Iniciación a la QCD

◇◇◇ Primera Sesión ◇◇◇

Malena Tejeda

XI Escuela de Física Fundamental

Universidad Veracruzana, Xalapa. 26 de Septiembre de 2016

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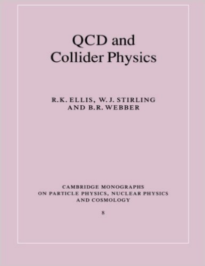
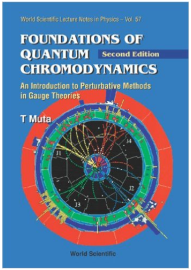
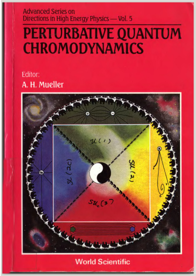
Books:







Web pages:
CTEQ: `http://users.phys.psu.edu/∼cteq/`
PDG: `http://pdg.lbl.gov`

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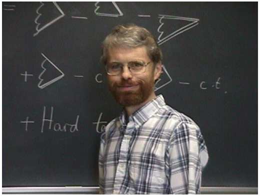
John Collins



Books

- John Collins, Foundations of Perturbative QCD (Cambridge University Press, 2011). Errata can be found here. This book is now (November 2013) available in paperback.
- John Collins, Renormalization: an introduction to renormalization, the renormalization group and the operator product expansion, (Cambridge University Press, Cambridge, 1984). Russian translation (V.A. Smirnov and O.I. Zavialov trans.) publish

Research Articles

See my profile in the INSPIRE database for a fairly complete list of my publications in elementary particle physics.

Selected publications:

- J.C. Collins and T.C. Rogers, "Understanding the large-distance behavior of transverse-momentum-dependent parton densities and the Collins-Soper evolution kernel", Phys. Rev. D91, 074020 (2015); arXiv:1412.3820.
- John Collins, "CSS Equation, etc, Follow from Structure of TMD Factorization", arXiv:1212.5974.
- S. Mert Aybat, John C. Collins, Jian-Wei Qiu, and Ted C. Rogers, "The QCD Evolution of the Sivers Function" arXiv:1110.6428.
- J. Collins, "New definition of TMD parton densities" in Proceedings of QCD Evolution workshop, Jefferson Laboratory, April 8--9, 2011, Int. J. Mod. Phys. Conf. Ser. 4, 85-96 (2011), arXiv:1107.4123.
- J. Collins, "Rapidity divergences and valid definitions of parton densities", in Proceedings of LIGHT CONE 2008 Relativistic Nuclear and Particle Physics July 7-11, 2008, Mulhouse, France, PoS LC2008:028,2008; arXiv:0808.2665.
- J.C. Collins and T.C. Rogers, "The Gluon Distribution Function and Factorization in Feynman Gauge", Phys. Rev. D77, 085009 (2008); arXiv:0805.1752.
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- John Collins and Dezhe Z. Jin, "Grandmother cells and the storage capacity of the human brain", q-bio.NC/0603014.
- John Collins, Alejandro Perez, and Daniel Sudarsky, "Lorentz invariance Violation and its Role in Quantum Gravity Phenomenology", in Quantum Gravity, D. Oriti ed. (Cambridge University Press); hep-th/0903002.
- John C. Collins, Aneesh V. Manohar, and Mark B. Wise, "Renormalization of the Vector Current in QED", Phys. Rev. D 73, 105019 (2006); hep-th/0512187.
- J.C. Collins and A. Metz, "Universality of soft and collinear factors in hard-scattering factorization", Phys. Rev. Lett. 93, 252001 (2004); e-Print archive: hep-ph/0408249.
- J. Collins, A. Perez, D. Sudarsky, L. Urrutia, and H. Vucetich, "Lorentz invariance: an additional fine-tuning problem", Phys. Phys. Rev. Lett. 93, 191301 (2004); gr-qc/0403053.
- J.C. Collins, "What exactly is a parton density?" Acta Phys. Polon. B34, 3103 (2003); e-Print archive: hep-ph/0304122
- J.C. Collins and X. Zu, "Parton Distribution Functions suitable for Monte-Carlo event generators", JHEP 06 (2002) 018 e-Print archive: hep-ph/0204127.
- J.C. Collins, "Leading-twist Single-transverse-spin asymmetries: Drell-Yan and Deep-Inelastic Scattering", Phys. Lett. B536, 43 (2002); e-Print archive: hep-ph/0204004.
- J.C. Collins and Jon Pumplin, "Tests of goodness of fit to multiple data sets", e-print archive: hep-ph/0105207.
- J.C. Collins, "Monte-Carlo Event Generators at NLO", Phys. Rev. D 65, 094016 (2002); e-Print archive: hep-ph/0110113.
- J.C. Collins, "Subtraction method for NLO corrections in Monte-Carlo event generators for leptoproduction", JHEP 05 (2000) 004; e-Print archive: hep-ph/0001040.
- L. Alvero, J.C. Collins, J. Terron and J. Whitmore, "Diffractive Hadronic Production of Jets and Weak Bosons", Phys. Rev. D59, 074022 (1999); e-print archive: hep-ph/9805268.
- J.C. Collins, "Hard-scattering factorization with heavy quarks: A general treatment", Phys. Rev. D 58, 094002 (1998); e-print archive: hep-ph/9806259.
- J.C. Collins, L. Frankfurt and M. Strikman, "Factorization for hard exclusive electroproduction of mesons in QCD", Phys. Rev. D56, 2982 (1997); e-print archive: hep-ph/9611433.
- J.C. Collins, "The Problem of Scales: Renormalization and All That", in "Theoretical Advanced Study Institute in Elementary Particle Physics, 1995: QCD and Beyond", D.E. Soper, ed., (World Scientific Singapore); e-print archive: hep-ph/951027
- X. Artru and J.C. Collins, "Measuring transverse spin correlations by 4-particle correlations in e^+ e^- to 2 jets", Z. Phys. C. 69, 277 (1996); e-print archive: hep-ph/9504220.
- J.C. Collins and D.E. Soper, "Issues in the Determination of Parton Distribution Functions", e-Print archive: hep-ph/9411214.
- CTEQ Collaboration, G. Sterman et al., ``Handbook on Perturbative QCD", Rev. Mod. Phys. 67, 157 (1995). Updated version

Current and Recent Courses

- Spring 2013: Standard Model: Phys. 542
- Fall 2013: Methods of Theoretical Physics: Phys. 525.

Software

I have developed a number of programs and other software, notably latexmk.

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Dave Soper

Other publications

1. Issues in the Determination of Parton Distribution Functions, e-Print Archive: hep-ph/9411214, (an electronic paper, not submitted to any journal), with J. C. Collins.
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10. Review of *Particle Physics, One Hundred Years of Discoveries*, by V. V. Ezhela *et al.*, Am. J. Phys. 64, 932 (1997).
11. BFKL Scattering at LEP2 and a Next e^+e^- Collider, e-Print Archive: hep-ph/9707444, in Deep Inelastic Scattering and QCD, 5th International Workshop, Chicago, April 1997, edited by J. Repond and D. Krakauer, AIP Conference Proceedings 407, 1997,
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Spain, September 1998, edited by Joan Sola (World Scientific, Singapore, 1999).
14. Hard diffraction from small size color sources, e-Print Archive: hep-ph/9905218, in *DPF 99, Proceedings of the Los Angeles Meeting*, 1999 meeting of the Division of Particles and Fields of the American Physical Society, Los Angeles, California, Januar
Z. Bern, (University of California, Los Angeles, 1999, http://www.dpf99.library.ucla.edu), with F. Hautmann and Z. Kunszt.
15. QCD calculations by numerical integration, in *`99 QCD and High Energy Hadronic Interactions*, Proceedings of the XXXIV Rencontre de Moriond, Les Arcs, France, March 1999, edited by J. Tran Thanh Van (The Gioi, Hanoi, 2001),
16. Diffractive parton distributions for a small size hadron, in *Proceedings of the 7th International Workshop on Deep Inelastic Scattering and QCD (DIS 99)*, Zeuthen, Germany, April 1999, Nucl. Phys. B (Proc. Sup.) 79, 260 (1999), with F. Hautmann and Z
17. QCD calculations by numerical integration, in *Proceedings of the 7th International Workshop on Deep Inelastic Scattering and QCD (DIS 99)*, Zeuthen, Germany, April 1999, Nucl. Phys. B (Proc. Sup.) 79, 444 (1999), edited by J. Bluemlein and T. Riem
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19. The QCD and standard model working group: summary report, e-Print Archive: hep-ph/0005114, from *Les Houches Workshiop on Physics at TeV Colliders*, June 1999, (unpublished), S. Catani *et al.*, 30 authors in all.
20. Heavy quark production, e-Print Archive: hep-ph/0005112 and hep-ph/0006300, from *Parton distributions working group*, edited by L. de Barbaro *et al.*, in *Physics at Run II: QCD and Weak Boson Physics Workshop*, (Fermilab, Chicago, 2000), R. Derni
21. QCD, e-Print Archive: hep-ph/0005025, in *Standard model physics (and more) at the LHC*, edited by G. Altareli and M. Mangano (CERN, Geneva, 2000), with S. Catani *et al.*, 63 authors in all.
22. Basics of QCD perturbation theory, e-Print Archive: hep-ph/0011256, in *Advanced Study Institute in Elementary Particle Physics (TASI 2000): Flavor Physics for the Millennium*, Boulder, 2000, edited by J. Bagger (World Scientific, Singapore, 2001).
23. Letting real-virtual cancellations happen by themselves in QCD calculations, e-Print Archive: hep-ph/0102031, in *Proceedings of the 5th International Symposium on Radiative Corrections (RADCOR-2000)*, Carmel, 2000, edited by H.~Haber, eConf C00
24. Using Coulomb gauge for next-to-leading order numerical calculations, in *Proceedings of the International Conference on High Energy Physics 2002*, Amsterdam, July, 2002, (Elsvier Science BV, 2003).
25. Partons and jets at the LHC, e-Print Archive: hep-ph/0308233, in *Proceedings of the conference QCD 2002* , Indian Institute of Technology, Kanpur, India, November 2002, edited by P. Jain, Pramana 61, 785 (2003).
26. QCD theory at the XL Rencontre de Moriond: Fish eyes and physics, e-Print Archive: hep-ph/0506069, to be published in *40th Rencontres de Moriond on QCD and High Energy Hadronic Interactions*, La Thuile, Aosta Valley, Italy, 12-19 Mar 2005.
27. A new parton shower algorithm: Shower evolution, matching at leading and next-to-leading order level, e-Print Archive: hep-ph/0601021, in *Proceedings of Ringberg Workshop on New Trends in HERA Physics 2005*, Ringberg Castle, Tegernsee, German
28. QCD and Monte Carlo event generators, in *Deep Inelastic Scattering, DIS 2006* , Proceedings of the 14th International Workshop, Tsukuba, Japan, April 2006, edited by Masahiro Kuze, Kunihiro Nagano, and Katsuo Tokushuku (World Scientific, Singap
ph/0607046, with Z. Nagy.
29. MSbar quark distribution and dipole scattering matrix elements at high energy, in *Photon 2007 International Conference*, Paris, France, July 2007, (to be published), e-Print at arXiv:0712.0526 [hep-ph], with F. Hautmann.
30. The NLO multileg working group: summary report, in *5th Les Houches Workshop on Physics at TeV Colliders*, Les Houches, France, June 2007, (published using arXiv), e-Print at arXiv:0803.0494 [hep-ph], with Z. Bern *et al.* (47 authors).
31. Structure of parton showers including quantum interference, in *43rd Rencontres de Moriond on QCD and High Energy Interactions*, La Thuile, Italy, March 2008, (to be published) e-Print at arXiv:0805.4371 [hep-ph], with Z. Nagy.
32. Jet Substructure at the Tevatron and LHC: New results, new tools, new benchmarks, in *Boost 2011 Workshop*, Princeton, May 2011, e-Print at arXiv:1201.0008 [hep-ph], J. Phys. G 39, 063001 (2012), with A. Altheimer *et al.* (71 authors).
33. Through a glass, darkley: theory summary, in *46th Rencontres de Moriond on QCD and High Energy Interactions*, La Thuile, Italy, March 2012, E. Augé, J. Dumarchez, B. Pietrzyk and J. Trân Thanh Vân, eds., (ARISF, Paris, 2012), e-Print at arXiv:120
34. Jets and QCD, in E. M. Henley and S. D. Ellis, eds., *100 Years of Subatomic Physics* (World Scientific, Singapore, 2013), with S. D. Ellis.
35. Deeply inelastic dark matter: Beam dumps as WIMP cannons, Frascati Phys. Ser. 56, 258 (2012), C. J. Wallace, M. Spannowsky and T. M. P. Tait.

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Joey Huston

Below is a picture of the ATLAS experiment at CERN.

If you want to keep track of the daily progress of the installation, click on this website.

Useful links:

CTEQ: a collaboration of experimentalists and phenomenologists of which I am co-spokesman. CTEQ produces one of the two most widely used sets of parton dist

Hard Interactions of Quarks and Gluons: A Primer for LHC Physics by J. Campbell, J. Huston and W.J. Stirling
This has been one of the most downloaded articles in Reports on Progress in physics this past year.

Jets in Hadron-Hadron Collisions by S. Ellis, K. Hatakeyama, J. Huston, P. Loch, M. Toennesmann
To be published in Progress in Particle and Nuclear Physics

SpartyJet: a program to facilitate physics analyses involving jets; in use in CDF and ATLAS. S

Les Houches: Physics at TeV Colliders; a series of workshops at Les Houches that I have helped organize dealing with hadron collider physics at both the Tevatron

TeV4LHC: using the data and experience at the Tevatron to prepare for the LHC. The QCD writeup can be found here.

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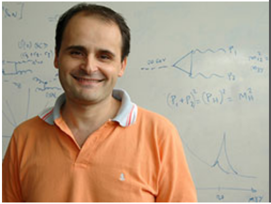
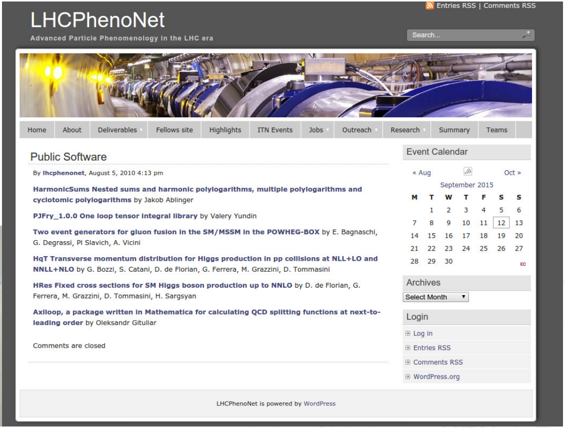
Daniel de Florian





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Nigel Glover

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Nigel Glover

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Professor Nigel Glover FRS
Fellow

Elected:
2013

Contact:

ORCID 0000-0002-0173-4175

Biography

Nigel Glover conducts research on the phenomenology of particle physics — the application of theoretical physics to making precise predictions for particle physics experiments. His calculations based on quantum chromodynamics — the theory of the strong nuclear force — are particularly important to measurements made at the Large Hadron Collider. Such measurements are providing insights into the fundamental nature of matter.

Calculations in quantum theory relating to complex systems often require perturbative methods — adding corrections to a well-understood simpler model. Nigel has been especially innovative in developing new techniques to enable more precise calculations, such as second-order corrections to scattering cross sections — a measure of the likelihood of deflection of a beam of particles from a target.

Nigel is a past recipient of a Royal Society Wolfson Research Merit Award. His research career has included positions at two major international accelerator laboratories — CERN in Europe and Fermilab in the United States. Nigel currently holds a European Research Council Advanced Grant (MC@NNLO) and coordinates the Marie Curie Initial Training Network, HiggsTools.

Hide full biography

Interests and expertise

Subject groups
Astronomy and physics
- Elementary particle physics

Keywords
Electroweak interaction, Elementary particles, Higgs bosons, Particle accelerators, Quantum chromodynamics, Quarks

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Nigel Glover

higgstools

HiggsTools

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About

- Partners
- Objectives of the Training Programme
- Objectives of the Research Programme
- ESRs
- Senior Scientists

About

This is the web site of HiggsTools, an Initial Training Network (ITN) supported by the 7th Framework Programme of the European Commission.

The network contract PITN-GA-2012-316704 was concluded between the European Commission and the consortium on 1st January 2014 with duration of 48 months.

Partners

HiggsTools consists of 10 Full Partners and 10 Associated Partners from European Universities and Research Institutes, one International Organisation (CERN), and 4 Associated Partners from the private sector.

Objectives of the Training Programme

The main goal of the project is to provide excellent initial training to young researchers in the field of high energy particle physics, paving the road for new discoveries about the fundamental nature of the Universe at a time when new discoveries are expected, and when the new Standard Model of Particle Physics is going to be forged.

Objectives of the Research Programme

The research goal of HiggsTools is the investigation of electroweak symmetry breaking. This question lies at the very frontier of knowledge of theoretical particle physics and phenomenology and, in fact, the primary goal of the Large Hadron Collider (LHC) at CERN is to unveil the mechanism of electroweak symmetry breaking.

During the period of the network it is certain that the mechanism of electroweak symmetry breaking will be further decoded and that the theoretical ideas that date back to 1964 will either be confirmed or supplemented through the discovery of new additional particles that contribute to it. The experiments at the LHC have already made an impressive step forward in answering this question, by discovering a particle that is looking more and more like a Higgs boson. It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, or possibly the lightest of several bosons predicted in some theories that go beyond the Standard Model. Finding the answer to this question will take time. The outcome of the Higgs studies at the LHC will either carve our present understanding of electroweak interactions in stone or will be the beginning of a theoretical revolution.

Positions

We will therefore create a cohort of 21 early-stage researchers (ESR) who will all be in the network for the same 36 month period and therefore

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George Sterman


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2003 J.J. Sakurai Prize for Theoretical Particle Physics Recipient

George Sterman
State University of New York, Stony Brook

Citation:

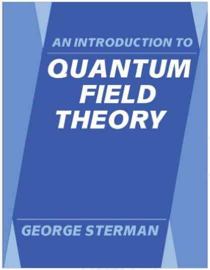
"For developing concepts and techniques in QCD, such as infrared safety and factorization in hard processes, which permitted precise quantitative predictions and experimental tests, and thereby helped to establish QCD as the theory of the strong interactions."

Background:
George Sterman received an A.B. in 1968 from the University of Chicago, where he attended lectures of J.J. Sakurai. He received his doctorate from the University of Maryland in 1974, and held research associate postitions at the University of Illinois (1974-1976), Stony Brook University (1976-1978), and the Institute for Advanced Study (1978-1979), before joining the faculty of the C.N. Yang Institute for Theoretical Physics at Stony Brook in 1979. He became director of the Institute in 2001.

His research interests are centered on how the complex outcomes observed in collision experiments arise in quantum field theories. This led to the development of the concept of infrared safety with Steven Weinberg, the prrof of the infrared finiteness of jet cross sections, and the formulation and proof of factorization theorems with Stephen Libby, and with John Collins and Davison E. Soper. In recent years he has developed ideas on the summation of large corrections to all orders in perturbation theory, and has formulated tools to relate perturbative and nonperturbative descriptions of quantum chromodynamics and other field theories.

He received a Guggenheim Fellowship (1985), is a Fellow of the American Physical Society, and has served as Divisional Associate Editor for Physical Review Letters. He is a member of the Coordinated Experimental-Theoretical Project on QCD (CTEQ) and has helped organize many CTEQ summer schools.

Selection Committee:
Roberto Peccei (Chair), Boris Kayser (vice-chair), Estia Eichten, Lynne Orr, Mikhail Voloshin



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These three lectures following:

- *Introduction to QCD* by Michelangelo L. Mangano (CERN, TH Division, Geneva, Switzerland)
- CTEQ web page `http://www.physics.smu.edu/scalise/cteq/`: lectures, handbook, pdfs

I am using a Beamer Theme FLIP 2012 by Flip Tanedo (distributed under the LaTeX Project Public License and under the GNU Public License)

3 lectures: *three quarks for Muster Mark!*

Lecture 1:

- QCD at the LHC
- Gauge invariance and Feynman rules for QCD

Lecture 2:

- Renormalization and running α_s
- pQCD in e^+e^--collisions: from partons to hadrons, jets, shape variables

Lecture 3:

- pQCD in lepton-hadron collisions: DIS and parton evolution
- pQCD at the LHC

√ Overlap with other lectures is unavoidable.

√ As with other things in life, the U and everything:

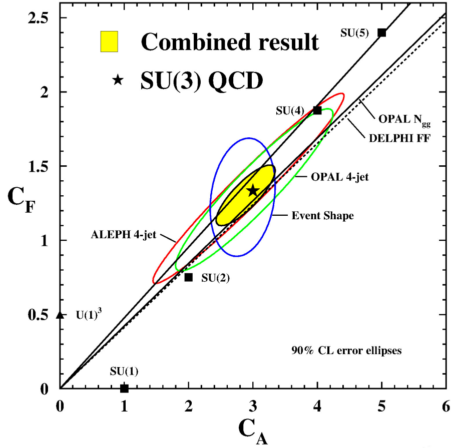
overlap is good :)

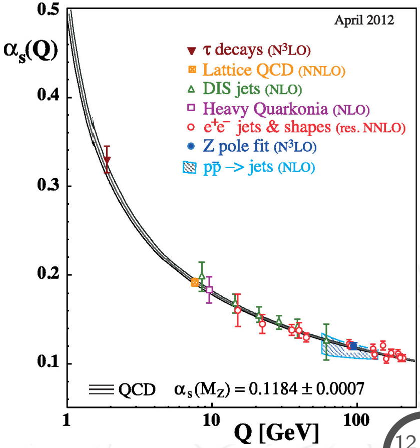
Status of pQCD

Tests of QCD dynamics at e^+e^- colliders, S. Kluth
Rept.Prog.Phys.69:1771-1846 (2006) `arXiv:hep-ex/0603011`
PDG `pdg.lbl.gov`

It is now carved in stone

- QCD: Nature favours $SU(3)$ gauge theory
- α_{QCD} running from all sorts of expmts and E scales

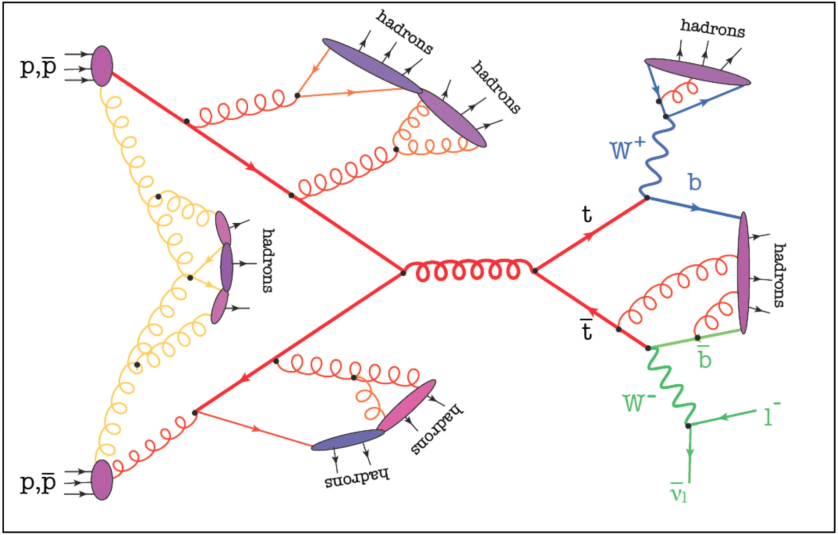




Why do we keep QCDing?

Physics@Colliders
cannot be done with quantitative seriousness
without pQCD beyond LO

QCD at the LHC



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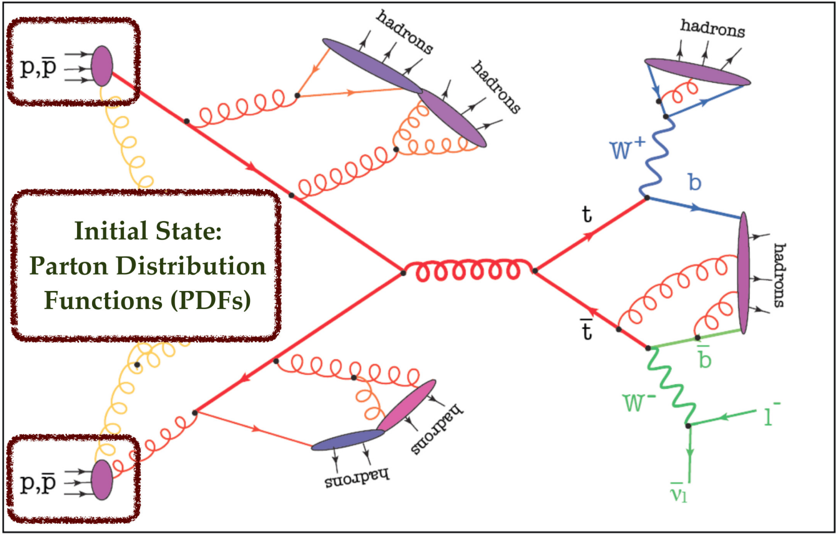
Juan Rojo La Thuile, 25/02/2014

QCD at the LHC



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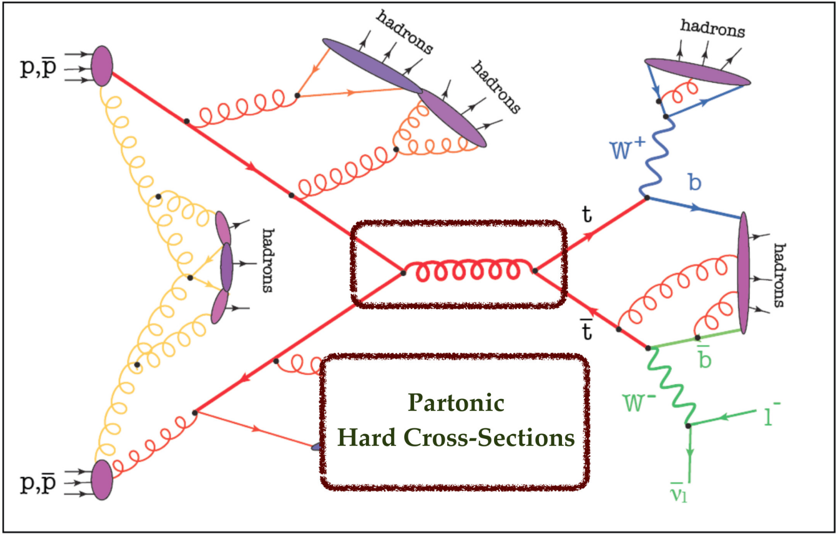
QCD at the LHC



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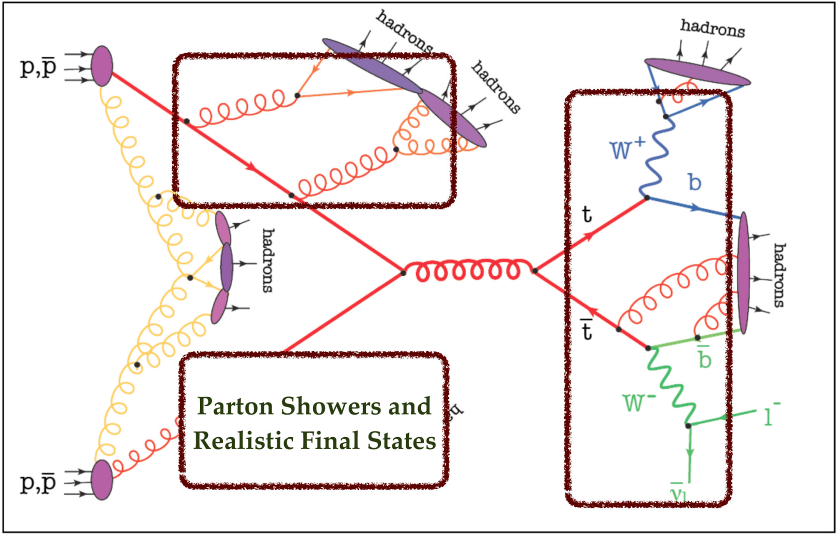
QCD at the LHC



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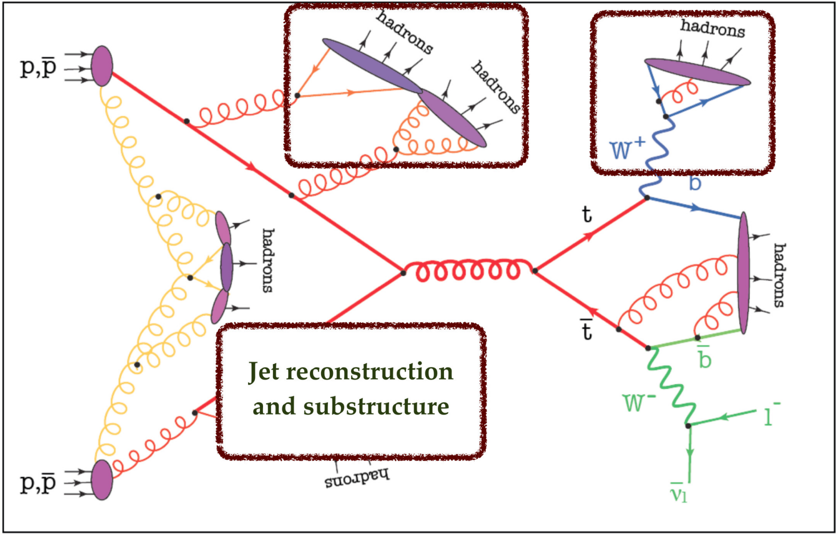
QCD at the LHC



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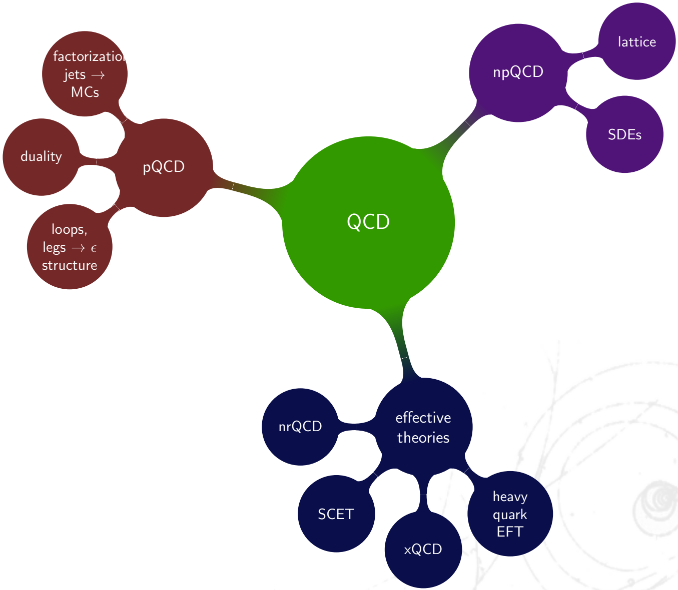
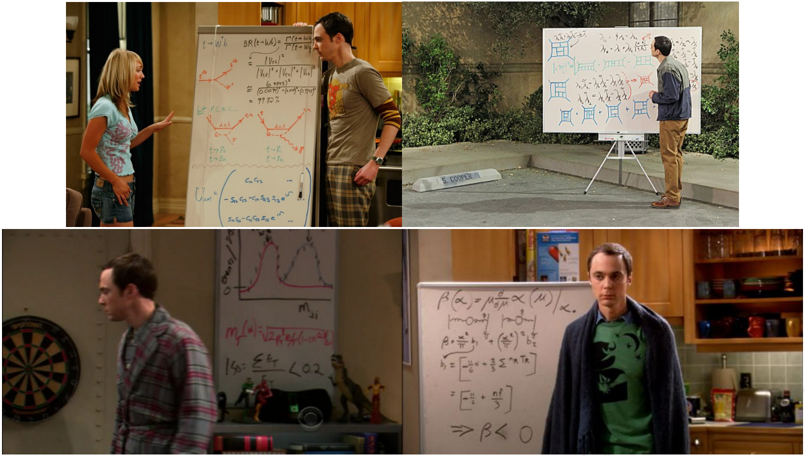
Why do we keep QCDing?

Physics@Colliders
cannot be done with quantitative seriousness
without pQCD beyond LO
but also
QCD is at the heart of everything!

QCD, QCD-style, QCD-ish, QCD-related



Yes, it is also on Sheldon's white boards



And in card games

http://www.jicfus.jp/en/promotion/pr/quark-card-dealer/

Quantum Chromodynamics (QCD)

- Theory of strong interactions.
- Formulated in terms of elementary fields (quarks and gluons), whose interactions obey the principles of a relativistic QFT, with a non-abelian gauge invariance SU(3).
- Emergence of QCD as theory of strong interactions could be reviewed historically, analyzing the various experimental data and the theoretical ideas available in the years 1960 - 1973 Personally recommend:

QCD today

huge set of subjects describes/feeds from huge sets of data

structure/distribution functions

deep-inelastic scattering (DIS)

sum rules, polarized DIS

small x physics (hard pomerons, diffraction)

LEP, LHC, RHIC,...

Still relevant to ask

- What are the fundamental notions of QCD?
- What are its fundamental applications?
- Do we get to learn from QCD via QED or do we learn from dual theories?

3 lectures, a lifetime

```
do until (observable is well described)
> start somewhere(else) in the theory
> get basic tools to calculate (new)observables
> look at (new)data and compare
enddo
```

3 lectures, a lifetime

pQCD: Feynman diag + reg/ren

do until (observable is *well* described)

> start somewhere(else) in the **theory**

> get basic tools to calculate **(new)observables**

> look at **(new)data and compare**

enddo

e^+e^-, pp, e^-p

$d\sigma$, $d\Gamma$, dN

Start somewhere

Imagine we know all about how

- √ hadrons are made of quarks
- √ quarks are spin-1/2, colour-triplet fermions
- √ quarks interact by exchange of an octet of spin-1 gluons
- √ running couplings: interaction strength not constant
- √ asymptotic freedom/confinement: quarks are free within hadron scale and not beyond
- √ familiarity with the fundamental ideas and formalism of QED: Feynman rules, renormalization, gauge invariance

Feynman rules for QED

Obtained from the Lagrangian:

$$\mathcal{L} = \overline{\psi}(i\partial\!\!\!/ - m)\psi - e\overline{\psi}A\!\!\!/\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \qquad (1)$$

where ψ is the electron field, of mass m and coupling constant e, and $F_{\mu\nu}$ is the electromagnetic field strength.

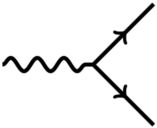
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu. \qquad (2)$$

Feynman rules for QED

The resulting Feynman rules are summarized

$$= \frac{i}{\not{p} - m + i\epsilon} = \frac{\not{p} + m}{p^2 - m^2 + i\epsilon} \qquad (3)$$

$$= -i\frac{g_{\mu\nu}}{p^2 + i\epsilon} \text{ (Feynman gauge)} \qquad (4)$$

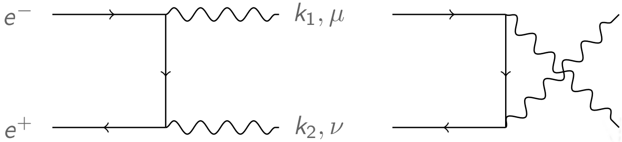


$$= -ie\gamma_\mu Q \qquad (5)$$

$Q = -1$ for the electron $Q = 2/3$ for the u quark, etc.

A basic QED process

$e^+e^- \to \gamma\gamma$ (for simplicity we shall always asume $m = 0$)



$$= D_1 + D_2 \quad (6)$$

A basic QED process

The total probability amplitude $\mathcal{M}_\gamma$ is given by:

$$\begin{aligned} \frac{i}{e^2}\mathcal{M}_\gamma &\equiv D_1 + D_2 \\ &= \overline{v}(\overline{q})\not{\epsilon}_2 \frac{1}{\not{q}-\not{k}_1}\not{\epsilon}_1 u(q) + \overline{v}(\overline{q})\not{\epsilon}_1 \frac{1}{\not{q}-\not{k}_2}\not{\epsilon}_2 u(q) \\ &\equiv \mathcal{M}_{\mu\nu}\epsilon_1^\mu \epsilon_2^\nu \end{aligned} \tag{7}$$

Gauge invariance

Demands that

$$\epsilon_2^\nu \partial^\mu \mathcal{M}_{\mu\nu} = \epsilon_1^\mu \partial^\nu \mathcal{M}_{\mu\nu} = 0 \tag{8}$$

$\mathcal{M}_\mu \equiv \mathcal{M}_{\mu\nu}\epsilon_2^\nu$ current that couples to the photon k_1.

A basic QED process: gauge invariance

Charge conservation requires $\partial_\mu \mathcal{M}^\mu = 0$:

$$\partial_\mu \mathcal{M}^\mu = 0 \Rightarrow \int \partial_0 \mathcal{M}^0 d^3x = \int \nabla \cdot \vec{\mathcal{M}} d^3x = \int_{S\longrightarrow\infty} \vec{\mathcal{M}} d\vec{\Sigma} = 0 \tag{9}$$

In momentum space, this means

$$k_1^\mu \mathcal{M}_\mu = 0. \tag{10}$$

i.e. theory is invariant if $\epsilon_\mu(k) \longrightarrow \epsilon_\mu(k) + f(k)k_\mu$.

This is the standard Abelian gauge invariance associated to the vector potential transformations:

$$A_\mu(x) \longrightarrow A_\mu(x) + \partial_\mu f(x) \tag{11}$$

A basic QED … ess: gauge invariance

- $\mathcal{M}_\gamma$ is …
- D_1 … lly gauge invariant.
- Ga… ndependent of ϵ_2 choice
- So … ev… for non-tranverse photons.

Homewo… ed gauge invariant.
Use $\not{q}u$ … e Dirac equation

$$k_1^\mu \epsilon \ldots (\not{k}_1 - \not{q})u(q)$$

$$\ldots \frac{1}{\ldots_1 - \bar{q}} \not{\epsilon}_2 u(q)$$

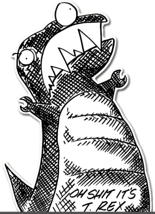
$$\ldots(\bar{q})\not{\epsilon}_2 u(q) = 0$$

A basic QED process: gauge invariance

- $\mathcal{M}_\gamma$ is gauge invariant.
- D_1 and D_2 are NOT individually gauge invariant.
- Gauge invariance realisation independent of ϵ_2 choice
- So $\mathcal{M}_\gamma$ is gauge invariant even for non-transverse photons.

Homework: check that $\mathcal{M}_\gamma$ is indeed gauge invariant.
Use $\not{q}u(q) = \overline{v}(\overline{q})\not{\overline{q}} = 0$ from the Dirac equation

$$\begin{aligned} k_1^\mu \epsilon_2^\mu M_{\mu\nu} &= \overline{v}(\overline{q})\not{\epsilon}_2 \frac{1}{\not{q} - \not{k}_1}(\not{k}_1 - \not{q})u(q) \\ &\quad + \overline{v}(\overline{q})(\not{k}_1 - \overline{q})\frac{1}{k_1 - \overline{q}}\not{\epsilon}_2 u(q) \\ &= -\overline{v}(\overline{q})\not{\epsilon}_2 u(q) + \overline{v}(\overline{q})\not{\epsilon}_2 u(q) = 0 \qquad (12) \end{aligned}$$



From Abelian to Non-Abelian gauge invariance

- $\surd$ generalize QED to a theory where 'electrons' carry a non Abelian charge: 'colour'
- $\rightarrow$ transform under a non trivial representation R of a non-Abelian group G (typically $SU(N)$ type)

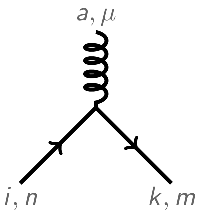
Splash of GT

Current operator belongs to the product $R \otimes \overline{R}$. The only rep that belongs to $R \otimes \overline{R}$ for any R is the adjoint rep. So field that couples to colour current must transform as the adjoint rep of the group G.

Generalization of photon field to non-Abelian symmetry is a set of vectors fields transforming under the adjoint of G

From Abelian to Non-Abelian gauge invariance

Simplest generalization of the coupling to fermions takes the form:



$$= ig\lambda^a_{ki}\gamma^\mu_{mn} \tag{13}$$

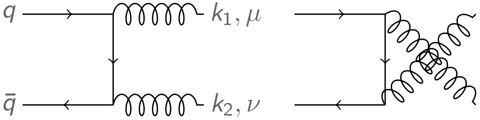
matrices λ^α algebra of the group on the rep R:

$$[\lambda^a, \lambda^b] = if^{abc}\lambda^c \tag{14}$$

characterized by a unique set of structure constants f^{abc}
Quark (q) fermion fields in R
Gluons (g) vector fields couple to the quark colour current

Non-Abelian version of $e^+e^- \longrightarrow \gamma\gamma$

Is $q\overline{q} \longrightarrow gg$ annihilation. Which diagrams?



Amplitude can be evaluated using λ matrices in Eq. (6):

$$\frac{i}{e^2}\mathcal{M}_\gamma \longrightarrow \frac{i}{g^2}\mathcal{M}_g \equiv (\lambda^b\lambda^a)_{ij}D_1 + (\lambda^a\lambda^b)_{ij}D_2 \qquad (15)$$

with (a, b) colour labels (i.e. group indices)of gluons 1 and 2, (i, j)colour labels of $\overline{q}$, q, respectively. Using Eq. (14), we can rewrite (15)as:

$$\mathcal{M}_g = (\lambda^a\lambda^b)_{ij}\mathcal{M}_\gamma - f^{abc}\lambda^c_{ij}D_1. \qquad (16)$$

$e^+e^- \longrightarrow \gamma\gamma$ vs $q\overline{q} \longrightarrow gg$

If we want the charge associated with the group G to be conserved, we still need to demand

$$k_1^\mu \epsilon_2^\nu \mathcal{M}_g^{\mu\nu} = \epsilon_1^\mu k_2^\nu \mathcal{M}_g^{\mu\nu} = 0. \tag{17}$$

Substituting $\epsilon_1^\mu \longrightarrow k_1^\mu$ in (16) we get instead, using (12):

$$k_{1\mu} \mathcal{M}_g^\mu = -g^2 f^{abc} \lambda_{ij}^c \overline{v}_i(\overline{q}) \not{\epsilon}_2 u_i(q) \tag{18}$$

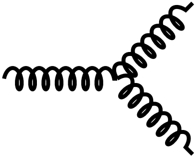
The gauge cancellation taking place in QED between the two diagrams is spoiled by the non-Abelian nature of the coupling of quarks to gluons (i.e. λ^a and λ^b do not commute, and $f^{abc} \neq 0$).

Non-Abelian gauge invariance and new intn terms

Gluons are charged (i.e. they transform under the symmetry group) so new interaction is possible! Factorize (18) as follows:

$$k_{1\mu}\mathcal{M}_g^{\mu} = i\left(f^{abc} g\epsilon_2^{\mu}\right) \times \left(ig\lambda_{ij}^{c}\overline{v}(\overline{q}\gamma_{\mu}u(q)\right) \qquad (19)$$

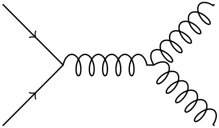
we can recognize in the second factor the estructure of the $q\overline{q}g$ vertex. The first factor has the appropiate colour structure to describe a triple-gluon vertex, with a, b, c the colour labels of the three gluons:



$$= gf^{abc}V_{\mu_1\mu_2\mu_3}(k_1, k_2.k_3) \qquad (20)$$

$q\overline{q} \longrightarrow gg$ has an extra diagram!

Eq. (19) therefore suggests the existence of a coupling like (20), with a Lorentz structure $V_{\mu_1\mu_2\mu_3}$ to be specified, giving rise to the following contribution to $q\overline{q} \longrightarrow gg$:



$$= \quad -ig^2 D_3 = (ig\lambda^a_{ij})\overline{v}(\overline{q})_i\gamma^\mu u(q)_j\left(\frac{-i}{p^2}\right)$$

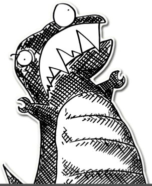
$$= \quad egf^{abc}V_{\mu\nu\rho}(-p, k_1, k_2)\epsilon_1^\nu(k_1)\epsilon_2^\rho(k_2) \quad (21)$$

Q. Who is this $V_{\mu_1\mu_2\mu_3}(p_1, p_2 p_3)$?
R. LI, Bose symmetry and dimensional analysis uniquely fix V, up to an overall constant.
Q. D_3 in $k_1 \cdot \mathcal{M}_g$ cancels that of the first two diagrams?
R. Yes!

Who is this *triple gluon vertex* (TGV)?

- Dim analysis fixes the coupling to be linear in the gluon momenta: $[A][A][A] = 3$ but $[TGV] = 4$
- So at most one derivative (i.e. one power of momentum) inside TGV
- LI requires V built with $g_{\mu_1\mu_2}\ p_{\mu_3}$
- Bose symmetry requires V to be fully antisymmetric under the exchange of any pair $(\mu_i, p_i) \longleftrightarrow (\mu_j, p_j)$ since f^{abc} is totally antisymmetric

Homework: why?



Who is this *triple gluon vertex*?

Unique and fully antisymmetric in all three indices, up to an overall factor:

$$V_{\mu_1\mu_2\mu_3} = V_0[(k_1 - k_2)^{\mu_3} g_{\mu_1\mu_2} + (k_2 - k_3)^{\mu_1} g_{\mu_2\mu_3} + (k_3 - k_1)^{\mu_2} g_{\mu_1\mu_3}] \quad (2$$

Set $\mu_3 = \mu, \epsilon_1 = k_1, k_3 = -(k_1 + k_2)$

$$k_1^{\mu_1} \epsilon_2^{\mu_2} V_{\mu_1\mu_2\mu} = V_0[-(k_1 + k_2)^{\mu}(k_1 \cdot \epsilon_2) + 2(k_1 \cdot k_2)\epsilon_2^{\mu} - (k_2 \cdot \epsilon_2)k_1^{\mu}] \quad (23$$

Non-Abelian gauge invariance

D_3's gauge variation:

$$k_1 \cdot D_3 = g^2 f^{abc} \lambda^c V_0 \left[\overline{v}(\overline{q}) \not{\epsilon}_2 u(q) - \frac{k_2 \cdot \epsilon_2}{2 k_1 k_2} \overline{v}(\overline{q}) \not{k}_1 u(q) \right] \tag{24}$$

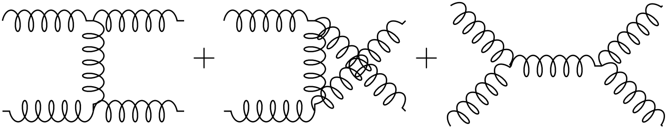
cancels the gauge var $D_1 + D_2$ for $V_0 = 1$

vanishes for physical gluon $k_2 \cdot \epsilon_2 = 0$

$D_1 + D_2 + D_3$ is gauge invariant (unlike QED) only for physical external on-shell gluons.

How about $gg \longrightarrow gg$?

With TGV we can induce process involving only gluons, such as $gg \longrightarrow gg$:



(25)

Story repeats itself:

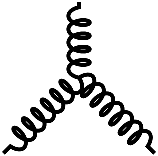
Verify gauge invariance $\rightsquigarrow$ need D_4 $\rightsquigarrow$ 4-gluon vx. LI, Bose symm and dim analysis fix it uniquely.

Gauge invariance and Feynman rules

$$= \quad \delta^{ab}\frac{-ig^{\alpha\beta}}{p^2 + i\epsilon}$$

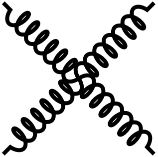
$$= \quad \delta^{ab}\frac{i}{p^2 + i\epsilon}$$

$$= \quad \delta^{ik} \left.\frac{i}{p^2 - m + i\epsilon}\right|_{mn}$$



$$= \quad gf^{abc}\left[g^{\alpha\beta}(p-q)^{\gamma} + g^{\beta\gamma}(q-r)^{\alpha} + g^{\gamma\alpha}(r-p)^{\beta}\right]$$

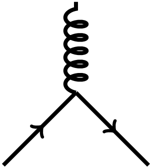
Gauge invariance and Feynman rules



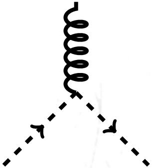
$$= \quad -ig^2 f^{xac} f^{xbd} \left(g^{\alpha\beta} g^{\gamma\delta} - g^{\alpha\delta} g^{\beta\gamma}\right)$$

$$- \quad ig^2 f^{xad} f^{xbc} \left(g^{\alpha\beta} g^{\gamma\delta} - g^{\alpha\gamma} g^{\beta\delta}\right)$$

$$- \quad ig^2 f^{xab} f^{xcd} \left(g^{\alpha\gamma} g^{\beta\delta} - g^{\alpha\delta} g^{\beta\gamma}\right)$$



$$= \quad ig\lambda^a_{ki} \gamma^\alpha_{mn}$$



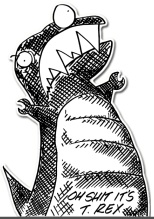
$$= \quad -gf^{abc} q^\alpha$$

Gauge invariance and Feynman rules

3-and 4-gluon vertices arise from the Yang-Mills Lagrangian:

$$\mathcal{L}_{YM} \;=\; -\frac{1}{4}\sum_a F^a_{\mu\nu}F^{a\mu\nu} \quad \text{with} \quad F^a_{\mu\nu}F = \partial_{[\mu}A^a_{\nu]} - gf^{abc}A^b_{[\mu}A^c_{\nu]} \tag{26}$$

Homework:
Why no $(n > 4)$-gluon vertex?



tree level: dimensional analysis +
locality of the couplings
loop level: renormalizability of
the theory

3 lectures: *three quarks for Muster Mark!*

Lecture 1:

- QCD at the LHC
- Gauge invariance and Feynman rules for QCD

Lecture 2:

- Renormalization and running α_s
- pQCD in e^+e^--collisions: from partons to hadrons, jets, shape variables

Lecture 3:

- pQCD in lepton-hadron collisions: DIS and parton evolution
- pQCD at the LHC

$\surd$ Overlap with other lectures is unavoidable.

$\surd$ As with other things in life, the U and everything:

overlap is good :)