen

Einordnung, Umfang, Vorraussetzungen

- Einordnung im Studiengang
  - Veranstaltung im Masterstudiengang Physik
  - Vertiefung in Spezialgebiet der **experimentellen Teilchenphysik**
  - **Wahlfach im Masterstudiengang Physik**, als Teilmodul eines Schwerpunkts- bzw. Ergänzungsfachs
- Umfang
  - 6 ECTS-Punkte: Vorlesung (2 SWS) + Übung (1 SWS)
  - 8 ECTS-Punkte: Vorlesung (2 SWS) + Übung (1 SWS) + Vertiefung (1 SWS)
  - Leistungsnachweis: erfolgreiche Teilnahme an Übungen und ggf. an Vertiefungen
- Voraussetzungen
  - Keine formalen Vorraussetzungen
  - Empfehlenswert: Moderne Experimentalphysik III (Bachelor), Moderne Theoretische Physik II und Rechnernutzung in der Physik (Bachelor), **Teilchenphysik I** (Master)

Format

Karlsruher Institut für Technologie

- Vorlesung (4022161) und Übungen (4022162) integriert
  - Optimierte Abstimmung zwischen Stoff der Vorlesungen und Übungen
  - Vertiefungen einzelner Themen in zusätzlichen Vorlesungen oder Übungen
- Übungen
  - Übungsblätter: Bearbeitung vorher, Besprechung während der Übungen
  - Zusätzliche Beispielaufgaben während der Übungen
  - Computergestützte Aufgaben: Bearbeitung während der Übungen
  - Paper-Seminare: Durcharbeiten und Beantworten von Fragen vorher, Besprechung während der Übungen
- Englische Vorlesungsfolien und Übungsblätter, Vortrag auf Deutsch

Termine & Orte

- Vorlesung (4022161) und Übungen (4022162) integriert
  - Mittwochs 14:00–15:30 (Kl. HS B, Geb. 30.22)
  - Dienstags 11:30–13:00 (Raum 11/12, Geb. 30.23)

Vorläufiges Programm

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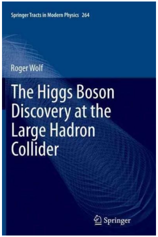
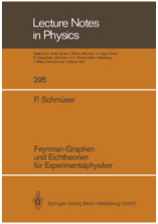
Date	Room	Type	Topic
Wed Apr 24.	Kl. HS B	LE 01	1. Organisation and introduction: particle physics at colliders + W/Z/H history
Tue Apr 30.	30.23 11/12	—	*no class*
Wed May 01.	Kl. HS B	—	*no class*
Tue May 07.	30.23 11/12	LE 02	2.1 Gauge theory & the electroweak sector of the SM I
Wed May 08.	Kl. HS B	LE 03, EX 01	2.3 Discovery of the W and Z bosons & EX gauge theories
Tue May 14.	30.23 11/12	LE 04	2.4 The Higgs mechanism
Wed May 15.	Kl. HS B	EX 02	Exercise “SM Higgs mechanism”
Tue May 21.	30.23 11/12	—	*no class*
Wed May 22.	Kl. HS B	LE 04	2.5 The electroweak sector of the SM II (Higgs mechanism + Yukawa couplings)
Tue May 28.	30.23 11/12	SP 01	Specialisation of 2.4 and 2.5
Wed May 29.	Kl. HS B	LE 05	3.1 From theory to observables & 3.2 Reconstruction + analysis of exp. data
Tue Jun 04.	30.23 11/12	EX 03	Exercise “Trigger efficiency measurement”
Wed Jun 05.	Kl. HS B	LE 06	3.3 Measurements in particle physics
Tue Jun 11.	30.23 11/12	EX 04	Exercise on statistical methods
Wed Jun 12.	Kl. HS B	LE 07	3.3 Measurements in particle physics
Tue Jun 18.	30.23 11/12	SP 02	Specialisation “Limit setting”
Wed Jun 19.	Kl. HS B	SP 03	Specialisation “Unfolding”
Tue Jun 25.	30.23 11/12	LE 08	4.1 Determination of SM parameters
Wed Jun 26.	Kl. HS B	LE 09	4.2 Measurement and role of W/Z bosons at the LHC
Tue Jul 02.	30.23 11/12	EX 05	Paper seminar “Z pole measurements”
Wed Jul 03.	Kl. HS B	LE 10	4.3 Processes with several W/Z bosons
Tue Jul 09.	30.23 11/12	EX 06	Paper seminar Higgs
Wed Jul 10.	Kl. HS B	LE 11	5.1 Discovery and first measurements of the Higgs boson
Tue Jul 16.	30.23 11/12	EX 07	Exercise “Machine learning in physics analysis”
Wed Jul 17.	Kl. HS B	LE 12	5.2 Measurement of couplings and kinematic properties
Tue Jul 23.	30.23 11/12	EX 08	Presentations: results of ML challenge
Wed Jul 24.	Kl. HS B	LE 13	5.3 Search for Higgs physics beyond the SM & 5.4 Future Higgs physics

Quellen & Literatur

Karlsruher Institut für Technologie

- R. Wolf: *The Higgs Boson Discovery at the Large Hadron Collider*, Springer 2015
- P. Schmüser: *Feynman-Graphen und Eichtheorien für Experimentalphysiker*, Springer 1988
- J. Ellis: *Higgs Physics*, 2013, arXiv:1312.5672 [hep-ph]
- A. Djouadi: *The anatomy of electroweak symmetry breaking I*, Phys. Rep. 457 (2008) 1, arXiv:0503172 [hep-ph]
- sowie die im Laufe der Vorlesungen angegebenen, dedizierten Quellen





1. Introduction: Particle Physics at Colliders

1.1 Reminder: experimental basics

W/Z/H: Which Collider?

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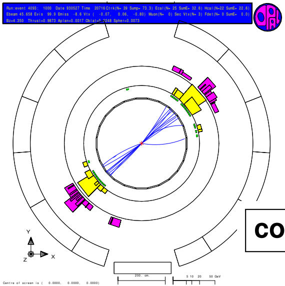
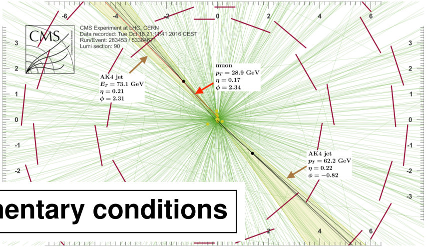
- **Hadron collider (pp or p$\bar{\text{p}}$)**
  - Unknown initial state (partons), dense event environment
  - High energies for production of new particles but $\mathcal{O}(10^{-10})$ fraction of signal events over difficult backgrounds $\rightarrow$ discovery machine
- **Lepton collider (e^+e^-)**
  - Known initial state (leptons), clean reconstruction $\rightarrow$ precision meas.
  - Small total cross section, but process of interest with large fraction
  - Limited centre-of-mass energy

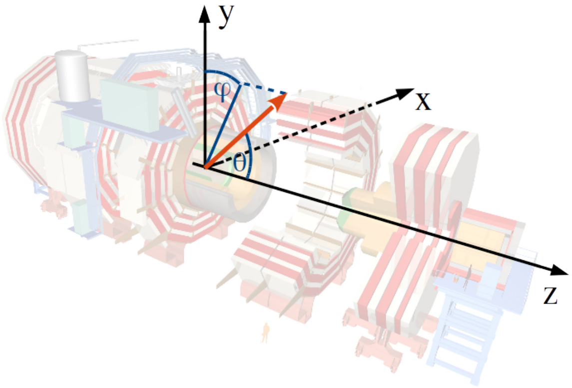




complementary conditions

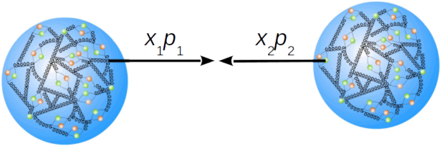
Kinematics at Collider Detectors

- Conventions for kinematic variables at collider detectors
  (motivated by cylindrical symmetry of detectors)
  - **Right-handed cylindrical coordinates** system
  - Azimuthal angle ϕ: angle to *x* axis in *xy* plane
  - Polar angle θ: angle to *z* axis (beam axis)



Reminder: Transverse Quantities

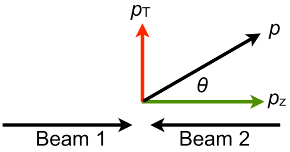
- Kinematics at **hadron colliders** (*pp*, $p\bar{p}$)
  - Collision of **partons with unknown fraction** x_i of total longitudinal momentum of proton (good approximation: all partons **massless** and **collinear** to beam)



$$\hat{E}^2_{\text{cms}} = x_1 x_2 E^2_{\text{cms}}$$

  - **Rest frame** of parton-parton collision **unknown** $\rightarrow$ parton centre-of-mass energy $\hat{E}_{\text{CM}}$ unknown
- **Transverse quantities** are **Lorentz invariant** under boosts **along beam direction**, e. g.

$$p_{\text{T}} = \sqrt{p_x^2 + p_y^2} = p \cdot \sin\theta$$



Reminder: Pseudorapidity η

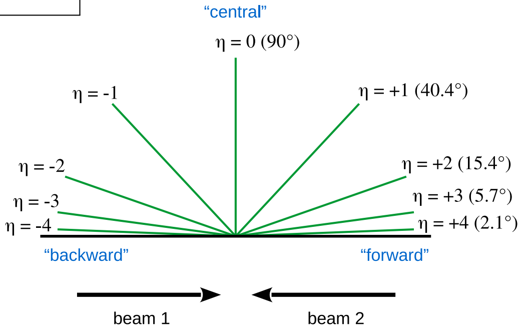
- Rapidity y is relativistic measure of velocity in z direction

$$y = \frac{1}{2} \ln \left(\frac{E+p_z}{E-p_z} \right) = \tanh^{-1} \left(\frac{p_z}{E} \right)$$

- Pseudorapidity

$$\eta = -\ln \tan \left(\frac{\theta}{2} \right)$$

  - Good **approximation of rapidity y** for momentum $\gg$ mass
  - **Easier to measure** than y: depends only on θ, not on mass

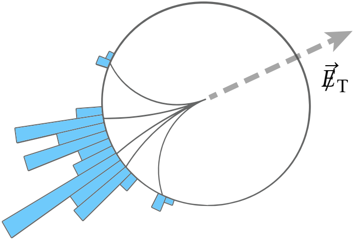


Rapidity **differences** are Lorentz invariant under boosts in z direction

Reminder: Missing Transverse Momentum

- Missing transverse momentum, often “missing transverse energy” (“missing E_T”, $\not{E}_T$, MET)
- **Indirect** detection of weakly interacting neutral particles, e. g. neutrinos
- Concept: colliding **partons without significant transverse momentum** $\rightarrow$ sum of transverse momenta of final-state particles is 0
  - **Measurement of imbalance** in transverse energy or momentum sum, e. g. based on energy deposits in calorimeter cells

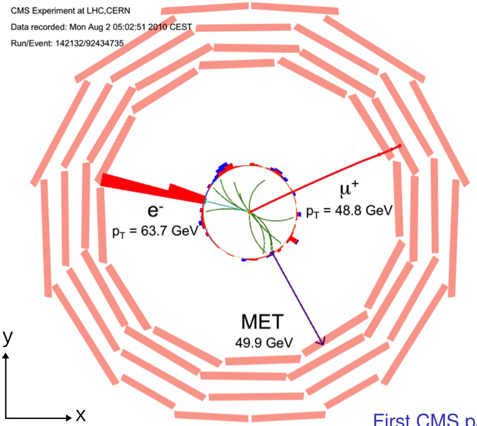
$$\vec{\not{E}}_T = -\sum_{\text{calo cells}} E_i \sin\theta_i \begin{pmatrix} \cos\phi_i \\ \sin\phi_i \\ 0 \end{pmatrix}$$



- Experimental **challenge**: many sources of ‘fake’ $\not{E}_T$, e. g. muons, non-instrumented regions, or noisy detectors

Real-Life Example

- Display of an H $\rightarrow$ WW candidate event at CMS
  - Decay channel: H $\rightarrow$ WW $\rightarrow$ eν $\mu\nu$
  - Signature in detector: electron, muon, and **MET due to 2 neutrinos**
  - Complication: **relative orientation** of neutrinos unknown



Phys. Lett. B 699 (2011) 25 (CMS-EWK-10-009)

First CMS paper mentioning Higgs!

1.2 Reminder: theory basics

Natural Units

- Common choice in particle physics:
  natural units with $\hbar = c = 1$
- Consequences
  - $c = 1 \rightarrow [L] = [T]$ (length and time have same unit)
  - $\hbar = 1 \rightarrow [E][T] = 1$, from Heisenberg's uncertainty principle

$\rightarrow$ Length and time have units of 1/energy: $[L] = [E]^{-1}$, $[T] = [E]^{-1}$

  - $E^2 = (pc)^2 + (mc^2)^2$, $c = 1$

$\rightarrow$ Momentum and mass have unit of energy: $[p] = [E]$, $[m] = [E]$

Important 4-Vectors and Notations

- Vectors

  3-vector: $x^a = \vec{x}$ $\quad (a = 1, 2, 3)$

  4-vector: $x^\mu = (t, \vec{x})$ $\quad (\mu = 0, 1, 2, 3)$

- Contravariant x^μ and covariant x_μ representations related by metric tensor $g_{\mu\nu}$ (Distinction not required but common in gauge theories)

$$x^\mu = (t, \vec{x})\,, \quad x_\mu = (t, -\vec{x})\,, \qquad x_\mu = g_{\mu\nu} x^\nu \equiv \sum_{\nu=0}^{3} g_{\mu\nu} x^\nu$$

- Important 4-vectors

energy-momentum:	$p^\mu = (E, \vec{p})$
time-space:	$x^\mu = (t, \vec{x})$
4-gradient:	$\partial^\mu = \frac{\partial}{\partial_\mu} = \left(\frac{\partial}{\partial_t}, -\vec{\nabla}\right)$
electromagnetic 4-potential:	$A^\mu = (\phi, \vec{A})$
field-strength tensor:	$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$

Relativistic Quantum Mechanics

- Formulation of quantum mechanics that incorporates relativistic dispersion relation $E^2 = \vec{p}^{\,2} + m^2 \rightarrow$ “smallest scale + highest energy”
- Most important **equations of motion** to describe particle dynamics

Spin-0 particles (*scalars*):	$\left(\partial_\mu \partial^\mu + m^2\right) \phi = 0$	**Klein-Gordon eq.**
Spin-1 particles (*vectors*):	$\left(\partial_\nu \partial^\nu + m^2\right) A^\mu = 0$	**Proca eq.**
Spin-$\frac{1}{2}$ particles:	$\left(i\gamma^\mu \partial_\mu - m\right) \psi = 0$	**Dirac eq.**

derived from canonical operator replacement

$$E \rightarrow \quad i\partial_t$$
$$\vec{p} \rightarrow -i\vec{\nabla}$$

- ψ: **four-dimensional spinor** describing at the same time fermion and anti-fermions with spin up/down

γ Matrices

- Important tool for relativistic formulation of Dirac equation

$$\gamma^\mu = (\gamma^0, \gamma^1, \gamma^2, \gamma^3)$$

$$\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu}$$

$$(\gamma^\mu)^\dagger \equiv (\gamma^\mu)^{T*} = \begin{cases} \gamma^0 \text{ for } \mu = 0 \\ -\gamma^\mu \text{ for } \mu = 1, 2, 3 \end{cases}$$

NB: γ^μ is **not a 4-vector** but the same in each coordinate system

- γ matrices in common *chiral* representation (4×4 matrices!)

$$\gamma^0 = \begin{pmatrix} \mathbb{1} & 0 \\ 0 & -\mathbb{1} \end{pmatrix}, \quad \gamma^a = \begin{pmatrix} 0 & \sigma_a \\ -\sigma_a & 0 \end{pmatrix}$$

with Pauli matrices

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \qquad [\sigma_a, \sigma_b] = 2i\epsilon_{abc}$$

- Special combination: $\gamma^5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3$ with $\{\gamma^5, \gamma^0\} = 0$, $(\gamma^5)^2 = 1$

Chirality ("Handedness")

- Important particle property in electroweak interaction
- **Eigenvalue of γ^5 operator** (+: right handed, -: left handed)
- Any spinor can decomposed into left- and right-handed components

$$\psi = (\psi_R + \psi_L) \quad \text{with} \quad \psi_{R/L} = P_{R/L}\psi,\; P_{R/L} = \frac{1}{2}\left(1 \pm \gamma^5\right)$$

- For **massless** particles: chirality = **helicity $\boldsymbol{\lambda}$** ('direction of rotation')
  - Projection of spin onto unit vector in direction of momentum
  - **Not Lorentz-invariant**: for massive particles, there is always a reference frame in which momentum but not spin is in opposite direction

Observables from Spinors

- Physical observables: **bilinear forms of spinors**

  Hermetian conjugate spinor: $\psi^\dagger \equiv \psi^{T*}$

  Adjoint spinor: $\overline{\psi} \equiv \psi^\dagger \gamma^0$

- Classification by **transformation behaviour** under *C* and *P*

Bilinear Form		***C***	***P***	***T***
$\overline{\psi}\psi$	scalar	+	+	+
$\overline{\psi}\gamma^5\psi$	pseudo-scalar	+	-	-
$\overline{\psi}\gamma^\mu\psi$	vector	-	γ^0: +, γ^i: -	γ^0: +, γ^i: -
$\overline{\psi}\gamma^\mu\gamma^5\psi$	axial-vector	+	γ^0: -, γ^i: +	γ^0: +, γ^i: -
$\overline{\psi}\Sigma^{\mu\nu}\psi$	tensor ($\Sigma^{\mu\nu} \equiv \frac{1}{4}[\gamma^\mu\gamma^\nu]$)	-	σ^{0j}: -, σ^{ij}: + σ^{0j}: -, σ^{ij}: +	σ^{0j}: +, σ^{ij}: + σ^{0j}: +, σ^{ij}: +

Lagrange Formalism

- All information of a physical system is contained in the **action**

$$\mathcal{S} = \int \mathrm{d}t \int \mathrm{d}^3x \; \underbrace{\mathcal{L}\left(\phi(x), \partial_\mu \phi(x)\right)}$$

Field $\phi(x)$: separate coordinate at each x (generalization of canonical coordinates)

Lagrange density $\mathcal{L}$

"$(E_{\text{kin}} - E_{\text{pot}})\,|_{\delta x} \equiv T - U|_{\delta x}$"

- Equations of motion from **principle of stationary action** $\mathrm{d}\mathcal{S} = 0$

$$\partial_\mu \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi(x))} - \frac{\partial \mathcal{L}}{\partial \phi(x)} = 0$$

Euler-Lagrange equations

- NB: $\mathcal{L}$ has dimension GeV^4

Lagrangian for Free Bosons and Fermions

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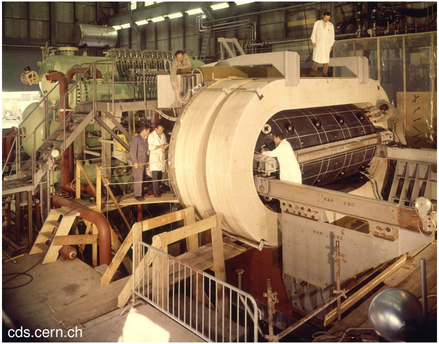
- Lagrange densities (*Lagrangian*) for different free particles of mass m

field	Lagrange density $\mathcal{L}$	equation of motion
scalar field $\phi(x)$ ($S = 0$)	$\frac{1}{2}\left[(\partial_\mu\phi)(\partial^\mu\phi)^* - m^2\phi^2\right]$	Klein-Gordon eq.
fermion field $\psi(x)$ ($S = \frac{1}{2}$)	$\overline{\psi}\,(i\gamma^\mu\partial_\mu - m)\,\psi$	Dirac eq.
vector field $A_\mu(x)$ ($S = 1$)	$-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m^2 A_\mu A^\mu$	Proca eq.

- NB: $\mathcal{L}$ is a *Lorentz scalar*: it is Lorentz-invariant, no 'free' indices μ

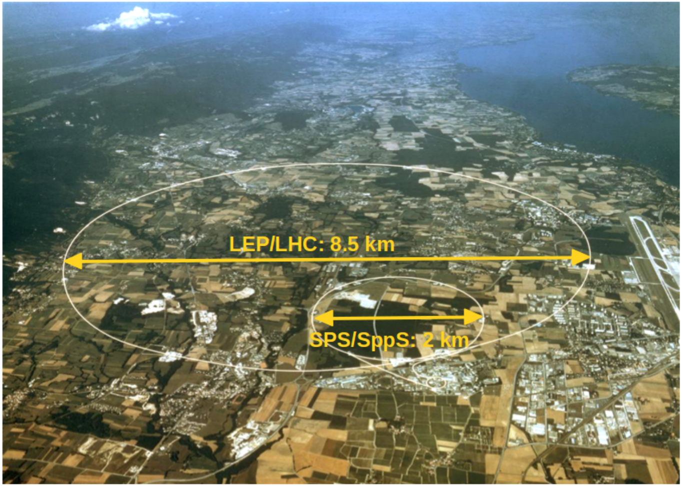
1.3 History of the W/Z/H bosons

W and Z Bosons: "Ancient History"

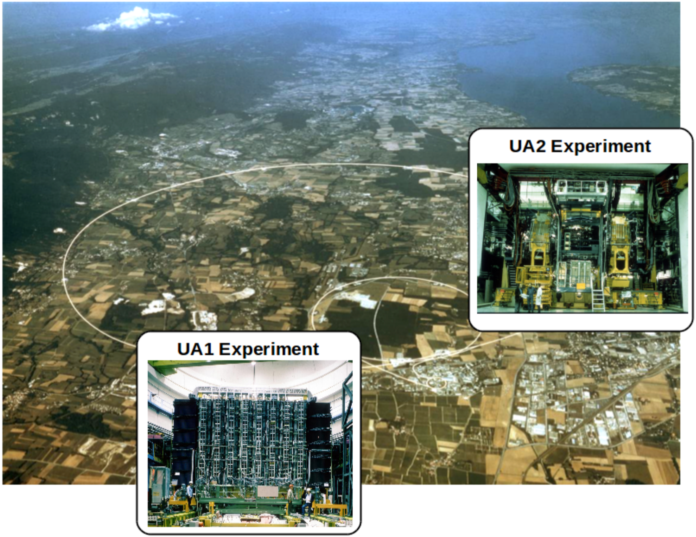


- Electroweak theory (Glashow, Salam, Weinberg, 1961–68)
- Renormalisability of electroweak theory (t'Hooft, Veltman, 1971)
- Discovery of neutral currents (Gargamelle, 1973)
  $\rightarrow$ indirect indication of Z bosons
- Expectation: W and Z boson masses of 60–100 GeV

CERN Accelerator Complex

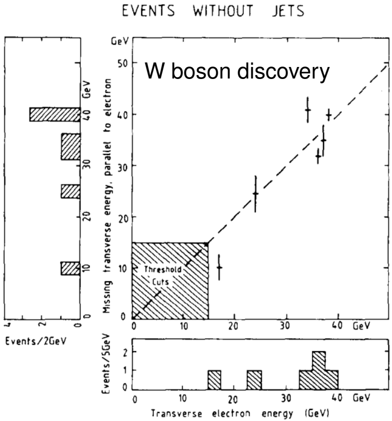


Super Proton-Antiproton Synchrotron (Sp$\bar{p}$S)

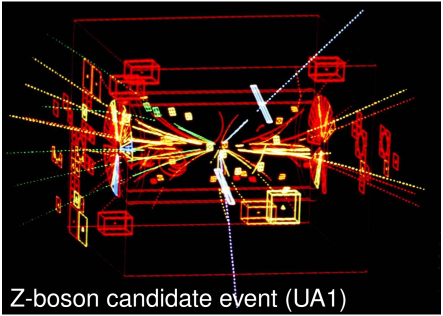


Discovery of W and Z Bosons

- Discovery of **W and Z bosons** at the Sp$\bar{p}$S (CERN, 1983)

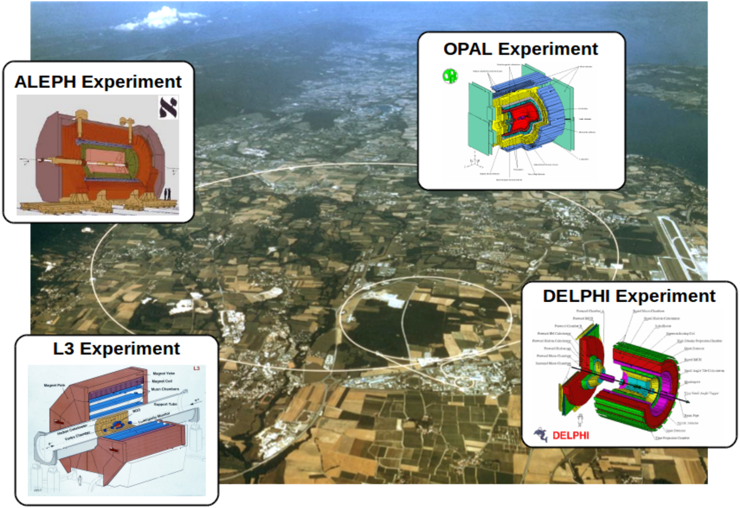


Phys.Lett. 122B (1983) 103-116

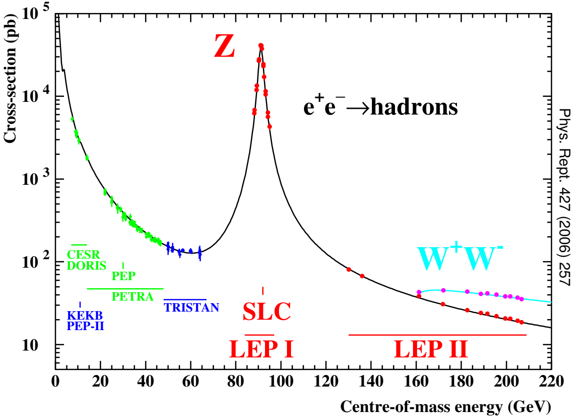


CERN

Large Electron Positron Collider (LEP)



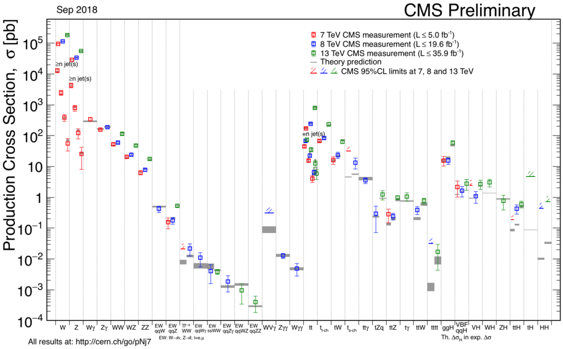
W and Z Bosons in the LEP Era



- LEP I (1989–1995): E_{cms} around Z resonance
  - Precision measurements of Z boson properties
- LEP II (1996–2000): E_{cms} at and beyond W-pair threshold
  - W mass and couplings measurements, Higgs-boson searches, . . .

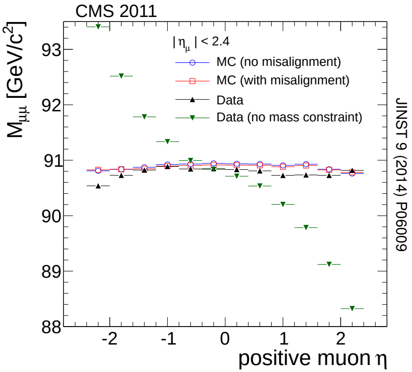
W/Z Physics at the LHC

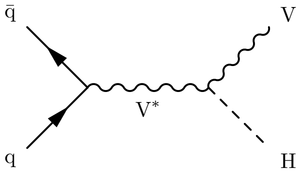
- V + jets and multi-V cross-section measurements
  - Triple and quartic gauge couplings
  - Differential cross-sections: probe of quark PDFs
- W-boson mass
- Diboson resonances: search for new physics



W/Z Bosons at the LHC: Vital Tools

- Calibrate detectors and measure efficiencies, e. g. tracker alignment
- Measure efficiencies, e. g. trigger efficiencies
- Calibrate analysis techniques, e. g. Higgs-boson reconstruction
- Tag signal events above background, e. g. $VH(b\bar{b})$ measurements



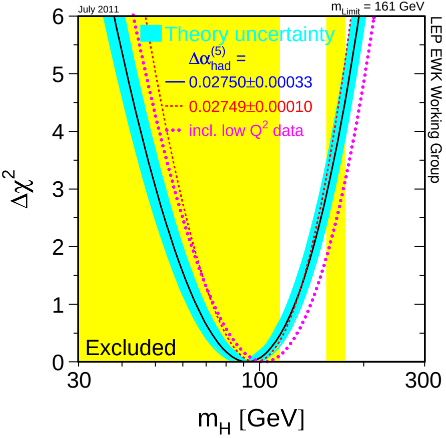


Beyond the Weak Bosons

- Problem with electroweak theory
  - Naive W/Z **mass terms not gauge invariant**
  - Fermion mass terms not gauge invariant due to different left- and right-handed couplings
- **Solution: Higgs mechanism**
  - Symmetric Lagrangian but asymmetric ground state (Higgs field with non-zero vacuum expectation value)

$\rightarrow$ prediction of **Higgs boson**

Higgs mass limits (before LHC)



The Higgs Boson

Nobel Foundation

Integral part of the Standard Model

Consequence of Higgs mechanism
that generates masses

Nuclear Physics B106 (1976) 292–340

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of the Higgs boson, we give a speculative cosmological argument for a small mass. If its mass is similar to that of the pion, the Higgs boson may be visible in the reactions $\pi^- p \to Hn$ or $\gamma p \to Hp$ near threshold. If its mass is $\lesssim 300$ MeV, the Higgs boson may be present in the decays of kaons with a branching ratio $O(10^{-7})$, or in the decays of one of the new par-

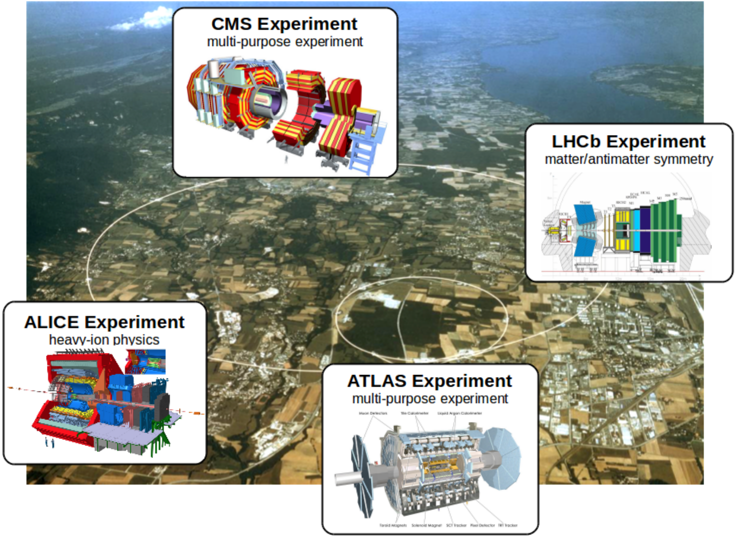
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

taken from R. Harlander, 2014

Accelerator Overview

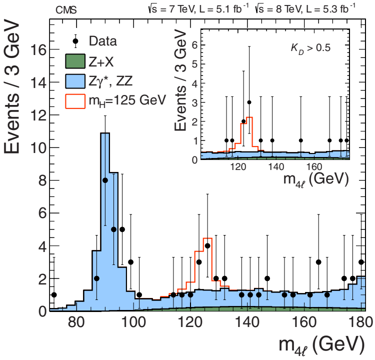
Lab	Accelerator	Data taking	Beams	E_{cms} [GeV]	Experiments
CERN	Sp$\bar{p}$S	1981–1990	$p\bar{p}$	540–630	UA1, UA2
CERN	LEP	1989–2000	e^+e^-	90–209	ALEPH, OPAL, DELPHI, L3
SLAC	SLC	1992–1998	e^+e^-	90	SLD
Fermilab	Tevatron	1987–2011	$p\bar{p}$	1800–1960	CDF, DØ
CERN	LHC	since 2009	pp	7000–1300	ATLAS, CMS, LHCb, ALICE

Large Hadron Collider (LHC)

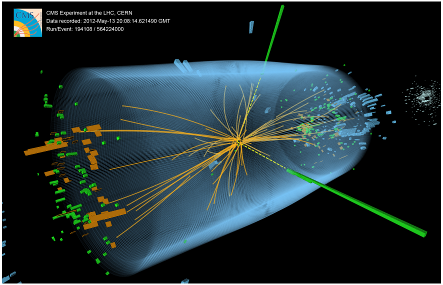


Discovery of the Higgs-Boson

- Discovery of a (the?) **Higgs boson** at the LHC (CERN, 2012)



Phys. Lett. B716 (2012) 30-61

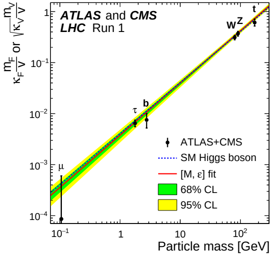


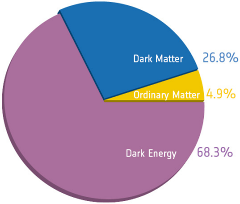
CERN

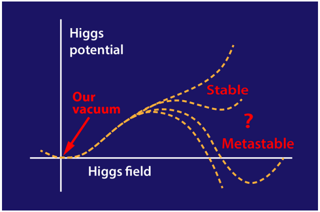
Higgs-Boson Physics at the LHC

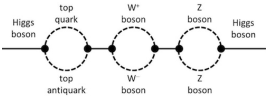
Karlsruher Institut für Technologie

- What are the properties of the Higgs boson?
- Is it *the* Standard Model Higgs boson?
- Is it a door to New Physics?
  - And already used as a tool in searches









Open questions at the forefront of current research!

Why are the Bosons Discovered in Europe?