

INTRODUCTION TO QUANTUM CHROMODYNAMICS

PARTICLE PHYSICS 2







BRIEFLY ABOUT ME...

PhD in 2007 from NKUA, Greece 2003-2010: At CERN (fellow) 2008-2010: Postdoc at UU (stationed at CERN) 2010 - Today: Senior scientist at Nikhef, Amsterdam 2015 - Today: Guest professor at **UU** and **TU-Delft** Since 2024: Professor at University of Maastricht





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Where can you find me

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BRIEFLY ABOUT ME...

Vertex TPCs Main TPC Vertex Magnets Teaching

Research interest



- year bachelor)
- Special relativity (1st year bachelor)
- Subatomic physics (3rd year bachelor)
- Particle physics 2 QCD (MSc)





• Quantum chromodynamics (QCD) Heavy-ion physics Alice @ LHC Connection with NS EoS

Introduction to elementary particle physics (1st





 $\begin{aligned} \mathcal{J} &= \frac{1}{4g^2} \left(\mathcal{G}_{\mu\nu} \mathcal{G}_{\mu\nu} + \frac{1}{2} \overline{g}_i \left(i \partial^{\mu} \mathcal{D}_{\mu} + m_i \right) g_i \right) \\ & \text{where } \mathcal{G}_{\mu\nu}^{\alpha} &= \partial_{\mu} \mathcal{H}_{\nu}^{\alpha} - \partial_{\mu} \mathcal{H}_{\mu}^{\alpha} + i \int_{\partial \alpha}^{\alpha} \mathcal{H}_{\mu}^{\beta} \mathcal{H}_{\nu}^{\alpha} \\ & \text{and } \mathcal{D}_{\mu} &= \partial_{\mu} + i t^2 \mathcal{H}_{\mu}^{\alpha} \end{aligned}$ That's it!







PRACTICAL MATTERS



COMMUNICATION

All communication from our side is done through the mailing list <u>pp2course-msc@nikhef.nl</u>

List populated using the lists we got from the coordinators of your programs

If you have not received a mail or if you know a case, 💯 contact me!!!

Panos.Christakoglou@nikhef.nl







TEACHING ASSISTANTS





noor.koster@nikhef.nl

Particle Physics 2 - 2023/2024

Noor Koster





ABOUT YOUR HOMEWORK

Can be sent as a pdf file

- Reasonable file size (less than 5 MB)
- Readable
- Deadline 1 week after the homework is given.

Hand in, either:

- By mail to the TAs
- At the start of tutorial/exercise class in person







MATERIAL

QCD material also posted on my web page



Masters level courses



Particle Physics 2 - Quantum Chromo-Dynamics (QCD)

- Basic information
 - \circ Lectures given in the 2nd semester of the common master program
 - \circ The lectures are given on Mondays and Wednesdays between 09:00 and 13:00 in H331 at Nikhef
 - The course is given together with Marcel Merk who focuses on the CP part
 - Prerequisites
 - Subatomic physics (bachelor)
 - Introduction to QFT
 - Particle Physics 1



Particle Physics 2 - 2023/2024





- Every Tuesday between 11:00 and 13:00 @ Nikhef (Office N327)

- Every Thursday between 11:00 and 13:00 @UU (Leonard S. Orsteinlaboratorium - Office 259)







LITERATURE

The lecture notes use material mainly from these books

PHYSICS TEXTBOOK

David Griffiths

WILEY-VCH

Introduction to **Elementary Particles**

Second, Revised Edition



Urheberrechtlich geschütztes Material

QUARKS & LEPTONS:

An Introductory Course in Modern Particle Physics



Francis Halzen Alan D. Martin











LITERATURE

The lecture notes use material mainly from these books



Quantum Chromodynamics

Untrebarreghtlich ofsicheraterial Walter Greiner

Stefan Schramm

Eckart Stein

Third Edition

Springer

Copylighted Materian INTERNATIONAL SERIES OF MONOGRAPHS ON PHYSICS + 113

Quantum Chromodynamics

High Energy Experiments and Theory

GÜNTHER DISSERTORI IAN KNOWLES MICHAEL SCHMELLING



OXFORD SCIENCE PUBLICATIONS







LITERATURE

The lecture notes use some, limited material also from these sources

QCD and **Collider Physics**

R.K. ELLIS, W.J. STIRLING AND B.R. WEBBER

CAMBRIDGE MONOGRAPHS ON PARTICLE PHYSICS, NUCLEAR PHYSICS AND COSMOLOGY









The Coordinated Theoretical-Experimental Project on QCD

Members Workshops Summer Schools PDFs Handbook Preprints Other CTEQ Pages HEP Links



CTEQ is a multi-institutional collaboration devoted to a broad program of research projects and cooperative enterprises in high-energy physics centered on Quantum Chromodynamics (QCD) and its implications in all areas of the Standard Model and beyond.





OFFICE HOURS

You have questions or comments about the lectures?

- I reserved two hours <u>every Tuesday</u>, between 12:00 and 14:00
- Address: Nikhef, Science Park 105, Room N325 or my zoom room
- Readjusted if needed e.g. everybody shows up at the same time
- You could also send a mail
 - I promise to try to answer as fast as possible
 - Note my teaching duties
 - Also other responsibilities e.g. research (ALICE @ LHC), committees, BSc/MSc/ PhD supervision,..., and maybe a life

on how to improve the course!

I will be more than glad to receive your comments, suggestions and ideas





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Nik hef



INTRODUCTION TO QCD

QCD ANNIVERSARY

50 Years of Quantum Chromodynamics

11-15 Sept 2023 Luskin Conference Center US/Pacific timezone



Overview

Timetable

Contribution List

Registration

Conference venue

Accommodation and travel info

Code of Conduct

QCD@50 Poster

Conference Admin

mparedes@physics.ucla..



Particle Physics 2 - 2023/2024

Enter your search term

Q





BIRTH OF PARTICLE PHYSICS

The list of elementary particles has changed many times over time

- The electron was the only particle that was always in that list!
- The first elementary particle to be ever identified
 - Discovered by Sir Joseph John Thomson in 1887
 - Thomson was awarded the Nobel prize for this discovery but also for his work on the conduction of electricity in gases
 - This discovery was done while Thomson investigated whether or not particle rays could be deflected by an electric field

J. J. Thomson (1856-1940)







SUBNUCLEAR STRUCTURE

In 1932 Chadwick discovered the neutron and it became clear that the nucleus consisted of protons and neutrons Soon more particles started popping up from experiments James Chadwick (1891 - 1974) 1890



Particle Physics 2 - 2023/2024 - QCD



Who ordered these? What are their properties? Are there any patterns?



GELL-MANN'S QUARK MODEL

George Zweig Murray Gell-Mann













$$s = -2$$





Fig. 1.4: The meson (left) and the baryon (right) octets.

Fig. 1.5: The baryon octet (left) and decuplet (right).



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The Nobel Prize in Physics 1969



q = 0

q = -1

Murray Gell-Mann Prize share: 1/1

The Nobel Prize in Physics 1969 was awarded to Murray Gell-Mann "for his contributions and discoveries concerning the classification of elementary particles and their interactions".

Photos: Copyright © The Nobel Foundation

Hint for quark fractional charge and a new quantum number \rightarrow colour(?)







EVIDENCE OF COLOUR

Fig. 11.3 Ratio R of (11.6) as a function of the total e^-e^+ center-of-mass energy. (The sharp peaks correspond to the production of narrow 1^- resonances just below or near the flavor thresholds.)





ARE NUCLEONS ELEMENTARY?

e-p scattering: Repeat similar experiment as Rutherford did in ~1909



Particle Physics 2 - 2023/2024



The Nobel Prize in Physics 1961 Robert Hofstadter, Rudolf Mössbauer

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The Nobel Prize in Physics 1961



Robert Hofstadter Prize share: 1/2



Rudolf Ludwig Mössbauer Prize share: 1/2

The Nobel Prize in Physics 1961 was divided equally between Robert Hofstadter "for his pioneering studies of electron scattering *in atomic nuclei and for his thereby achieved discoveries* concerning the structure of the nucleons" and Rudolf Ludwig Mössbauer "for his researches concerning the resonance absorption of gamma radiation and his discovery in this connection of the effect which bears his name".

Photos: Copyright © The Nobel Foundation





ARE NUCLEONS ELEMENTARY?



SLAC-MIT experiment



Particle Physics 2 - 2023/2024



The Nobel Prize in Physics 1990 Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

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The Nobel Prize in Physics 1990



Jerome I. Friedman Prize share: 1/3



Henry W. Kendall Prize share: 1/3



Photo: T. Nakashima **Richard E. Taylor** Prize share: 1/3

The Nobel Prize in Physics 1990 was awarded jointly to Jerome I. Friedman, Henry W. Kendall and Richard E. Taylor "for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics".

Photos: Copyright © The Nobel Foundation











DEEP INELASTIC SCATTERING

Bjorken's scaling hypothesis

• if scattering is caused by point-like constituents, then the structure functions should be independent of Q²

Feynman's parton model

- a proton consists of constituents
- the term "parton" was used by Feynman at the early stages of his formulation and stands until our days
 - Physicists were reluctant to talk about quarks at that stage, let alone about gluons

James Bjorken



Richard Feynman (1918-1988)









DISCOVERY OF QUARKS AND GLUONS

Positron-Electron Tandem Ring Accelerator: TASSO experiment @ electron-positron collisions between 1978 and 1986 PETRA @ DESY









DIS EXPERIMENTS

DESY (Deutsches Elektronen-Synchroton) Laboratory, Hamburg, (1992-2007) <u>27.5 GeV</u> <u>920 GeV</u> √s~318 GeV e[±] D



Particle Physics 2 - 2023/2024



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PERIODIC TABLE OF PARTICLE PHYSICS







FORCES AND MEDIATORS

Developing QFTs that describe the interactions between these elementary particles













THE STANDARD MODEL

Quantum ElectroDynamics (QED)



The Nobel Prize in Physics 1965 Sin-Itiro Tomonaga, Julian Schwinger, Richard P. Feynman

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The Nobel Prize in Physics 1965



Sin-Itiro Tomonaga Prize share: 1/3



Julian Schwinger Prize share: 1/3



Richard P. Feynman Prize share: 1/3

The Nobel Prize in Physics 1965 was awarded jointly to Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman "for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles".

Photos: Copyright © The Nobel Foundation





The Nobel Prize in Physics 1979 Sheldon Glashow, Abdus Salam, Steven Weinberg

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1979



Sheldon Lee Glashow Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current".

Photos: Copyright © The Nobel Foundation

Particle Physics 2 - 2023/2024

Electroweak Unification (GSW)

The Nobel Prize in Physics



Abdus Salam Prize share: 1/3

Steven Weinberg Prize share: 1/3

Strong interactions











FOCUS ON STRONG INTERACTIONS







ASYMPTOTIC FREEDOM

The coupling constant is denoted by $\alpha_{\rm S}$ and as in the case of QED is not a constant

- In contrast to QED though, we will see that the strong coupling constant changes quite rapidly as a function of the distance between the interacting particles
 - At short distances as becomes quite small, allowing the quarks e.g. within a proton to move freely without interacting much with their neighbouring quarks.
 - This phenomenon is called asymptotic freedom
 - Its existence was postulated in 1973 by Frank Wilczek, David Gross, and independently by David Politzer the same year. All three shared the Nobel Prize in physics in 2004



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THE BIRTH OF QCD



The Nobel Prize in Physics 2004 David J. Gross, H. David Politzer, Frank Wilczek

The Nobel Prize in Physics 2004



David J. Gross



H. David Politzer



Frank Wilczek

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek "for the discovery of asymptotic freedom in the theory of the strong interaction".

VOLUME 30, NUMBER 26

PHYSICAL REVIEW LETTERS

¹⁴Y. Nambu and G. Jona-Lasino, Phys. Rev. 122, 345 (1961); S. Coleman and E. Weinberg, Phys. Rev. D 7, 1888 (1973).

¹⁵K. Symanzik (to be published) has recently suggested that one consider a $\lambda \varphi^4$ theory with a negative λ to achieve UV stability at $\lambda = 0$. However, one can show, using the renormalization-group equations, that in such theory the ground-state energy is unbounded from below (S. Coleman, private communication).

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138 (Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

VOLUME 30, NUMBER 26

PHYSICAL REVIEW LETTERS

Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross[†] and Frank Wilczek Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540 (Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field-theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

Non-Abelian gauge theories have received much attention recently as a means of constructing unified and renormalizable theories of the weak and electromagnetic interactions.¹ In this note we report on an investigation of the ultraviolet (UV) asymptotic behavior of such theories. We have found that they possess the remarkable feature, perhaps unique among renormalizable theories, of asymptotically approaching free-field theory. Such asymptotically free theories will exhibit, for matrix elements of currents between on-mass-shell states, Bjorken scaling. We therefore suggest that one should look to a non-Abelian gauge theory of the strong interactions to provide the explanation for Bjorken scaling, which has so far eluded field-theoretic understanding.

The UV behavior of renormalizable field theories can be discussed using the renormalization-group equations,^{2,3} which for a theory involving one field (say $g\varphi^4$) are

 $[m\vartheta/\vartheta m + \beta(g)\vartheta/\vartheta g - n\gamma(g)]\Gamma_{asy}(n)(g; P_1, \dots, P_n) = 0.$

Particle Physics 2 - 2023/2024

¹⁶W. A. Bardeen, H. Fritzsch, and M. Gell-Mann, CERN Report No. CERN-TH-1538, 1972 (to be published).

¹⁷H. Georgi and S. L. Glashow, Phys. Rev. Lett. <u>28</u>, 1494 (1972); S. Weinberg, Phys. Rev. D 5, 1962 (1972). ¹⁸For a review of this program, see S. L. Adler, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published).

25 June 1973

 $\begin{aligned} \mathcal{J} &= \frac{1}{4g^2} \left(\int_{u_U}^{\alpha} \int_{u_U}^{\alpha} + \frac{1}{2} \overline{g}_i \left((\partial^{-\mu} D_u + m_i) g_i \right) \\ & \text{where } G_{u_U}^{\alpha} \equiv \partial_{\mu} \overline{H}_{\nu}^{\alpha} - \partial_{\nu} \overline{H}_{\mu}^{\alpha} + i \int_{u_U}^{\alpha} \overline{H}_{\mu}^{\beta} \overline{H}_{\nu}^{\alpha} \\ & \text{and } D_{\mu} \equiv \partial_{\mu} + i t^{\alpha} \overline{H}_{\mu}^{\alpha} \\ & \overline{Thats it} . \end{aligned}$







THE STANDARD MODEL

Quantum ElectroDynamics (QED)



The Nobel Prize in Physics 1965 Sin-Itiro Tomonaga, Julian Schwinger, Richard P. Feynman

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Richard P. Feynman Prize share: 1/3

The Nobel Prize in Physics 1965 was awarded jointly to Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman "for their fundamental work in quantum electrodynamics, with *deep-ploughing consequences for the physics of elementary* particles".

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The Nobel Prize in Physics 1979 Sheldon Glashow, Abdus Salam, Steven Weinberg

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1979



Sheldon Lee Glashow Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current".

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Electroweak Unification (GSW)

The Nobel Prize in Physics



Abdus Salam Prize share: 1/3

Steven Weinberg Prize share: 1/3

Quantum ChromoDynamics (QCD)



The Nobel Prize in Physics 2004 David J. Gross, H. David Politzer, Frank Wilczek

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The Nobel Prize in Physics 2004



David J. Gross Prize share: 1/3



H. David Politzer Prize share: 1/3



Frank Wilczek Prize share: 1/3

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek "for the discovery of asymptotic freedom in the theory of the strong interaction".

Photos: Copyright © The Nobel Foundation





... AND ITS MISSING PIECE

The Higgs mechanism



The Nobel Prize in Physics 2013 François Englert, Peter Higgs

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The Nobel Prize in Physics 2013



Photo: A. Mahmoud **François Englert** Prize share: 1/2



Photo: A. Mahmoud Peter W. Higgs Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Photos: Copyright © The Nobel Foundation





CERN experiments observe particle consistent with long-sought Higgs boson

Geneva, 4 July 2012. At a seminar held at CERN¹ today as a curtain raiser to the year's major particle physics conference, ICHEP2012 in Melbourne, the ATLAS and CMS experiments presented their latest preliminary results in the search for the long sought Higgs particle. Both experiments observe a new particle in the mass region around 125-126 GeV.

"We observe in our data clear signs of a new particle, at the level of 5 sigma, in the mass region around 126 GeV. The outstanding performance of the LHC and ATLAS and the huge efforts of many people have brought us to this exciting stage," said ATLAS experiment spokesperson Fabiola Gianotti, "but a little more time is needed to prepare these results for publication."

"The results are preliminary but the 5 sigma signal at around 125 GeV we're seeing is dramatic. This is indeed a new particle. We know it must be a boson and it's the heaviest boson ever found," said CMS experiment spokesperson Joe Incandela. "The implications are very significant and it is precisely for this reason that we must be extremely diligent in all of our studies and crosschecks."

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CMS $\sqrt{s}=7$ TeV, L=5.1 fb⁻¹ $\sqrt{s}=8$ TeV, L=5.3 fb⁻¹ 7905. 1200 800 l events/1. 0001 700 600 120 130 S/(S+B) weighted 125 m,, (GeV) 500 S+B fit B fit component <u>±</u>1σ ±2σ 130 110 120 150 140 $m_{\gamma\gamma}$ (GeV)













QCD VS QED

Similar formulation between QED and QCD but with fundamental differences

- in QED there is one charge (i.e. electric charge) in QCD we have three (i.e. colour)
 - There are three kind of colours in QCD,: red (R), green (G) and blue (B).
 - Gluons have two colours, carrying one unit of color and one of anticolor.
 - There are 3x3 = 9 possibilities for the gluons but as we will see later there are only 8.
 - Since the gluons carry color, they can also couple directly to other gluons making the existence of gluon-gluon vertices possible.
- Another difference comes from the fact that particles decaying strongly have typical lifetimes of 10-23 sec
- Finally, the coupling strength...





QUANTUM CHROMODYNAMICS - QCD



Fig. 1.14: The basic diagram that represents the most elementary process in QCD.



Fig. 1.15: The lower order diagram that describes the interaction between two quarks.





FEYNMAN RULES OF QCD

- Labeling: We label every external line with the ingoing and outgoing momenta $P_1,..., P_n$, adding also an arrow indicating whether a particle is approaching or moving away from the vertex. If the diagram includes antiparticles, we still label them as particles but with the reverse direction of the arrow. We then label the 4-momenta for all internal lines $q_1,..., q_i$ and we give an arbitrary direction to the relevant arrow.
- External lines: Each external line contribute the following factors:

Incoming quark $\rightarrow u^s \cdot c$ Outgoing quark $\rightarrow \overline{u}^s \cdot c^{\dagger}$ Incoming anti-quark $\rightarrow \overline{v}^s \cdot c^{\dagger}$ Outgoing anti-quark $\rightarrow v \cdot c$

Incoming gluon $\rightarrow \varepsilon_{\mu} \cdot a^{\alpha}$ Outgoing gluon $\rightarrow \varepsilon_{\mu}^* \cdot a^{\alpha*}$

where u and v are the relevant Dirac spinors. In the previous c are the matrices that represent the colour:

$$\begin{pmatrix} 1\\0\\0 \end{pmatrix} \text{ for } \mathbf{R}, \begin{pmatrix} 0\\1\\0 \end{pmatrix} \text{ for } \mathbf{G}, \begin{pmatrix} 0\\0\\1 \end{pmatrix} \text{ for } \mathbf{B}$$

and a are the 8-element column matrices, one for each gluon state (i.e. α goes from 1 to 8):

 Vertices: For each vertex we note down in the diagram the coupling constant factor ≈ g_s. This factor is connected to the coupling constant via the equation

$$g_s = \sqrt{4\pi \alpha_s}$$

For a quark-gluon vertex (see fig. 3.4) the factor is of the form:

$$\frac{-ig_s}{2}\lambda^{\alpha}\gamma^{\beta}$$

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where the parameters λ^{α} are the Gell-Man λ -matrices of SU(3).

For a 3-gluon vertex (see fig. 3.4) the factor is of the form:

$$-g_{s}f^{\alpha\beta\gamma}\left[g_{\mu\nu}(\mathbf{k_{1}}-\mathbf{k_{2}})_{\rho}+g_{\nu\rho}(\mathbf{k_{2}}-\mathbf{k_{3}})_{\mu}+g_{\rho\mu}(\mathbf{k_{3}}-\mathbf{k_{1}})_{\nu}\right]$$

where the factors $f^{\alpha\beta\gamma}$ are the structure constants of SU(3) and \mathbf{k}_i are the 4-momenta of each internal line (with i = 1, 2, 3).

Finally, for a 4-gluon vertex (see fig. 3.4) the factor is of the form:

$$-ig_{s}^{2}\left[f^{\alpha\beta\eta}f^{\gamma\delta\eta}(g_{\mu\sigma}g_{\nu\rho}-g_{\mu\rho}g_{\nu\sigma})+f^{\alpha\delta\eta}f^{\beta\gamma\eta}(g_{\mu\nu}g_{\sigma\rho}-g_{\mu\sigma}g_{\nu\rho})+f^{\alpha\gamma\eta}f^{\delta\beta\eta}(g_{\mu\rho}g_{\nu\sigma}-g_{\mu\nu}g_{\sigma\rho})\right]$$

· Propagators: For each internal line, we give a factor of

$$q - \overline{q} : \frac{i(q + m)}{q^2 - m^2}$$
gluon : $-ig_{\mu\nu}\delta^{\alpha\beta}$

where $q \equiv \gamma_v q^v$.

• δ-functions and integration: The remaining steps are identical as in the general rules described before.

Figure 3.4 presents the lines for the basic particles and anti-particles but also the propagators for the strong interactions.



Fig. 3.4: The most characteristic lines for the Feynman diagrams in strong interactions.



CONFINEMENT

For small values of momentum transfer, large spatial range, the strong interactions are exceptionally strong

• Quarks are bound together within hadrons

Breaking the colour string between a quark-antiquark pair is not easy

- At some point, it is energetically more favourable to create a new pair of quarks and antiquarks
 - Quarks and gluons can not move freely









PARTICLE ACCELERATORS Studying QCD in the laboratory







PARTICLE DETECTORS pp collisions small number of particles













QCD: THE DOMINANT FORCE AT THE LHC



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Nikhef



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MULTIBODY FACET OF QCD





0:00 o*clo



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~4 decades of experimental program



EVIDENCE FOR A DENSE LIQUID

Two phenomena in particular point to the quark-gluon medium being a dense liquid state of matter: jet quenching and elliptic flow. Jet quenching implies the quarks and gluons are closely packed, and elliptic flow would not occur if the medium were a gas.





What is the nature of this primordial matter?









STUDYING PHASE TRANSITIONS IN THE LAB Pb-Pb collisions I large number of particles



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Nikhef



QCD PHASE DIAGRAM



Can we bring the QCD phase diagram at a textbook level version?





Nikhef



MSC PROJECTS

Search of the strongest magnetic field in the universe

Magnetar's field: 10^{12} - 10^{15} G



B in heavy ion collisions: 10¹⁹-10²⁰ G







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Direct searches of parity violation in QCD



Characterising the perfect liquid









MSC PROJECTS



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Simulation studies for the future HI detector





Nikhef

QCD PHASE DIAGRAM



Dutch consortium consisting of

- Experimentalists & theorists
- GW, astrophysicists, nuclear and high energy heavy-ion physicists

Some of the topics could have (direct) connections to GW physics

Full Application - NWO Open Competition Domain Science - XL, 2021-2022



NWO Open Competition Domain Science - XL Round 2021-2022

Grant application form

PART A: Scientific proposal

General information A.1

A.1.1 Grant application title

Probing the phase diagram of quantum chromodynamics











LAST TUTORIAL SESSION OF QCD Tuesday, February the 27th at 13:00

Discussion about MSc projects

My experience as a MSc student

• What to expect from a MSc project (in ALICE)

The future of (our) students after their MSc

My experience as a PhD candidate

• What does it mean to do an experimental PhD?

Paul Veen



















