Standard Model at the LHC
(Lecture 1: Theoretical Recap)

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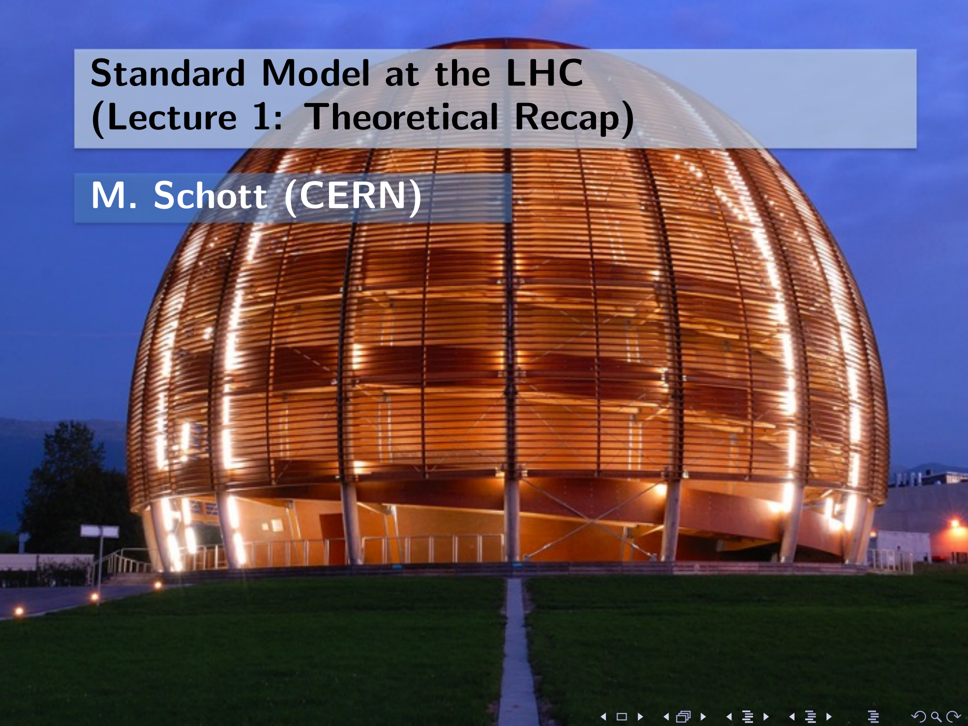


Content

Goal of this lecture series

- The discovery of the Higgs-Boson (?) at the LHC was one of the mile-stones in modern particles physics
- We want to discuss,
  - how do we measure physics at the LHC
  - how did we discover the new particle at the LHC
  - how can we test the Standard Model of particle physics at the LHC

Overview

- Lecture 1: Theoretical Recap of the Standard Model
- Lecture 2: The LHC Detectors and Data Analysis
- Lecture 3: Measuring Production Cross-Sections
- Lecture 4: The Higgs Boson
- Lecture 5: Precision Measurements

Basic Concepts

The Standard Model of particle physics is a

- relativistic Quantum Field Theory
- Gauge Theory

The most simplest part of the Standard Model describes the interaction of electrical charged particle

- Quantum Electro Dynamics (QCD)

Basic Approach

- Define symmetry group
- $\rightarrow$ deduce Lagragian density which is invariant/symmetric in the corresponding group
- Derive Feynman rules

Quantum Electro Dynamics

The QED Lagrangian is invariant under U(1)-group transformations

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\Psi}(i\partial - m)\Psi + e\bar{\Psi}\gamma^{\mu}\Psi A_{\mu}$$

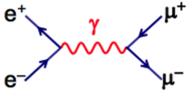
Expressed for experimentalists

We have here

- the Dirac-Spinor Ψ (4-components) which describes the matter field
- the field-strength tensor $F_{\mu\nu}$
- A the electromagnetic four-potential

How to make predictions from theory

We have now a nice Lagrangian, but it doesnt predict so far anything. It would be nice if we could at least calculate something which we can confirm in a measurement later on, e.g. the process $e^+e^- \to \gamma \to \mu^+\mu^-$



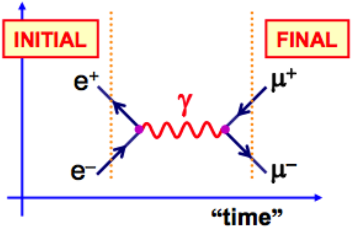
- Idea: Measure the rate and the distribution of $\mu^+\mu^-$ in dependence of the collision energy.
- Calculate a cross-section!
  - Relation of Rate and cross-section and how to measure a cross-section: Lecture 3
  - here: predict/calculate a cross-section

Calculating a cross-section

Cross Section σ given by

$$\sigma = \frac{|M_{fi}|^2}{flux} \times (phasespace)$$

- flux given by experiment
- phase space : 'easy' QM consideration
- M : matrix element
    - contains fundamental physics process
    - interpret as probability from initial to final state



Feynman Rules for QED

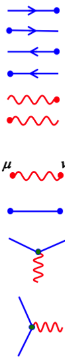
In quantum field theories the Feynman diagrams are obtained from the Lagrangian by Feynman Rules.

- Propagator factor for each internal line (i.e. each internal virtual particle)
- Dirac Spinor for each external line (i.e. each real incoming or outgoing particle)
- Vertex factor for each vertex

Concept

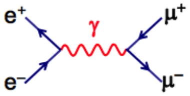
The matrix element is the product of all factors

spin 1/2	incoming particle	$u(p)$
	outgoing particle	$\bar{u}(p)$
	incoming antiparticle	$\bar{v}(p)$
	outgoing antiparticle	$v(p)$
spin 1	incoming photon	$\varepsilon^\mu(p)$
	outgoing photon	$\varepsilon^\mu(p)^*$
spin 1	photon	$-\frac{ig_{\mu\nu}}{q^2}$
spin 1/2	fermion	$\frac{i(\gamma^\mu q_\mu + m)}{q^2 - m^2}$
spin 1/2	fermion (charge $-e$)	$ie\gamma^\mu$



Back to our simple Cross-Section

- Draw Feynman Diagram



- Construct Matrix Element

$$-iM = [\bar{v}(p_2) ie\gamma^{\mu} u(p_1)] \frac{-ig_{\mu\nu}}{q^2} [\bar{u}(p_3) ie\gamma^{\mu} v(p_4)]$$

- Get Predictions

$$\frac{d\sigma}{d\Sigma} = \frac{\alpha^2}{4s}(1 + cos^2\theta)$$

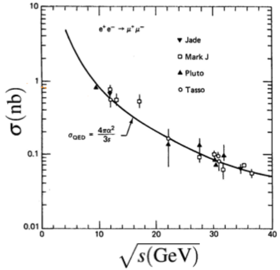
$$\sigma = \frac{4\pi\alpha^2}{3s}$$

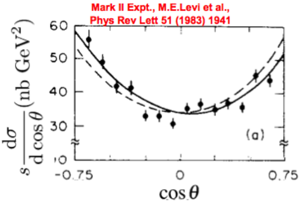
Compare to measurements

- Measurement of $e^+e^- \rightarrow \gamma \rightarrow \mu^+\mu^-$ at $\sqrt{s} = 29 GeV$
- Lowest order cross section calculation provides a good description of the data

Reminder

- It is not always so easy, because this was only lowest order
- Higher order calculations are rather tricky (and we need theoreticians to do them)





Quantum Chromo Dynamics (1/2)

The strong interaction should explain

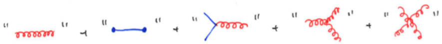
- why quarks are bound in hadrons
- the nuclear-force

The theory of the strong interaction, Quantum Chromodynamics (QCD), is very similar to QED but with 3 conserved (colour) charges.

- quarks carry colour charge
- anti-quarks carry anti-charge
- The force is mediated by massless gluons
- SU(3) symmetry group

Quantum Chromo Dynamics (2/2)

The gauge symmetry determines the exact nature of the interaction as it predicts the Feynman rules.



We have now new two vertices: The gluon self-interactions! It is believed (!), that they give rise to the confinement:

- no color charge directly observed
- only colour singlet states can exist as free particles

Important experimental consequence

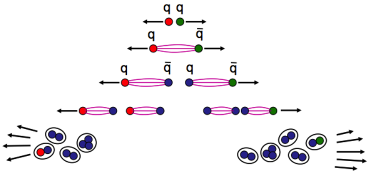
quarks/gluons cannot be directly detected, as they will "hadronize", i.e. "transform" to a bunch of hadrons

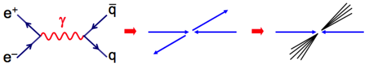
Hadronization

Consider a quark and anti-quark produced in electron positron annihilation

- initially quarks separate at high velocity
- Colour flux tube forms between quarks
- Energy stored in the flux tube sufficient to produce qq pairs
- Process continues until quarks pair up into jets of colourless hadrons

This process is called hadronisation. It is not (yet) calculable, but we have good approximations.

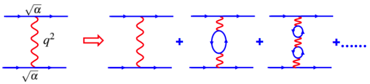




Running Couplings (1/4)

In QED, the 'bare' charge of an electron is screened by virtual e^+e^- pairs.

- behaves like a polarizable dielectric
- In terms of Feynman diagrams:

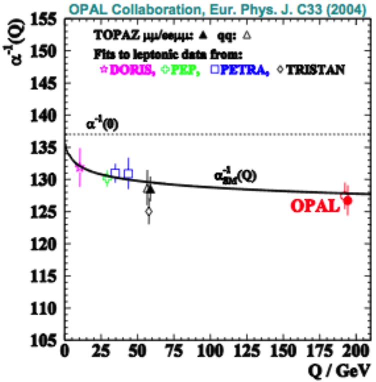


- Add matrix element amplitudes: $M = M_1 + M_2 + ...$
- Giving an infinite series which can be summed

$$\alpha(Q^2) = \alpha(Q_0^2)/[1 - \frac{\alpha(Q_0^2)}{3\pi} ln(Q^2/Q_0^2)]$$

Running Couplings (2/4)

- QED Coupling becomes infinite at $Q \sim 10^{26} GeV$, but this is 'far' away
- The QED coupling increases rather slowly
  - atomic physics: $1/\alpha = 137.036$
  - HEP physics: $1/\alpha = 127.4$

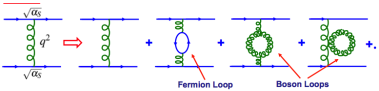


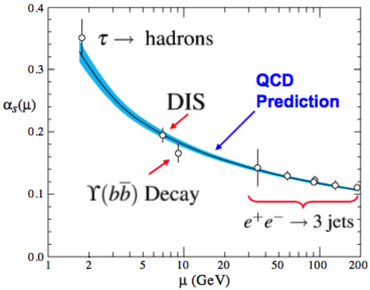
Important

- (1/137) is a small number
- $\rightarrow$ Perturbation Theory can be applied in our calculations

Running Couplings (3/4)

Things are different at QCD. Lets look again at the Feynman diagrams





- now we have boson loops which lead to negative interference
- the sum can be smaller than the original diagram alone

$$\alpha_S(Q^2) = \alpha_S(Q_0^2)/[1 + B_{>0} \cdot \frac{\alpha_S(Q_0^2)}{3\pi} ln(Q$$

- Prediction: α_S decreases with Q^2

Running Couplings (4/4)

At low Q^2, i.e. small energy

- $\alpha_S \approx 1$
- cannot use perturbation theory
- QCD calculations at low energies are so difficult, e.g. properties hadrons, hadronisation of quarks to jets

At high $Q^2 \approx m_Z^2$ we find

- $\alpha_S \approx 0.12$
- Asymptotic freedom (Nobel Prize for Physics, 2004)
- Can use perturbation theory here
  - perturbative QCD (pQCD)

SM Predictions at the LHC

Test calculations of pQCD

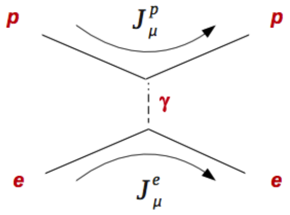
The Weak Force: Fermi Theory

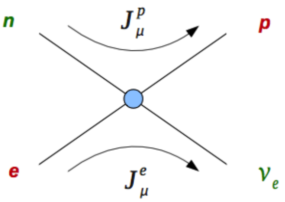
The Weak force accounts for many decays in particle physics

- neutron decay, muon decay, ...

The Fermi-Theory is inspired by QED:

- QED Matrix element for $pe \rightarrow pe$
  - $M = (\bar{p}\gamma^\mu p)\frac{e}{q^2}(bare\gamma_\mu e)$
  - coupling strength e is only parameter of theory
- Fermi Theory for neutron decay $n \rightarrow pe^- \bar{\nu}_e$
  - $M = (\bar{n}\gamma^\mu p)G_F(\bar{\nu}_e\gamma^\mu e)$
  - Fermi-Contant G_F





The Weak Force: Parity Violation

- We know from the Wu Experiment that the weak-force violates parity
- Only the left-handed components of particles and right-handed components of antiparticles participate in weak interactions in the Standard Model
- Need to modify the Fermi theory only a little bit
  - $M = (\bar{n}\gamma^{\mu}(1-\gamma^5)p)G_F(\bar{v}_e\gamma^{\mu}(1-\gamma^5)e)$
  - This operator only involves e_L^-, ν_L or (e_R^+, ν_R)

The Weak Force: The Weak Current (1/2)

Fermi Theory breaks down at high energies → introduce Weak Charged Current Propagator

- The charged-current Weak interaction is different from QED and QCD in that it is mediated by massive W-bosons (80.3 GeV)
- This results in a more complicated form for the propagator:

$$\frac{1}{q^2} \rightarrow \frac{1}{q^2 - m^2}$$

- In addition the sum over W boson (spin 1) polarization states modifies the numerator

$$\frac{-i[g_{\mu\nu} - q_\mu q_\nu / m_W^2]}{q^2 - m_W^2}$$

- This results to the matrix element

$$M_{fi} = [\frac{g_W}{2}\bar{\Psi}\frac{1}{2}\gamma^\mu(1-\gamma^5)\Psi]\frac{-i[g_{\mu\nu} - q_\mu q_\nu / m_W^2]}{q^2 - m_W^2}[\frac{g_W}{2}\bar{\Psi}\frac{1}{2}\gamma^\nu(1-\gamma^5)\Psi]$$

The Weak Force: The Weak Current (2/2)

In the limit ($q^2 \ll m_W^2$) we get back the Fermi-Theory Matrix Element. This gives us the relation

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2}$$

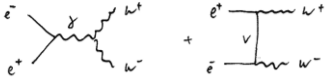
Still usually use G_F to express strength of weak interaction as the is the quantity that is precisely determined in muon decay

Weak Current Summary

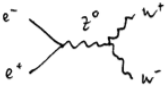
- Weak interaction is of form Vector-Axial-vector (V-A): $\frac{-ig_W}{\sqrt{2}}\frac{1}{2}\gamma^\mu(1-\gamma^5)$
- Consequently only LH chiral particle states and RH chiral anti-particle states participate in the weak interaction
- Maximal Parity Violation
- At low q^2: only weak because of the large m_W

The Weak Force as Gauge Theory

Problem: Production of W-Bosons in e^+e^- collisions



Cross-Section rises with $\sqrt{s}$ and violates unitarity
Idea: Introduce new Boson, which interfers negatively



$$|M_{\gamma WW} + M_{ZWW} + M_{\nu WW}|^2 < | + M_{\gamma WW} + M_{\nu WW}|^2$$

This only works when couplings of Z, γ and W are related.

Electroweak Unification (1/2)

Start again with Gauge-Principle and construct a lagrangian density which is invariant under

$$\Psi \to e^{-\alpha(x)\sigma/2}\Psi$$

- σ are generators of SU(2) symmetry (3 Pauli-Matrices)
- Thee generators $\to$ 3 gauge bosons W_1, W_2, W_3
- associated charge of weak-interaction: Weak Isospin I_W
    - charged weak interaction couples only to LH components of particles ($I_W = 1/2$)
    - for RH components of particles: $I_W = 0$
- It turns out that W_3 has to be a neutral
    - Is this the Z-Boson? No!

Electroweak Unification (2/2)

- In nature we observe two neutral spin-1 gauge-bosons: γ and Z
- W_3 has not the right properties to be Z (left-handed/right-handed couplings)
- 'Usual' idea of theoreticial: Require again a new symmetry
  - U(1) symmetry with new Charge Y (weak hypercharge)
  - New neutral Gauge Boson (Spin-1): B

Interpret the physical fields Z and γ as linear combinations of B and W_3 (very adhoc, but it works!)

$$A_\mu = B_\mu cos\theta_W + W^3_\mu sin\theta_W$$

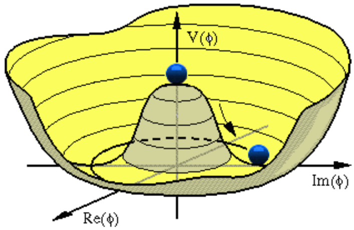
$$Z_\mu = -B_\mu cos\theta_W + W^3_\mu sin\theta_W$$

The weak-hypercharge Y is then given by $Y = 2Q - 2I^3_W$

Why do we need the Higgs-Boson?

This here is just a reminder!

- explicit mass terms for W and Z bosons (like $\sim m_W W^2$) would break the gauge-invariance of the theory
    - no renormalization possible $\rightarrow$ theory looses its predictivity
- L only gauge-invariant when gauge-bosons are massless
- W and Z Boson have a mass

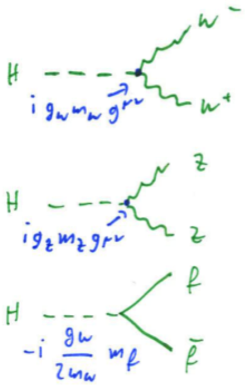


Idea

- introduce Higgs-field
- scalar field, Spin 0
- electricm neutral but $Y = 1/2$

Properties of the Higgs Boson

- Higgs-Field couples to W and Z Bosons ($Y = 1/2$) $\rightarrow$ gives effective masses for $W^{\pm}$ and Z
- Higgs-Field does not couple to γ
- Also fermion masses can be described (but not predicted) through the coupling of the Higgs-field with fermions
- All properties of the Higgs-Field/Boson in the Standard Model are determined - except the Higgs-Boson mass m_H



Summary of the electroweak sector

The Electroweak Unification with the Higgs mechanism has predictive power

Electroweak Predictions

$$m_W = \left(\frac{\pi\alpha_{em}}{\sqrt{2}G_F}\right)^{1/2}\frac{1}{sin\theta_W}$$

$$m_Z = \frac{m_W}{cos\theta_W}$$

- Only 3 out of the 5 parameters in the electroweak sector ($\alpha_{em}, G_F, m_W, m_Z, sin^2\theta_W$) are indepedent
- Prediction of a new particle, associated to the excitations of the Higgs-Field: The Higgs-Boson!

Proton-Proton Collisions (1/3)

We know know how to calculate cross-sections for electron-positron collisions

- What about proton-proton collisions?

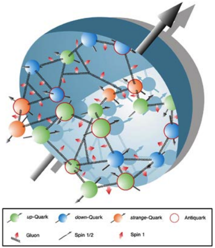
Colliding protons are not like protons at rest. When 2 protons move towards eachother, the quarks on each side start interacting

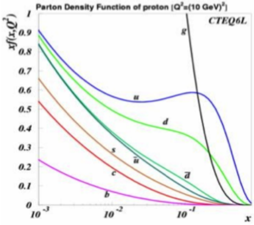
- Emitting gluons
- Gluons can split up in quarks and anti-quarks
- Resulting in a complex 'soup' of gluons and quarks of all flavours!
- $\rightarrow$ need to know structure of the proton

Proton-Proton Collisions (2/3)

The parton density functions (describing the structure of the proton) cannot be predicted

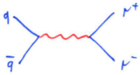
- they need to be measured
- the proton a priori can contain: $u, \bar{u}, d, bard, s, bars, g, \ldots$
- It has to remain a (u,u,d) hadron overall, implying so-called "sum-rules": e.g. $\int [u(x) - \bar{u}(x)] dx = 2, \ldots$
- here: x=momentum fraction carried by a parton over the total hadron energy





Proton-Proton Collisions (3/3)

On basic level, we expect to have the interaction of a quark and anti-quark



But we can only collide hadrons. A quark is "picked" in each hadron, carrying a momentum fraction x of the hadron energy.

$$\sigma = \sum_q \int dx_1 dx_2 q(x_1)\bar{q}(x_2)\sigma_{q\bar{q}\to l^+l^-}(x_1, x_2, s)$$

Hence we have to "unfold" the proton PDFs in each of our cross-section calculations.

How to get cross-sections as experimentalist

- Do I have to calculate these cross-sections every day? No!
- In every days life we use computer programs (event generators) which are doing this for us
  - provide not only cross-sections, but also distributions of particles which are produced in collisions

Event Generators

- Step 1: Hard subprocess: Described by Matrix Element
- Step 2: Decay of Resonances
- Step 3: Initial and Final State radiation
- Step 4: Multi-Parton Interactions
- Step 5: Hadronization

- Check out: Mad-Graph: http://madgraph.hep.uiuc.edu/

Summary of Lecture 1

We have just revisited the basic theoretical concepts of the SM
* Calculating Cross-Sections at the LHC
* Jets Hadronization
* Predictions of the Electroweak Sector

$\rightarrow$ Next Lecture: How do we measure proton-proton collisions