Experimentelle Elementarteilchenphysik I und II (P23.1.1)

Prof. Dr. Heiko Lacker

http://hu-berlin.de/de/eephys/teaching/lectures/SS 2017

	Wann?	Wo?
Vorlesung	Montag, 13:15-14:45	New 14; 1'09
	Mittwoch, 13:15-14:45	New 14; 1'09
Übung	Mittwoch, 17:00-18:30 ?	New 14; 1'12
	Wöchentlich, ab 26.04.2017	

- Inhaltliche Voraussetzungen: - Einführung in die Kern- und Teilchenphysik
  - Einführung in das Standardmodell

- Studienpunkte und Zulassung zur Modulabschlußprüfung:
  Erfolgreiche Teilnahme an den Übungen (50% der Aufgaben)
  mind. einmal Vorrechnen, aktive Teilnahme

- Mischung aus Übungsaufgaben und Fragen zu Publikationen

- Prüfung: mündlich

Experimentelle Elementarteilchenphysik 1 und 2 (P23.1.1)

Attention:

Wednesday, 19th of April, 2. Lecture instead of problem class: 17:00 – 18:30

Monday, 24th of April, Lecture: 13:00 – 13:45

Contents and Goals of the Lectures:
Experimental Foundations of the Standard Model

<u>**Experimentelle Elementarteilchenphysik I (1st half of term, until 31st of May):**</u>

Reminder/Short Reviews of Theoretical Basics

Fermion couplings with the gauge fields γ, Z, W, g

(Self) couplings of the gauge fields Z, W, g

Strong interactions

<u>**Experimentelle Elementarteilchenphysik II (2nd half of term, 7th of June):**</u>

Nature of Mass (Higgs mechanism/Higgs boson)

Quark mixing matrix and CP violation

Neutrinos

Literature

Covers a lot:

- Leader, Predazzi: An introduction to Gauge Theories and Modern Particle Physics, Cambridge University Press

General:

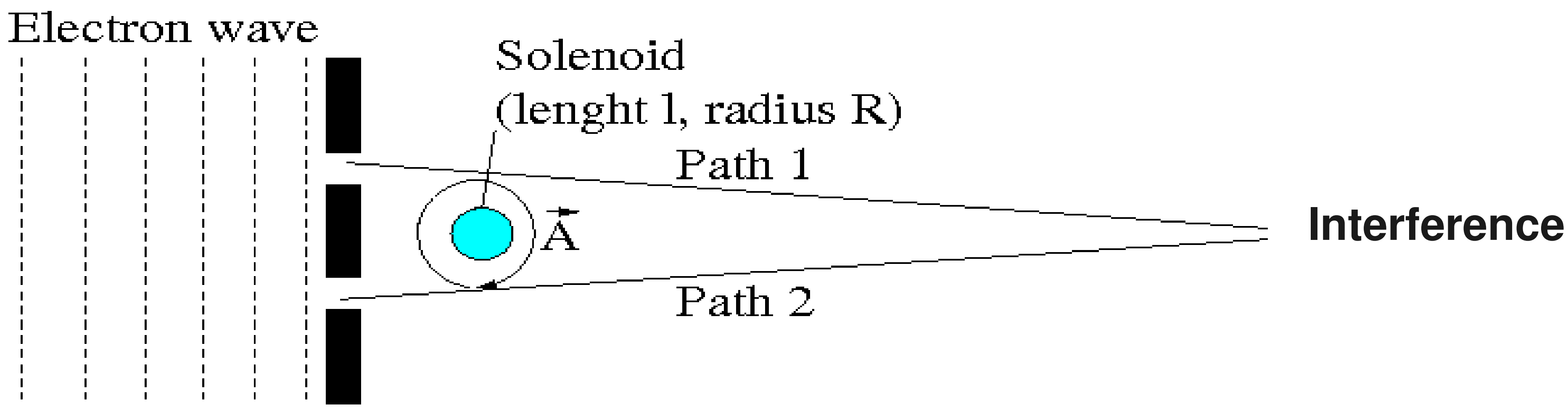
- Particle Data Group: Review of particle Properties, http://pdg.lbl.gov/
- Martin, Shaw: Particle Physics
- Kane: Modern Particle Physics
- Perkins: Hochenergiephysik/High Energy Physics, 4. edition
- Bettini: Introduction to Elementary Particle Physics

Theorie background:

- Quigg: Gauge Theories
- Halzen, Martin: Quarks and Leptons
- Aitchison, Hey: Gauge Theories in Particle Physics
- Nachtmann: Elementarteilchenphysik
- Giunti & Kim: Fundamentals of Neutrino Physics and Astrophysics

1. Introduction: Fundamental Interactions

1.1 Aharanov-Bohm effect



Outside solenoid: $\vec{B}=0,\ \text{but}\ \vec{A}\neq 0$

$$\oint \vec{A}\,d\vec{r}=2\pi r|\vec{A}|=\int rot\vec{A}\,d\vec{a}=\int \vec{B}\,d\vec{a}=\Phi_m=\frac{\mu_0 n \mathrm{I}}{l}\pi R^2$$

1. Introduction: Fundamental Interactions

1.1 Aharanov-Bohm effect

QM: If Ψ_0 **solves** $\frac{1}{2\mathrm{m}}(-i\hbar\vec{\nabla})^2\psi = i\hbar\frac{\partial\psi}{\partial t}$

then $\psi_0 \exp\left(i\cdot\frac{e}{\hbar}\int\vec{A}\,d\vec{s}\right)$ **solves** $\frac{1}{2\mathrm{m}}(-i\hbar\vec{\nabla}-e\vec{A})^2\psi = i\hbar\frac{\partial\psi}{\partial t}$

Relative phase shift between path 1 and 2:

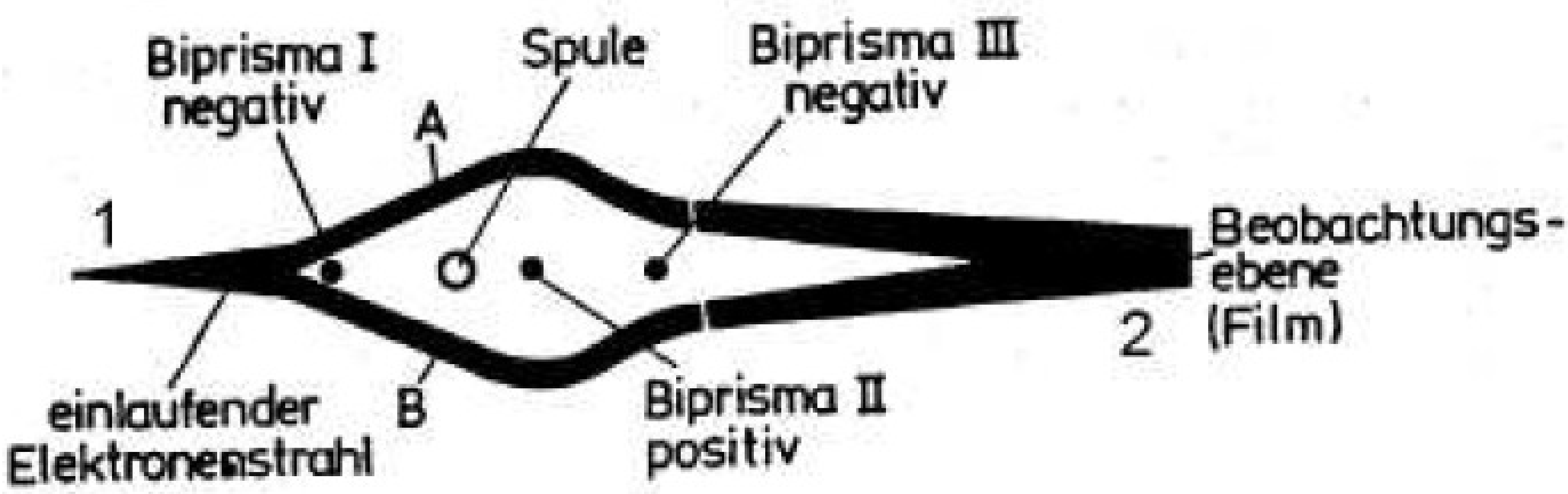
$$\delta\phi(\mathrm{I}) = \delta\phi(\mathrm{I}=0) + \frac{e}{\hbar}\left[\int_1\vec{A}\,d\vec{r} - \int_2\vec{A}\,d\vec{r}\right] = \delta\phi(\mathrm{I}=0) + \frac{e}{\hbar}\oint\vec{A}\,d\vec{r}$$

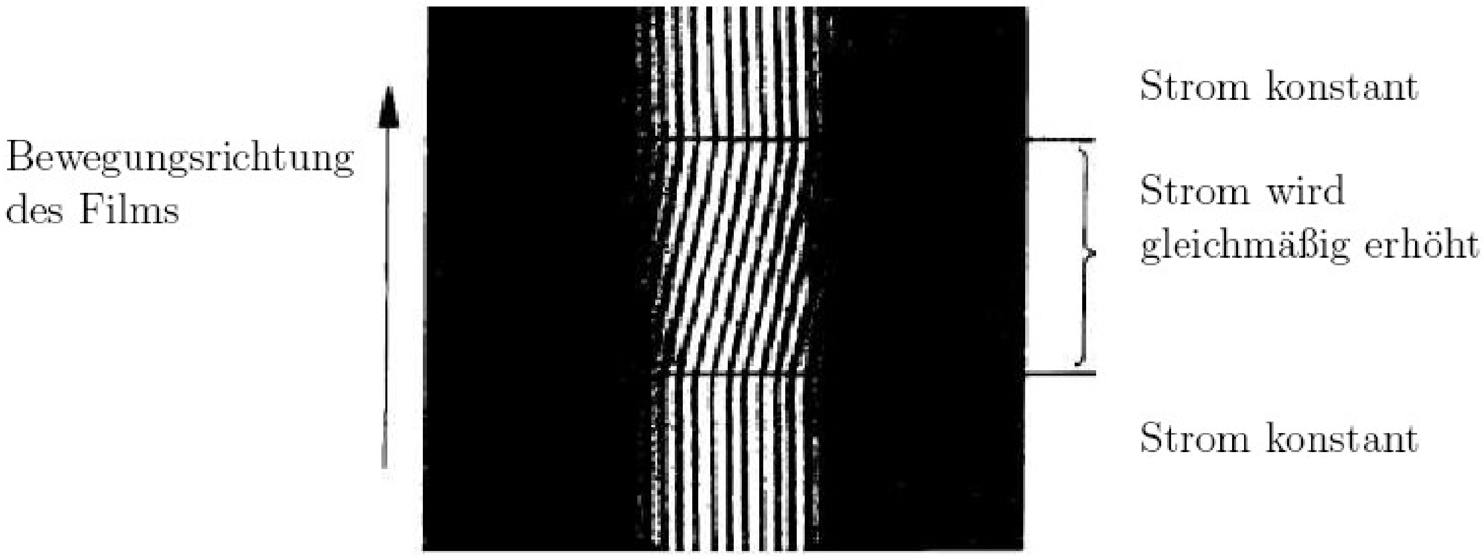
$$= \delta\phi(\mathrm{I}=0) + \frac{e}{\hbar}\Phi_m = \delta\phi(\mathrm{I}=0) + \frac{e}{\hbar}\frac{\mu_0 n\pi R^2}{l}\mathrm{I}$$

=> (vector) potential induces local phase trafo α(x) of electron wave function

=> Gauge invariance ($\vec{A}\rightarrow\vec{A}\,' = \vec{A}+\vec{\nabla}\alpha$ **) compensates any local phase trafo** $\alpha(\vec{x})$

Möllensted and Bayh (1962): demonstration of Aharonov-Bohm effect





(vector) potential induces local phase trafo
=> any local phase trafo can be compensated by a (vector) potential

1.2 Yang-Mills theories

Conserved "charge" g (consequence of invariance under global phase trafo)

Recipe to introduce an interaction coupling to g:

a) Free Dirac particle: $\mathscr{L}_{free} = \overline{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi \quad (\overline{\psi} = \psi^{+}\gamma^{0}\text{: adjoint spinor})$

b) Local phase trafo (Lie group): $\psi(x) \rightarrow \exp\left(i g \vec{T}\cdot\vec{\alpha}(x)\right)\cdot\psi(x)$

Generators of Lie group: $\vec{T} = (T_1, \ldots, T_n)$ **m x m matrices**

Fermion fields with group quantum numbers: $\psi(x) = (\psi_1, \ldots \psi_m)$

Lie algebra: $[T_a, T_b] = T_a T_b - T_b T_a = i\cdot f_{abc}\cdot T_c$

Structure constants of Lie group: f_{abc} **(=0 for abelian groups)**

1.2 Yang-Mills theories

c) Require invariance of $\mathscr{L}$ under local phase trafo

=> Introduction of gauge fields A_μ^a

$$\partial_\mu \rightarrow \partial_\mu + i g T_a A_\mu^a$$

g: coupling strength

g T_a: charge operator

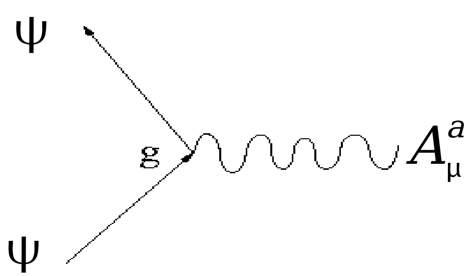
Dirac equation invariant under $\psi(x) \rightarrow \psi'(x) = \exp\left(i g \vec{T} \cdot \vec{\alpha}(x)\right) \cdot \psi(x)$

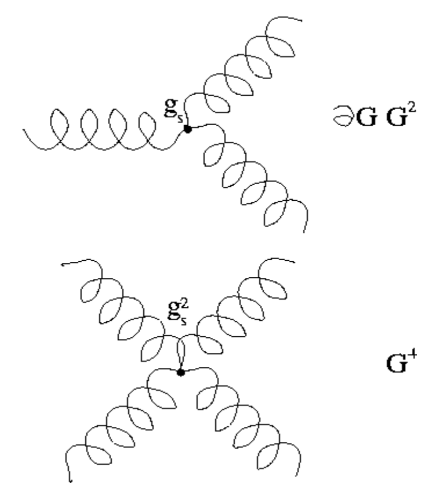
If at the same time $A_\mu^a(x) \rightarrow A_\mu^{a\prime}(x) = A_\mu^a(x) - \partial_\mu \vec{T} \cdot \vec{\alpha}(x)$

d) Add field dynamics: $\mathscr{L}_{field} = -\frac{1}{4} F_{\mu\nu}^a F^{a,\mu\nu}$ $\quad F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g f_{abc} A_\mu^b A_\nu^c$

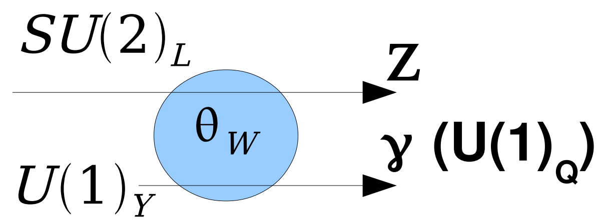
self-coupling

$$\mathscr{L}_{interaction} = -g j_a^\mu A_\mu^a = -g \bar{\psi} \gamma^\mu T_a \psi A_\mu^a$$





1.3 Fundamental gauge fields of the Standard Model (SM)

Interaction	E.M.: QED	Electroweak: QFD	Strong: QCD
Gauge Group	$U(1)_Q$	$SU(2)_L x U(1)_Y$	$SU(3)_C$
Gauge field	A_μ photon γ uncharged	$W_\mu^{\pm}$ W_μ^{0} B_μ 	G_μ^{a} , a=1, ..., 8 gluons g colour charges
Mass	m=0 (limit: 10^{-18} eV)	m=0; after sym. breaking: $m_{W/Z}$ = 80(91) GeV	m=0
Coupling	electrical charge	weak isospin: T,T_3 (SU(2)) weak hypercharge: $Y=2(Q-T_3)$ ($U(1)_Y$)	3 colour charges
Strength	e (unit charge), $\alpha=e^2/4\pi\sim1/137$	g (SU(2)) g' ($U(1)_Y$) $\frac{gg'}{\sqrt{g^2+g'^2}}=e$	g_S , $\alpha_S=g_S^2/4\pi\sim0.12$ ($@m_Z$)
Self coupling	---	partial	yes

2. Theory of electroweak interactions

2.1 Reminder: Chiral fermions

Free fermions described by Dirac eq.: $i\gamma^\mu \partial_\mu \psi = m\psi$, **Dirac spinor:** $\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$

γ^μ: 4x4 matrices with $\{\gamma^\mu, \gamma^\nu\} = \gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu = 2 g^{\mu\nu} 1\mathrm{I}$

$\gamma^0 = \gamma^{0+}$; i=1,2,3: $\gamma^i = -\gamma^{i+}$

$\gamma^5 := i\gamma^0\gamma^1\gamma^2\gamma^3 =: \gamma_5$ $\{\gamma^5, \gamma^\mu\} = 0$ **Chirality operator**

$P_{L,R} = \frac{1 \mp \gamma^5}{2}$ **projection operators** $(P^2_{L,R} = P_{L,R}; P_L P_R = P_L P_R = 0; P_L + P_R = 1)$

=> Decomposition in left- and right-handed fermions:

Fermion: $f = P_R f + P_L f = f_R + f_L$, $\gamma^5 f_{R,L} = \pm f_{R,L}$

Antifermion: $f^C = P_L f^C + P_R f^C = f^C_L + f^C_R = (f_R)^C + (f_L)^C$, $\gamma^5 f^C_{R,L} = \pm f^C_{R,L}$, $\gamma^5 (f_{R,L})^C = \mp (f_{R,L})^C$

Special case: **m=0, respectively, p** $\rightarrow$ **∞**

left(right)-handed <=> negative (positive) helicity