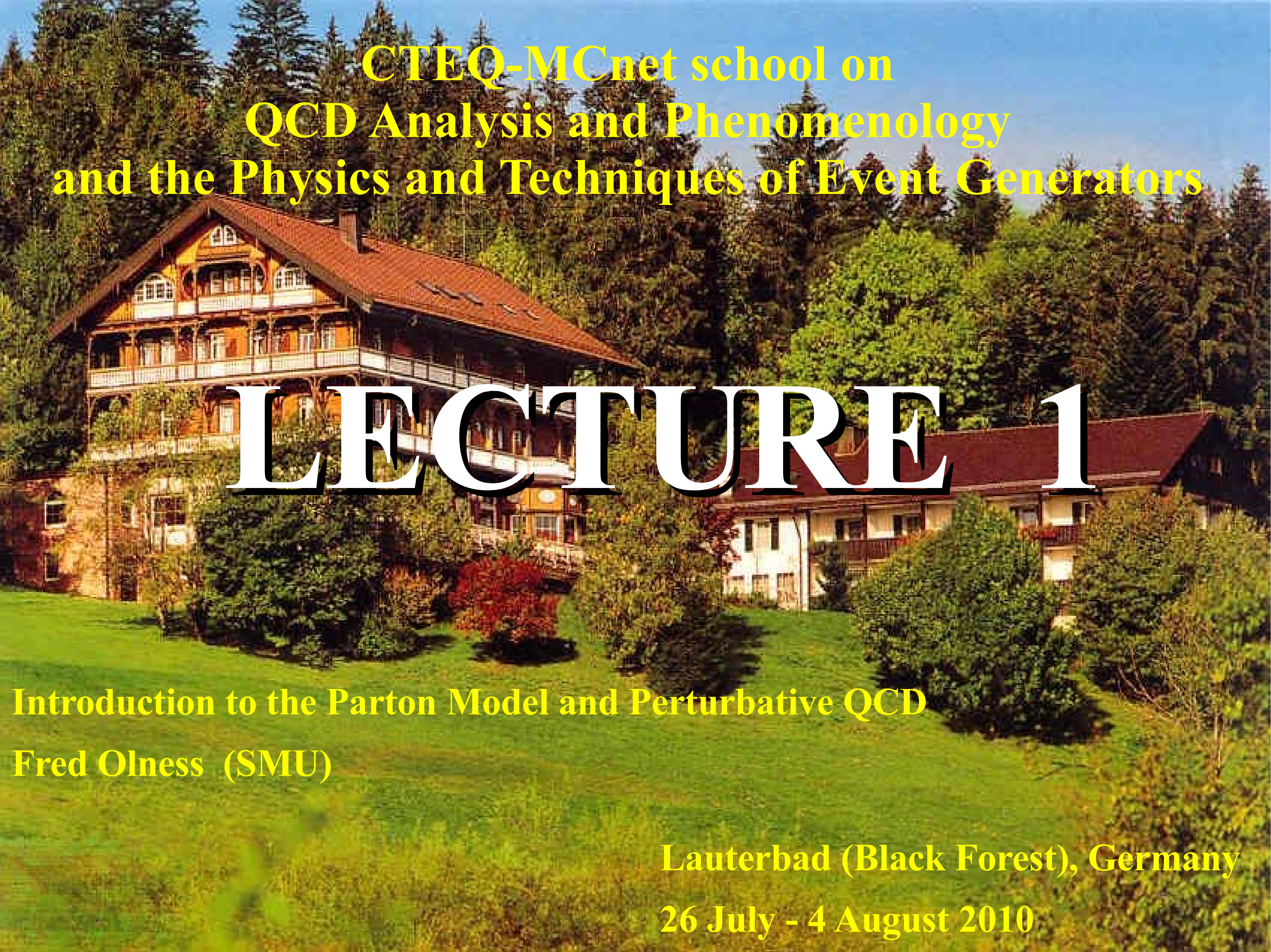


CTEQ-MCnet school on QCD Analysis and Phenomenology and the Physics and Techniques of Event Generators

LECTURE 1

Introduction to the Parton Model and Perturbative QCD

Fred Olness (SMU)

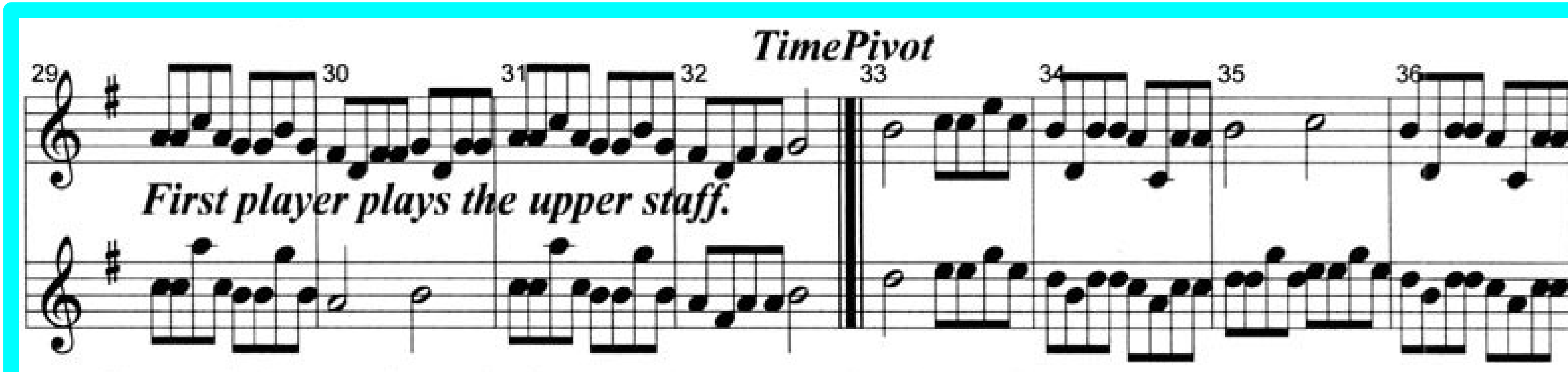
Lauterbad (Black Forest), Germany

26 July - 4 August 2010

Introduction:

Welcome to QCD:

$$
\begin{aligned}
\mathcal{L}_{\mathrm{QCD}} &= \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a \\
&= \bar{\psi}_i (i\gamma^\mu \partial_\mu - m)\psi_i - g G^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a \,,
\end{aligned}
$$



Mozart: Inverted retrograde canon in G

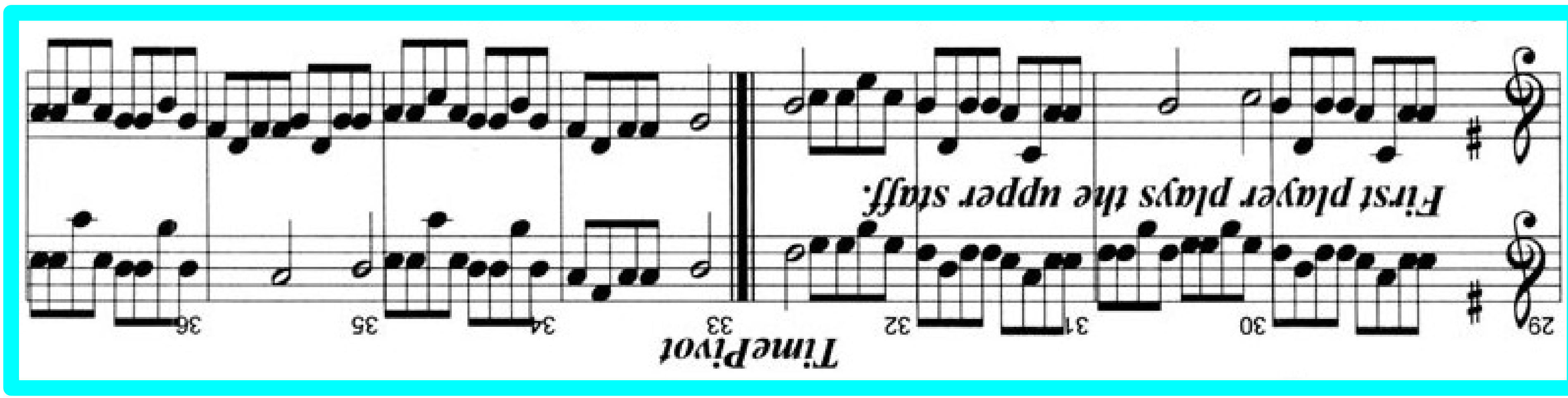
Patterns, Symmetry (obvious & hidden), interpretation

Notes $\Rightarrow$ themes $\Rightarrow$ Melody/Harmony $\Rightarrow$ interaction/counterpoint $\Rightarrow$ structure

Welcome to QCD:

$$\mathcal{L}_{\rm QCD} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

$$= \bar{\psi}_i (i\gamma^\mu \partial_\mu - m)\psi_i - g G^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a \,,$$



Mozart: Inverted retrograde canon in G

Patterns, Symmetry (obvious & hidden), interpretation

Notes $\Rightarrow$ themes $\Rightarrow$ Melody/Harmony $\Rightarrow$ interaction/counterpoint $\Rightarrow$ structure

The Game

Fields → Lagrangian ← Symmetry

Lagrangian

↓

Perturbation Theory Rules

↓

Greens Functions

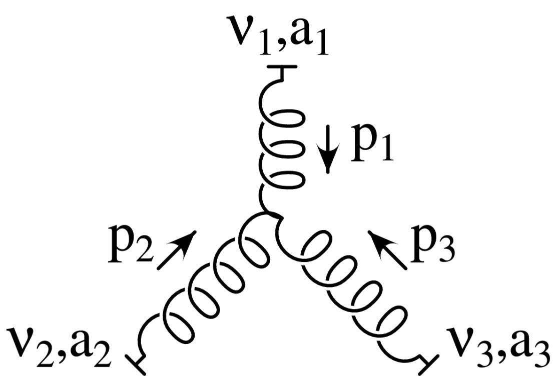
↓

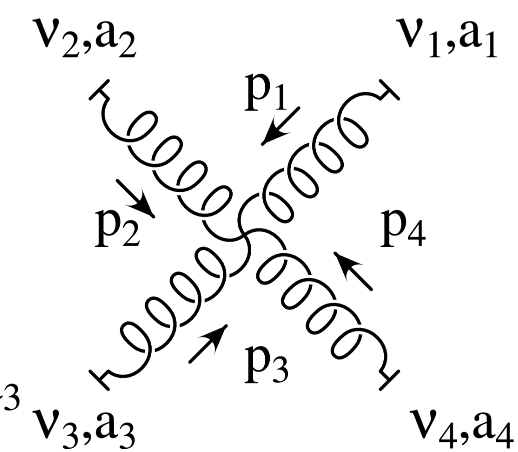
S-Matrix

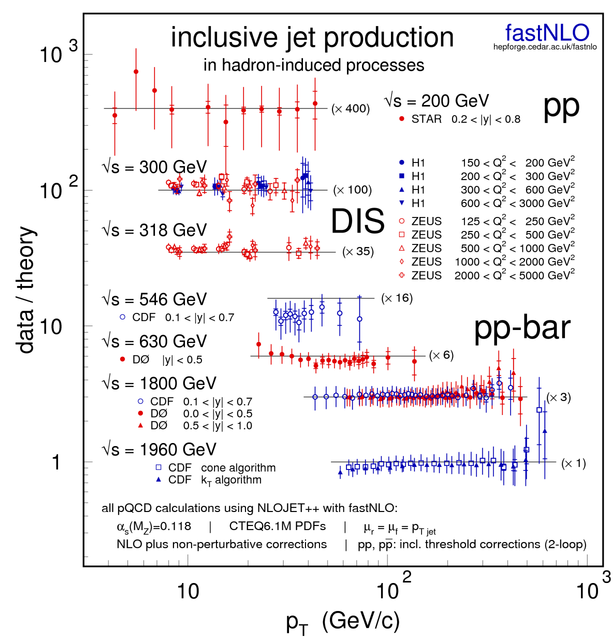
↓

Cross sections Observables

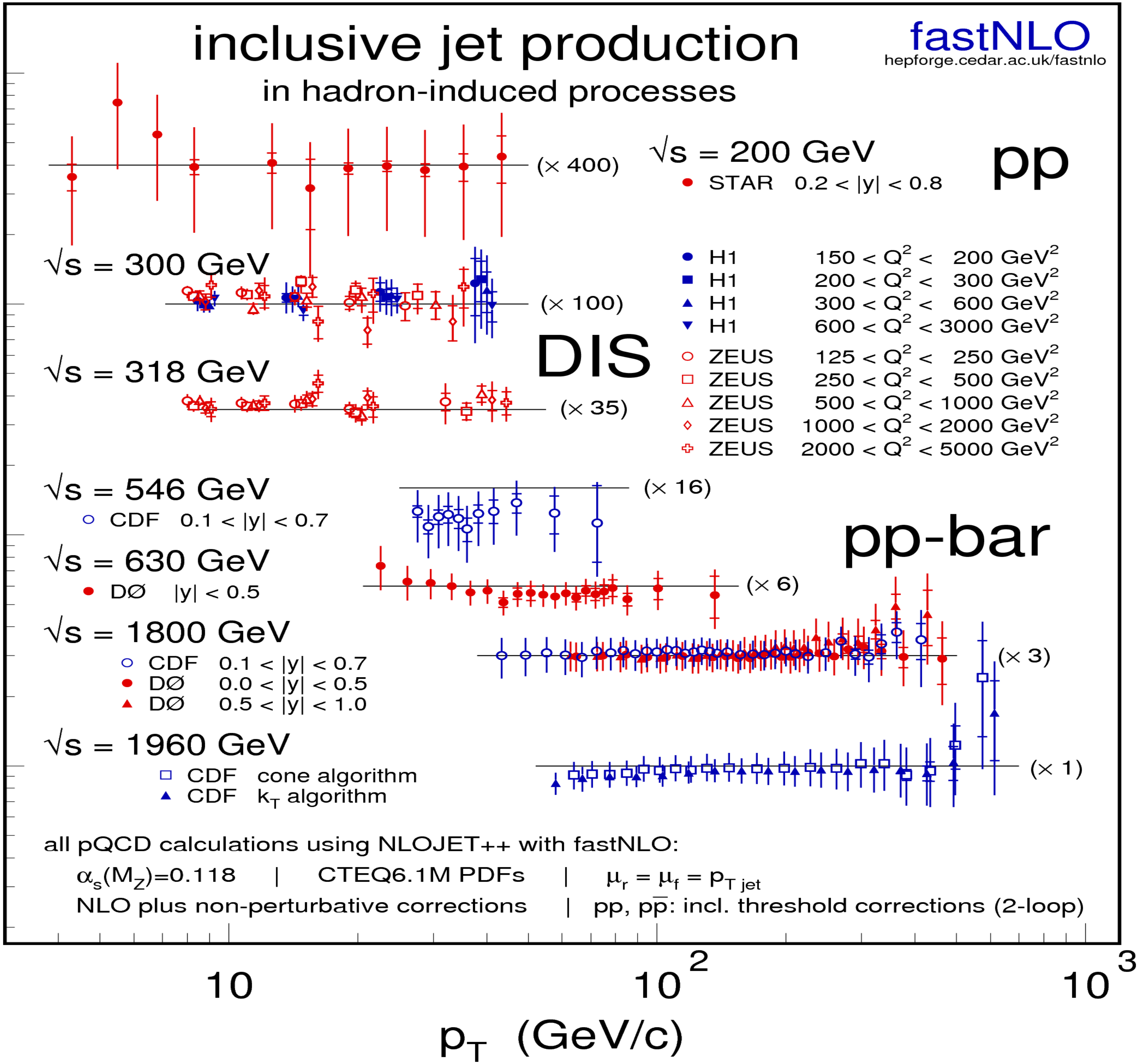
$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$







QCD does a remarkable job!!!

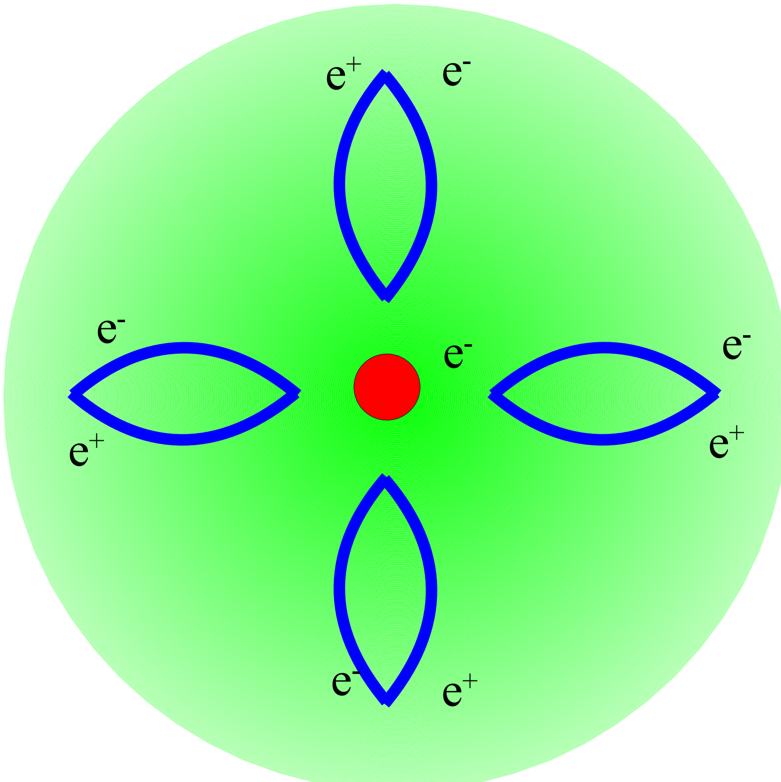


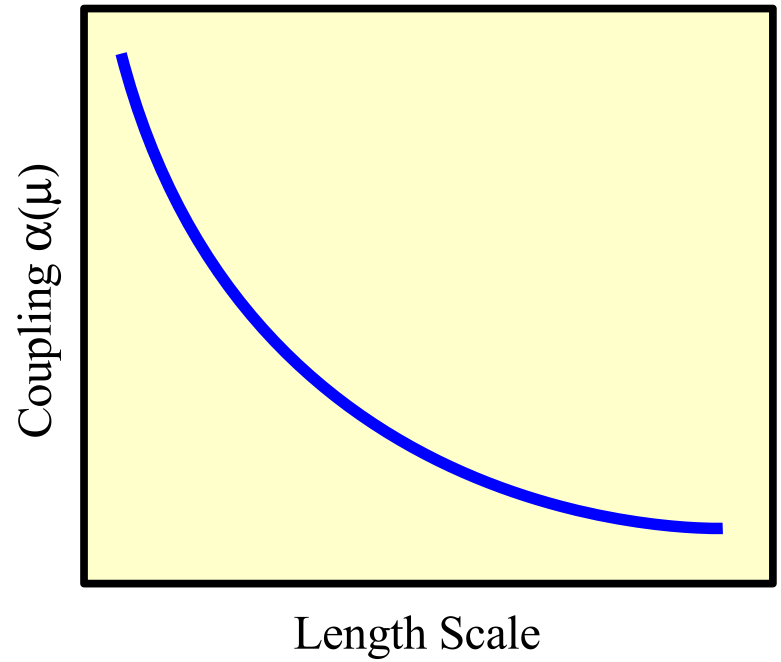
QCD is just like QED,

.... *only different*

QCD is just like QED, only different ...

QED: Abelian U(1) Symmetry





Perturbation theory at large distance is convergent

$$\alpha(\infty) \sim \frac{1}{137}$$

$$\alpha(M_Z) \sim \frac{1}{128}$$

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \ ,$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - 0$$

Abelian

α is good expansion parameter

QCD is Non-Abelian SU(3) Symmetry; Quarks are Confined!!!

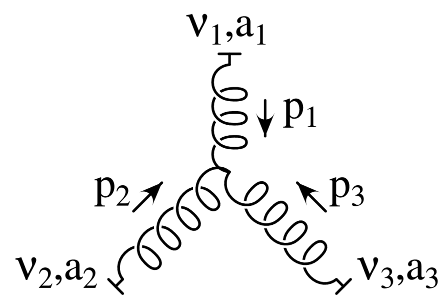
$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij}\right)\psi_j - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$

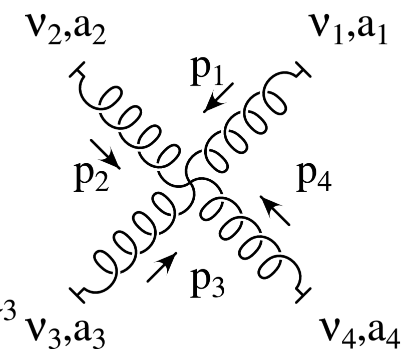
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g f^{abc} A^b_\mu A^c_\nu$$

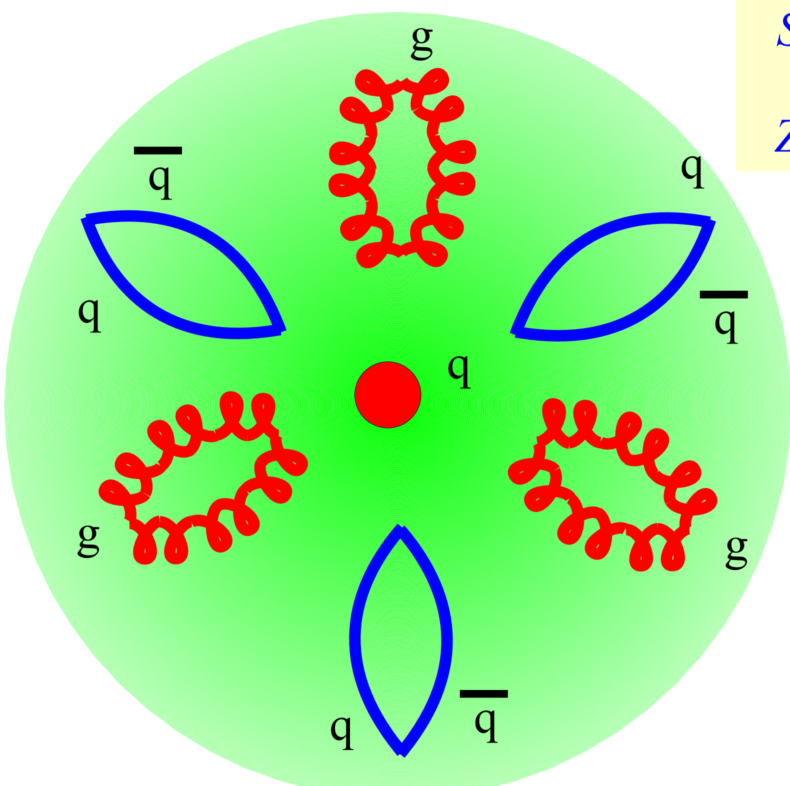
$$[T_a, T_b] = i \sum_{c=1}^{8} f_{abc} T_c$$

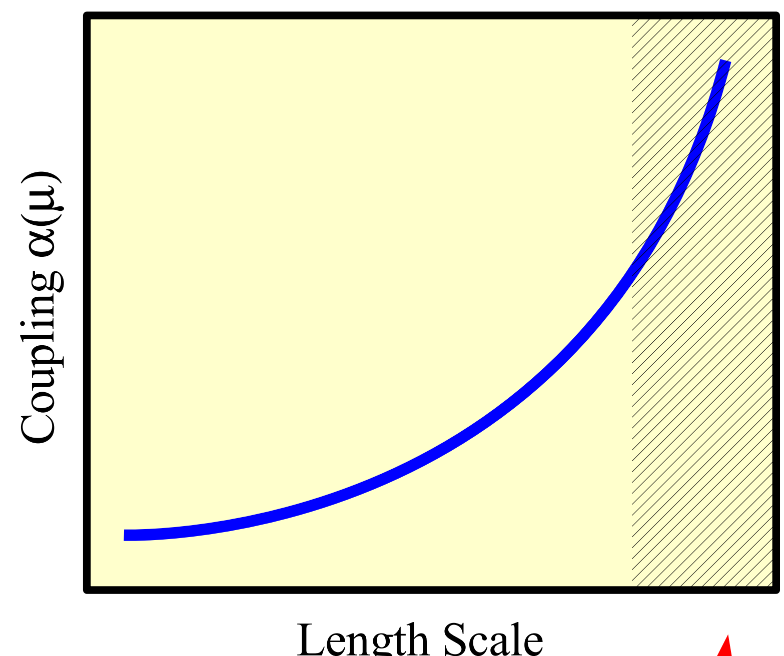
Non-Abelian

See lecture by Dieter Zeppenfeld





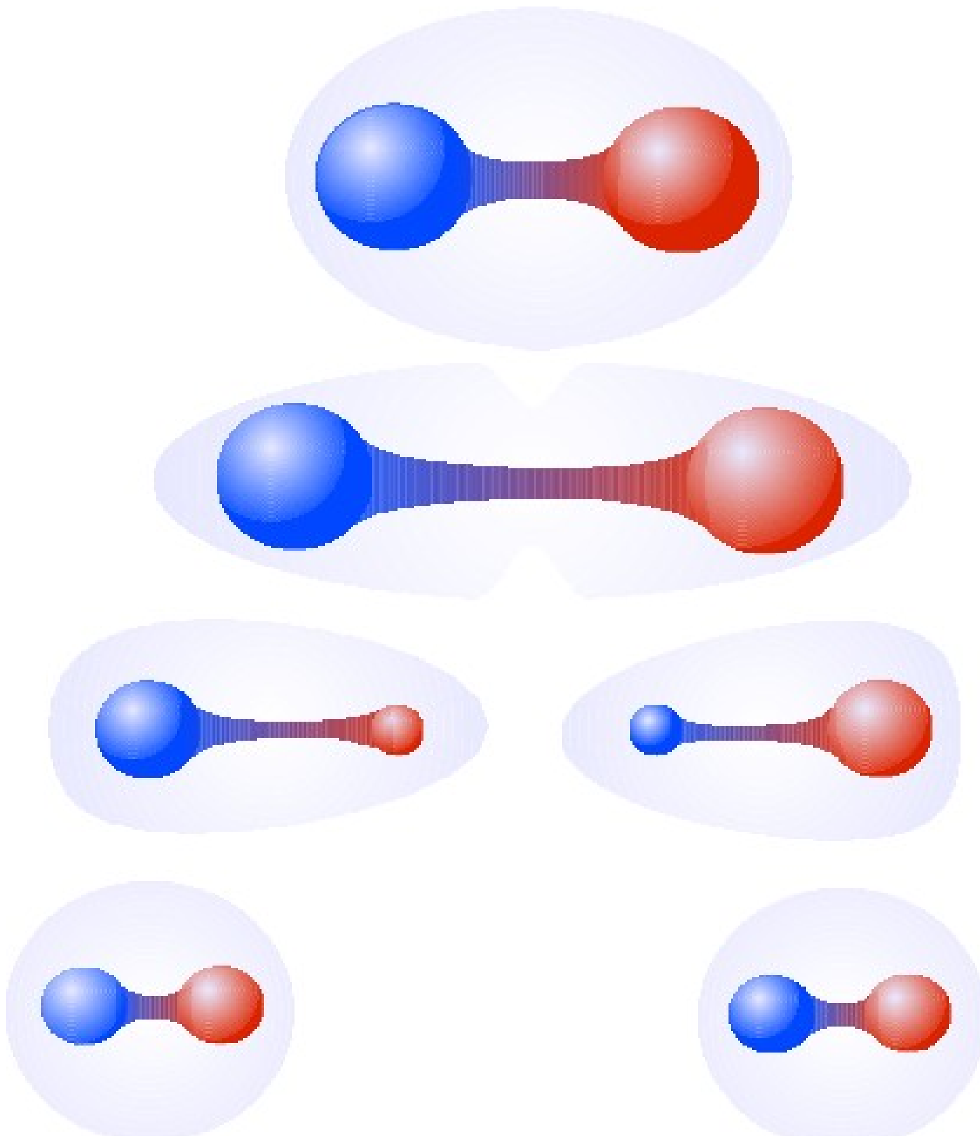




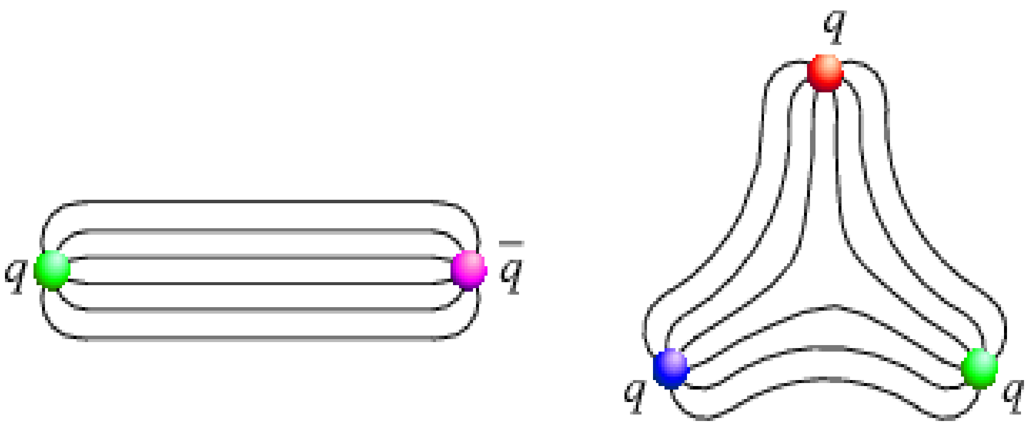
$$\alpha_s(M_Z) \sim 0.118$$

Cannot perform Perturbation theory at large distance

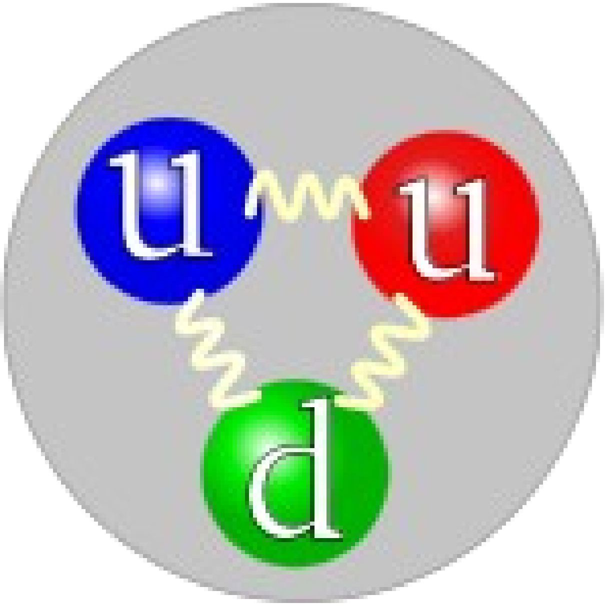
Quark Confinement & String Interpretation



Thomas Lippert, NIC-ZAM, Jülich, for the SESAM Collaboration)



http://www.scholarpedia.org/



http://en.wikipedia.org/

Quarks are confined

Statement of the problem

Theorist #1: The universe is completely described by the symmetry group SO(10)

Theorist #2: You're wrong; the correct answer is SuperSymmetric flipped SU(5)xU(1)

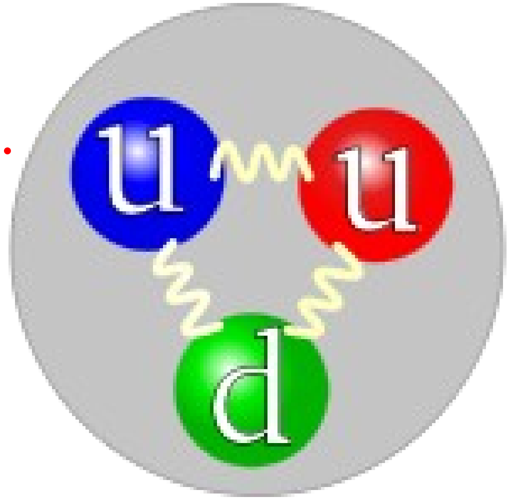
Theorist #3: You've flipped! The only rational choice is E8xE8 dictated by SuperString Theology.

Experimentalist: Enough of this speculative nonsense. I'm going to measure something to settle this question. What can you predict???

Theorist #1: We can predict the interactions between fundamental particles such as quarks and leptons.

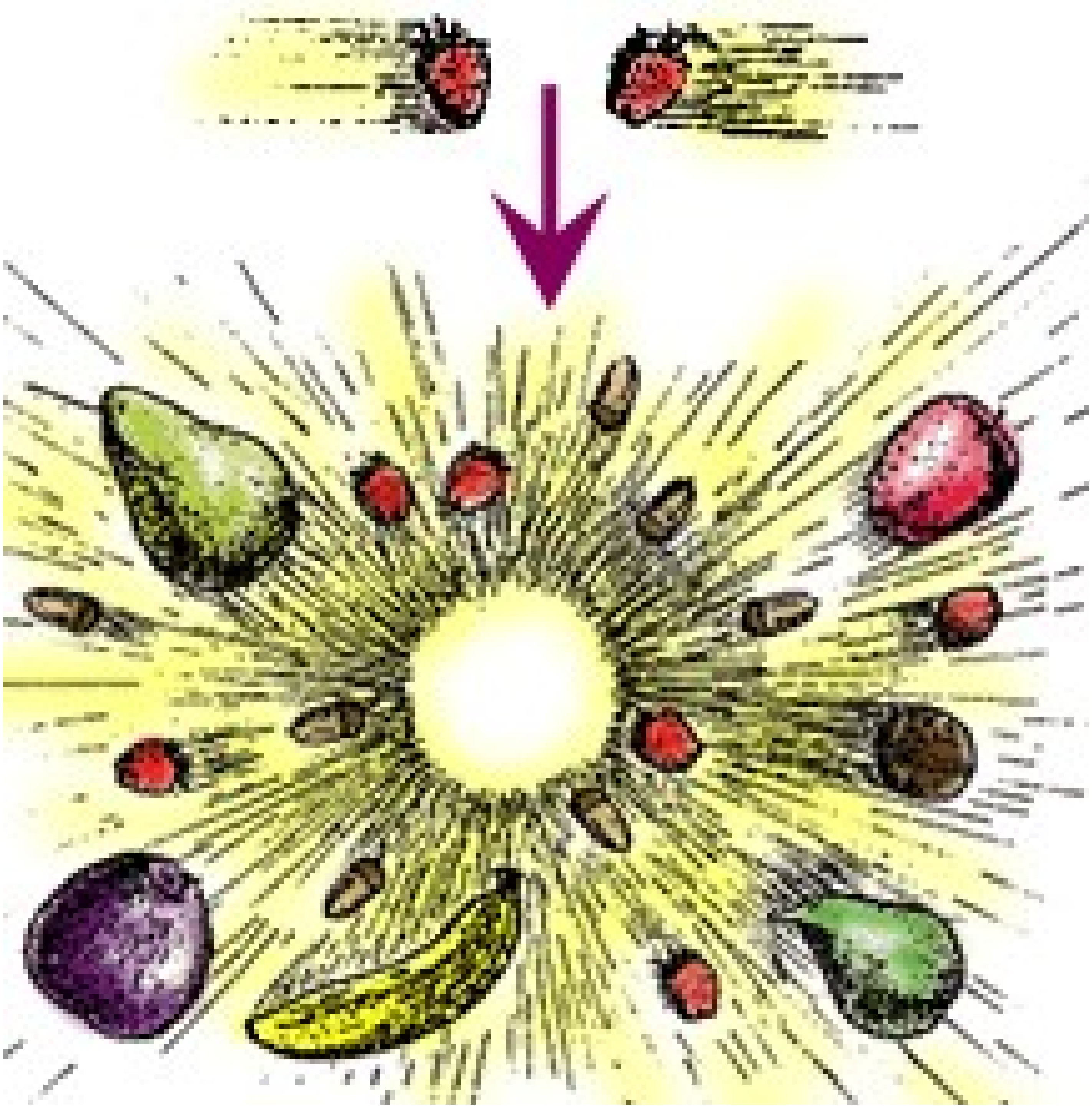
Experimentalist: Great! Give me a beam of quarks and leptons, and I can settle this debate.

Accelerator Operator: Sorry, quarks only come in a 3-pack and we can't break a set!



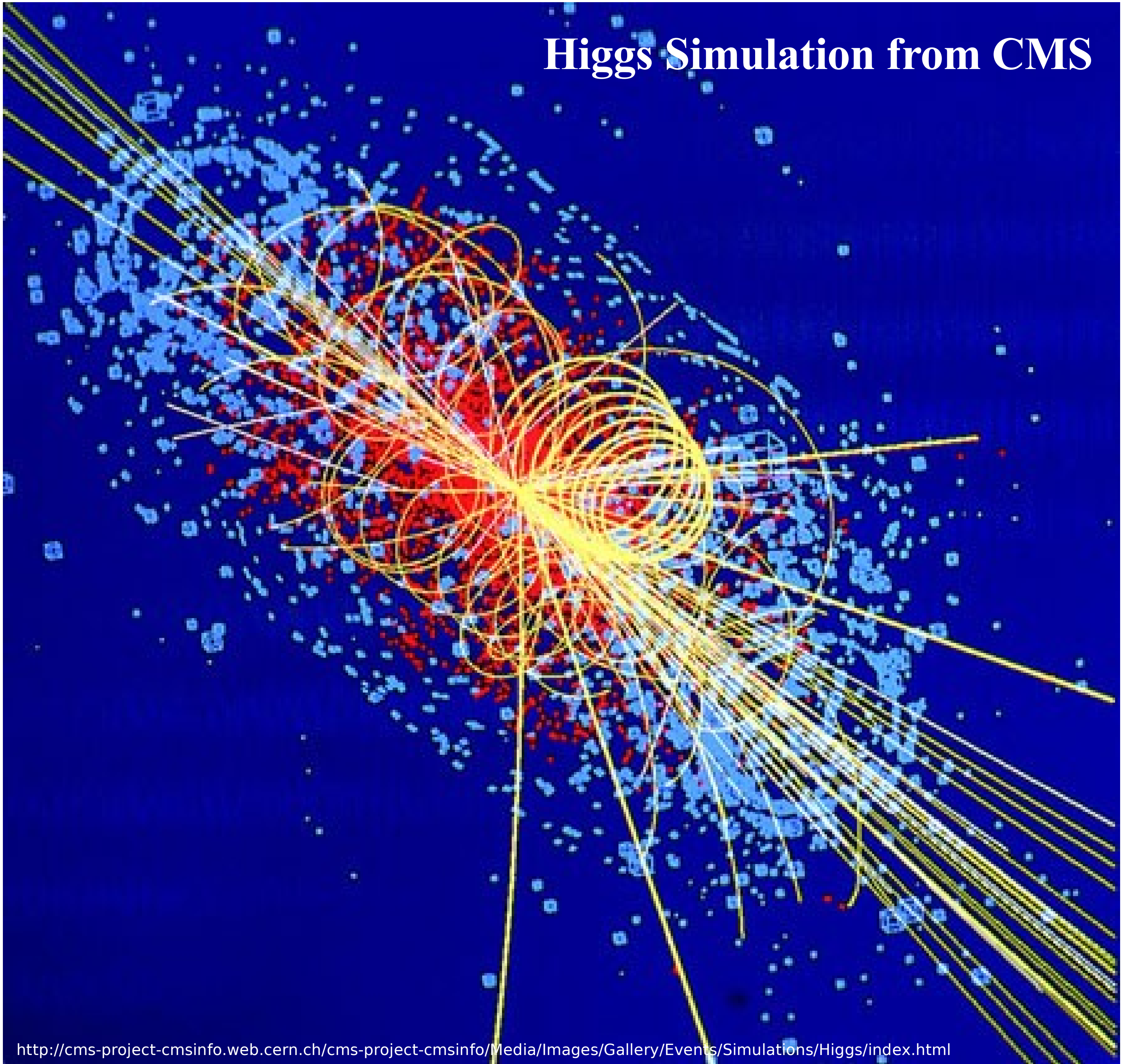
http://en.wikipedia.org/

One interpretation of a hadron-hadron collision



Did we find the Higgs?

A bit more realistic interpretation of a hadron-hadron collision



OUTLINE

QCD is a theory with a rich structure

Working in the limit of a spherical horse ...

We are going to look at the essence of what makes QCD so different from the other forces.

As a consequence, we will need to be creative in how we study the properties, now we define observables, and interpret the results.

QCD has a history of more than 40 years, and we are still trying to fully understand its structure.

The goal of these lectures

Provide pictorial/graphical/heuristic explanations for everything that confused me as a student

$\Rightarrow$

BEFORE

AFTER

Overview ... what is to come

Lecture 1:

Overview& essential features
Nature of strong coupling constant
& how it varies with scale
Issues beyond LO and SM
Renormalization Group Equation &
Resummation
Scaling and the proton Structure

Lecture 2:

The structure of the proton
Deeply Inelastic Scattering (DIS)
The Parton Model
PDF's & Evolution
Scaling and Scale Violation

cf., Burkard Reisert

cf., Stefano Forte

Lecture 3:

Issues at NLO
Collinear and Soft Singularities
Mandelstam Variables
An example from Freshman Physics
Regularized Distributions
Extension to higher orders

Lecture 4:

Drell-Yan and e^+e^- Processes
W/Z/Higgs Production & Kinematics
3-body Phase Space & Dalitz Plots
Sterman-Weinberg Jets
Infrared Safe Observables
Rapidity & Pseudo Rapidity
Jet Definitions

cf., Jeff Owens

cf., Ken Hatakeyama

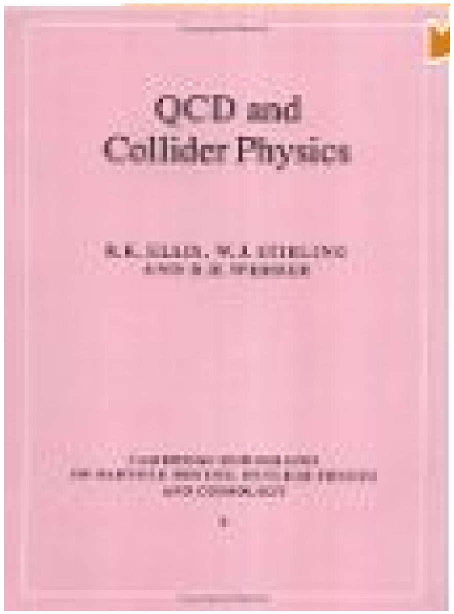
Overview ... what is to come

Homework:

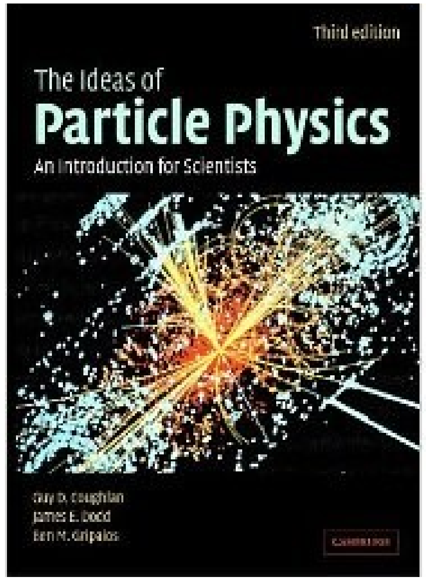
Physics is not a spectator sport

Useful References & Thanks:

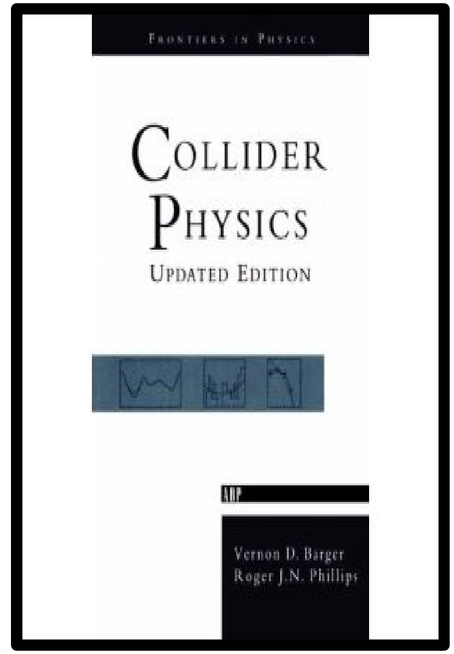
Useful References



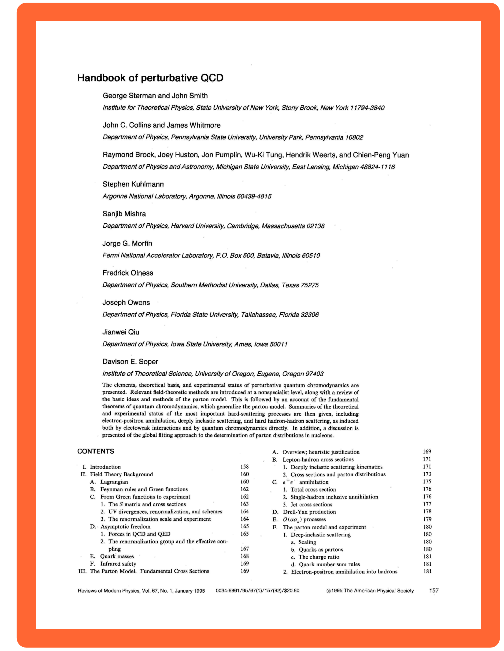
Ellis, Stirling, Webber



Coughlan, Dodd, Gripaios



Barger & Phillips


Handbook of perturbative QCD

George Sterman and John Smith

Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794-3840

John C. Collins and James Whitmore

Department of Physics, Pennsylvania State University, University Park, Pennsylvania 16802

Raymond Brock, Joey Huston, Jon Pumplin, Wu-Ki Tung, Hendrik Weerts, and Chien-Peng Yuan

Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824-1116

Stephen Kuhlmann

Argonne National Laboratory, Argonne, Illinois 60439-4815

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Jianwei Qiu

Department of Physics, Iowa State University, Ames, Iowa 50011

Davison E. Soper

Institute of Theoretical Science, University of Oregon, Eugene, Oregon 97403

CONTENTS

CTEQ Handbook
Reviews of Modern
Physics

Applications of Perturbative QCD,
Richard D. Field

Resource Letter: Quantum Chromodynamics
Andreas S. Kronfeld, Chris Quigg
arXiv:1002.5032

An Introduction to QFT
Peskin & Schroeder

Particle Data Group
http://pdg.lbl.gov

The CTEQ Pedagogical Page

Linked from **`cteq.org`**

Everything you wanted to know about Lambda-QCD but were afraid to ask

Randall J. Scalise and Fredrick I. Olness

Regularization, Renormalization, and Dimensional Analysis:
Dimensional Regularization meets Freshman E&M

Fredrick Olness & Randall Scalise

Calculational Techniques in Perturbative QCD: The Drell-Yan Process.

Björn Pötter has prepared a writeup of the lecture given by Jack Smith.
This is a wonderful reference for those learning to do real 1-loop calculations.

Thanks to ...

Thanks to:

Dave Soper, George Sterman, Steve Ellis for ideas borrowed from previous CTEQ introductory lecturers

Thanks to Randy Scalise for the help on the Dimensional Regularization.

Thanks to my friends at Grenoble who helped with suggestions and corrections.

Thanks to Jeff Owens for help on Drell-Yan and Resummation.

To the CTEQ and MCnet folks for making all this possible.

OpenOffice.org Source Project

and the many web pages where I borrowed my figures ...

Power Point

The Strong Coupling, Scaling, and Stuff

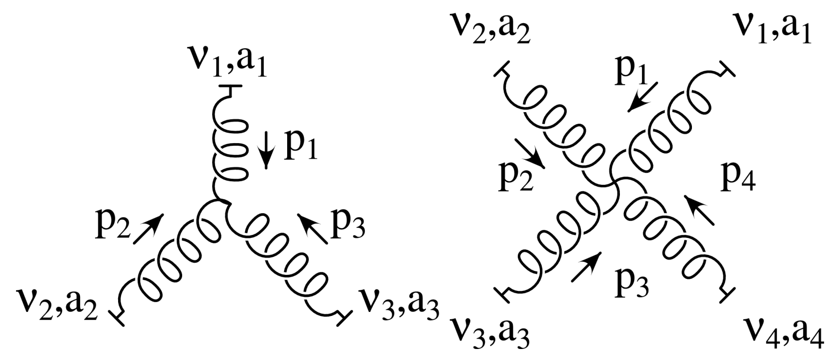
QCD is Non-Abelian SU(3) Symmetry; Quarks are Confined

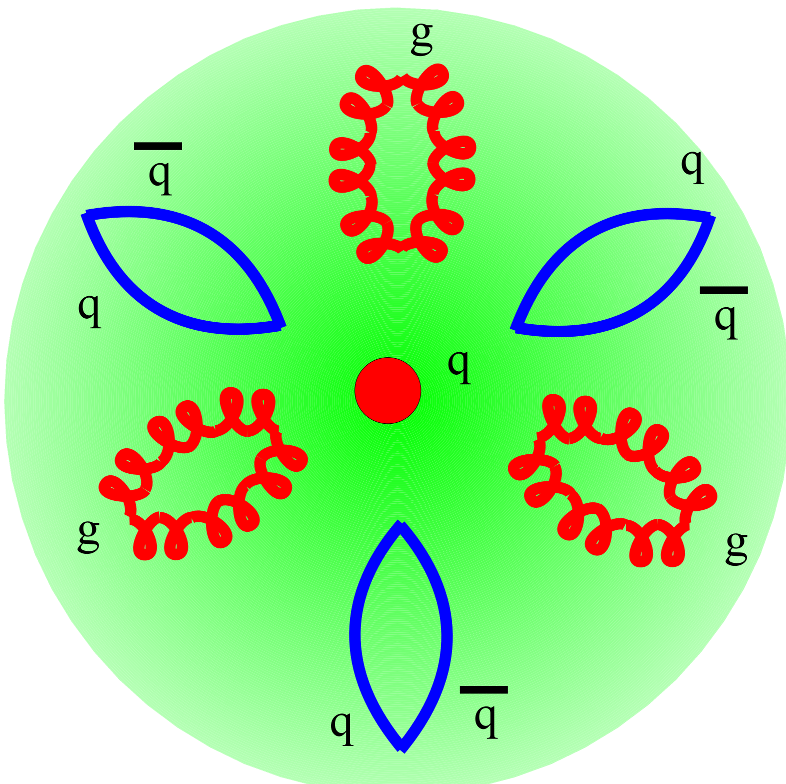
$$\mathcal{L}_{\rm QCD} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

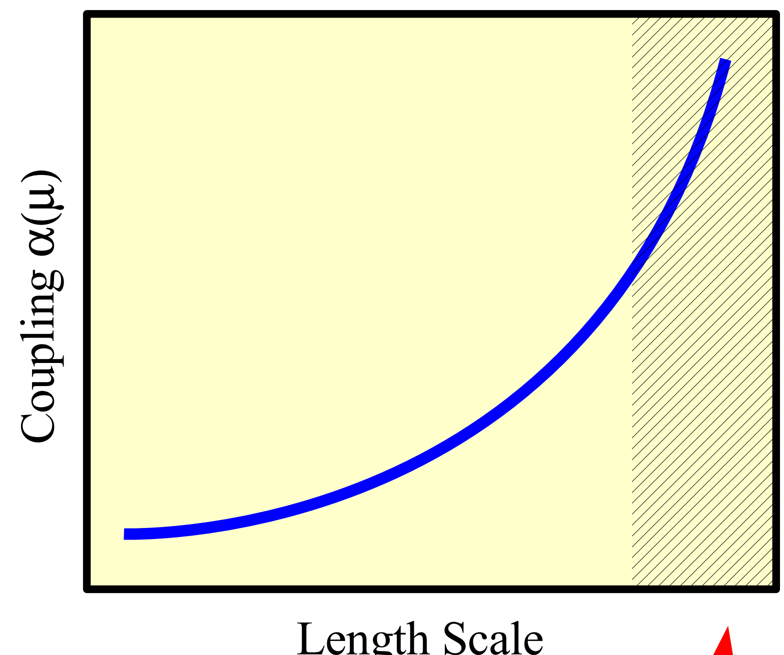
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g f^{abc} A^b_\mu A^c_\nu$$

Non-Abelian

$$[T_a, T_b] = i \sum_{c=1}^{8} f_{abc} T_c$$







$\Lambda \sim 200\,\mathrm{MeV} \sim 1\ \mathrm{fm}$

Cannot perform Perturbation theory at large distance

Where did that β-function come from ???

Consider a physical observable: $R(Q^2/\mu^2,\alpha_s)$

Q is the characteristic energy scale of the problem

μ is an artificial scale we introduce to regulate the calculation (more later)

The Renormalization Group Equation (RGE) is:

$$\frac{dR}{d\mu^2}=0$$

$$\left\{\mu^2\frac{d}{d\mu^2}\right\}R\left(\frac{Q^2}{\mu^2},\alpha_s(\mu^2)\right) = 0$$

Using the chain rule:

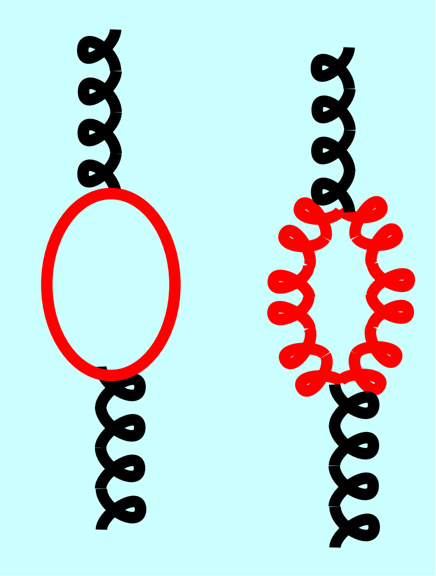
$$\left\{\mu^2\frac{\partial}{\partial\mu^2}+\underbrace{\left[\mu^2\frac{\partial\alpha_s(\mu^2)}{\partial\mu^2}\right]}_{\beta\left(\alpha_s(\mu)\right)}\frac{\partial}{\partial\alpha_s(\mu^2)}\right\}R\left(\frac{Q^2}{\mu^2},\alpha_s(\mu^2)\right) = 0$$

β function tell us how α_s changes with energy scale!!!

The β-function: $\beta(\alpha_s(\mu))$

β function tell us how α_s changes with energy scale!!!

$$\beta\left(\alpha_s(\mu)\right)=\mu^2\,\frac{\partial\alpha_s(\mu^2)}{\partial\mu^2}=\frac{\partial\alpha_s(\mu^2)}{\partial\ln\mu^2}$$

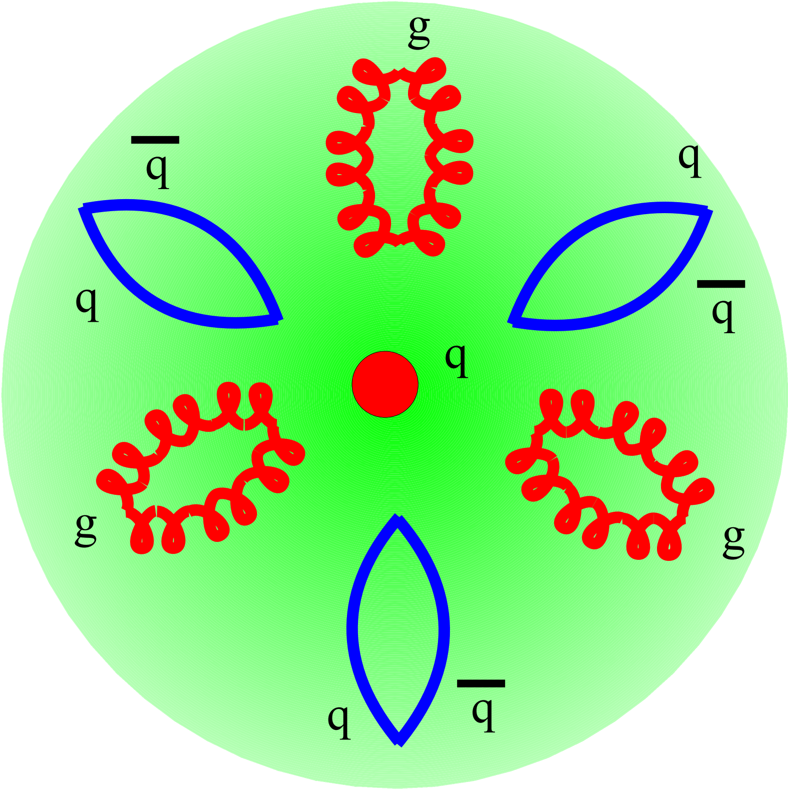


We can calculate this perturbatively

$$\beta\left(\alpha_s(\mu)\right)=\;-\;\left\{b_0\alpha_s^2+b_1\alpha_s^3+b_2\alpha_s^4+\dots\right\}$$

$$b_0=\frac{33-2N_F}{12\pi}$$

$$\beta=-\alpha_S^2\left[\frac{33-2N_F}{12\pi}\right]+\dots$$



Note: b_0 and b_1 are scheme independent.

β is negative; let's find the implications

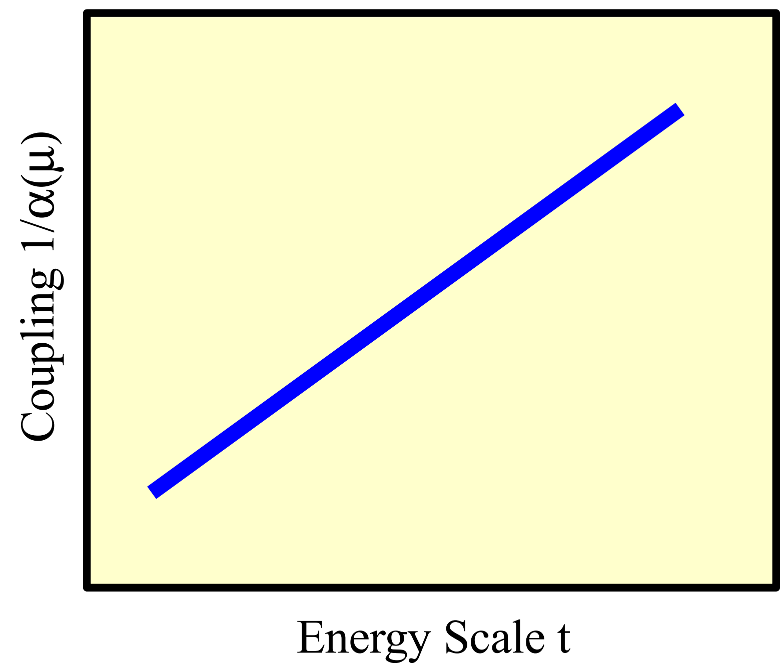
Solve for the running coupling

Let: $t = \ln \mu^2$

$$\beta = \frac{\partial \alpha_s}{\partial t} \simeq -b_0 \alpha_s^2 + \ldots$$

$$\frac{\partial \alpha_s}{\alpha_s^2} = -b_0 \, \partial t$$

$$\frac{1}{\alpha_s} = b_0 \, t$$



$$b_0 = \frac{33 - 2N_F}{12\pi}$$

$$\beta = -\alpha_S^2 \left[\frac{33 - 2N_F}{12\pi} \right] + \ldots$$

Observe $\beta_{QCD} < 0$ for $N_F < 17$ or for 8 generations or less.
Thus, in general $\beta_{QCD} < 0$ in the QCD theory
Contrast with QED: $\beta_{QED} > 0 = +\alpha^2/3\pi + \ldots$

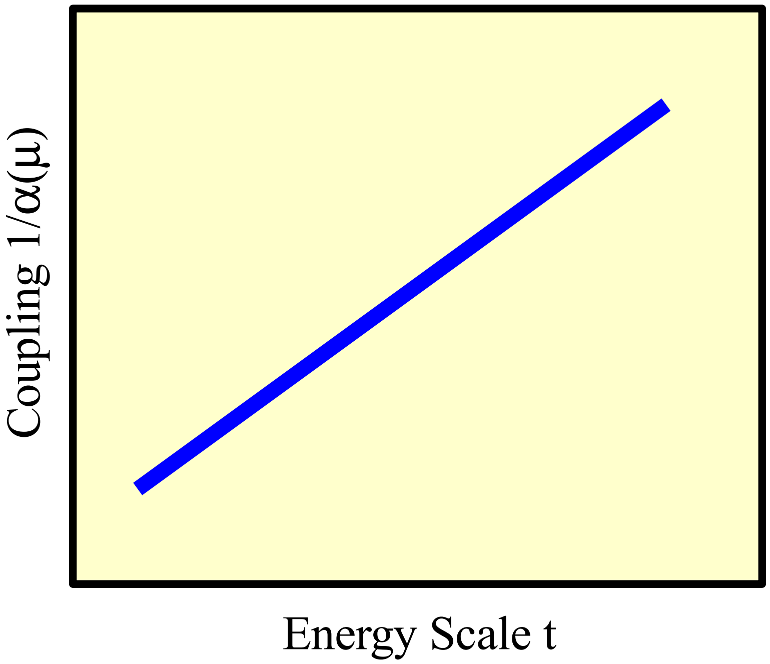
The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek "for the discovery of asymptotic freedom

Solve for the running coupling and Λ_{QCD}

Let: $t = \ln \mu^2$

$$\left.\frac{1}{\alpha_S}\right]_{\mu_0}^{\mu_1} = b_0\, t\Big]_{\mu_0}^{\mu_1}$$

$$\frac{1}{\alpha_S(\mu_1)} - \frac{1}{\alpha_S(\mu_0)} = b_0\, \ln(\mu_1/\mu_0)$$



β functions gives us running, but we still need a reference

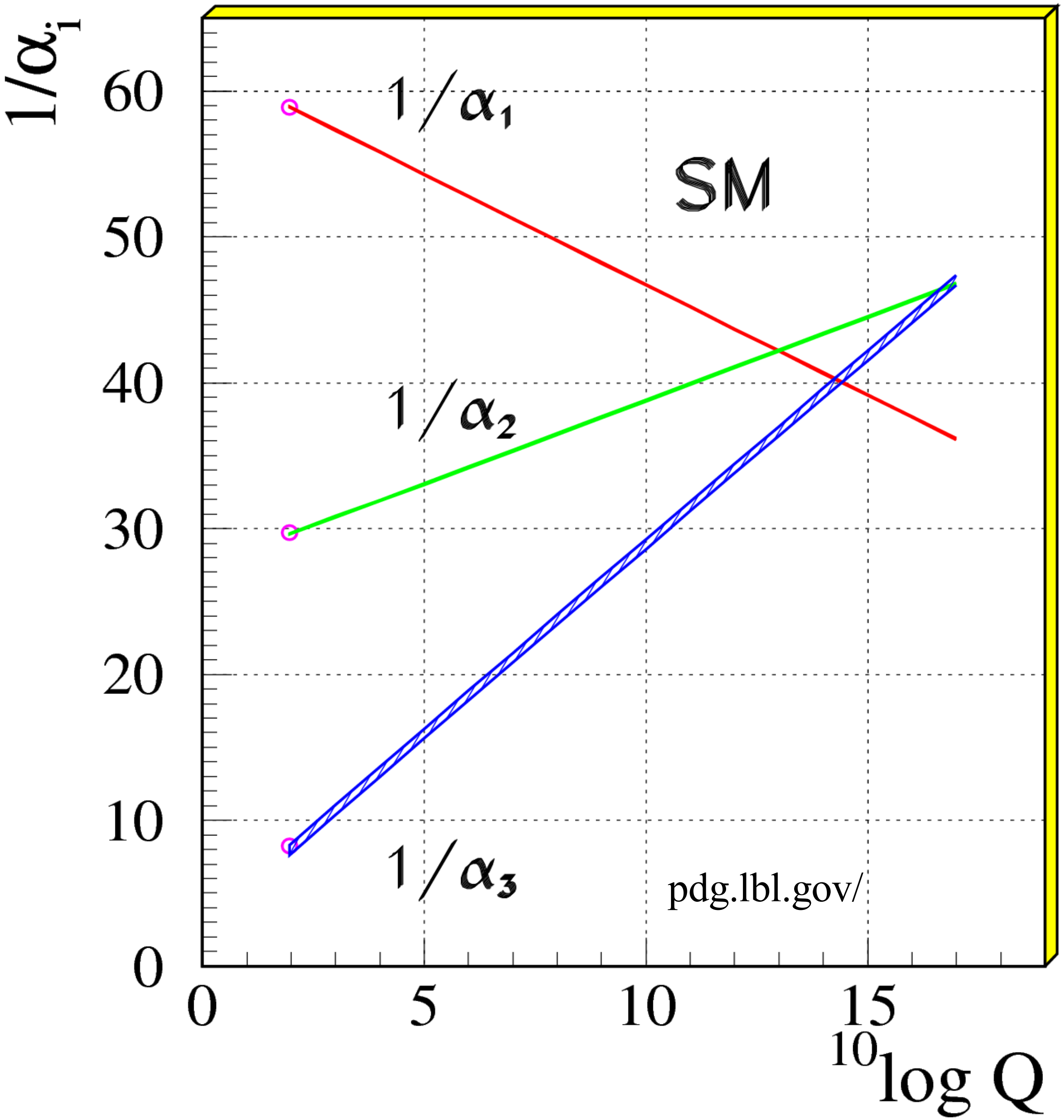
$$\alpha_s(\mu) = \frac{1}{b_0\, \ln(\mu/\Lambda_{QCD})}$$

Landau Pole
$\Lambda = \mu$

$$\Lambda = \mu\, e^{-1/(b_0\, \alpha_s(\mu))}$$

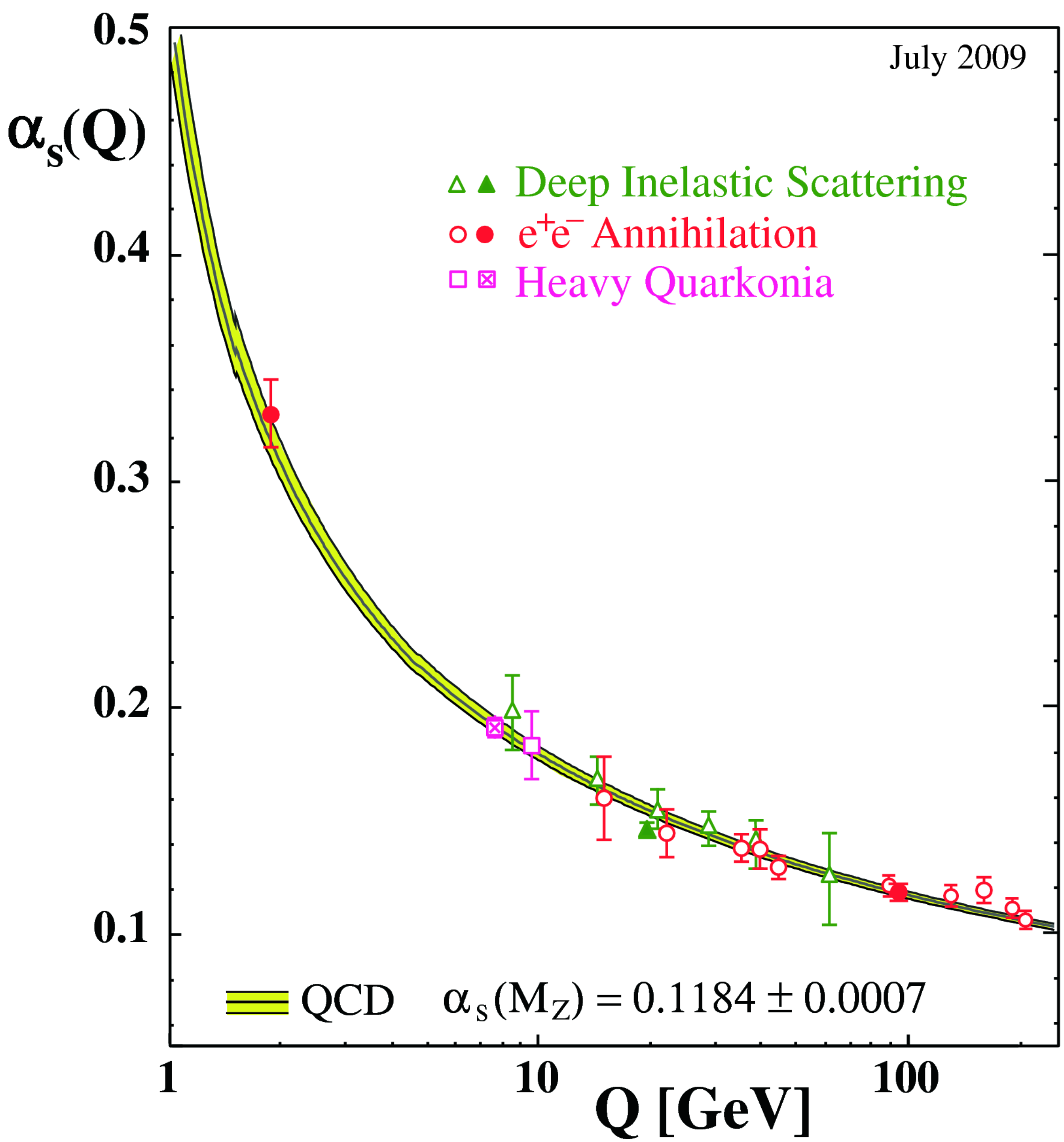
$$\Lambda_{QCD} \sim 200\,\mathrm{MeV} \sim 1\ \mathrm{fm}$$

The Standard Model (SM) Running Couplings: U(1), SU(2), SU(3)



$$
\begin{aligned}
b_1 &= \quad 0 + (2/3)N_F + \tfrac{1}{10}N_{Higgs} \\
b_2 &= -22/3 + (2/3)N_F + \tfrac{1}{6}N_{Higgs} \\
b_3 &= \quad -11 + (2/3)N_F + 0
\end{aligned}
$$

Comparison with data



$$\alpha_s(M_Z) = 0.118$$

Low Q points have more discriminating power

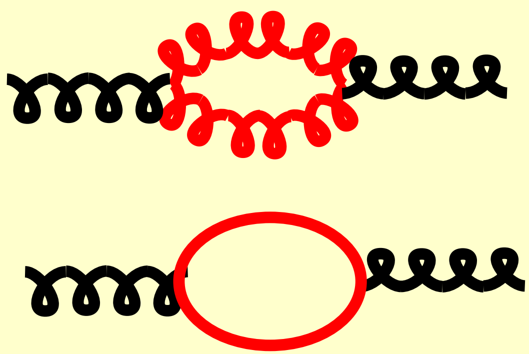
Caution: α_s is NOT a physical observable

Siegfried Bethke Eur.Phys.J.C64:689-703,2009

BEYOND NLO

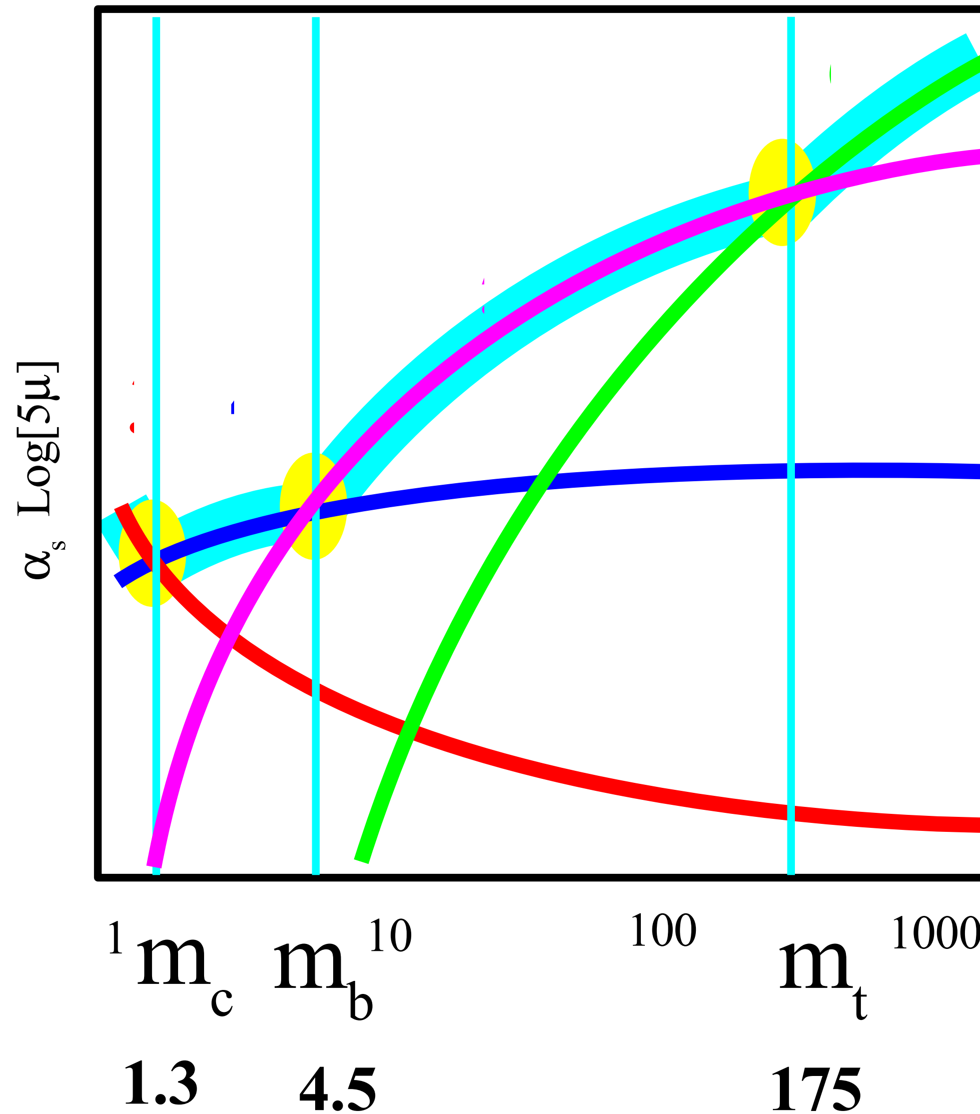
Strong Coupling across mass thresholds

N_F Matters



$$\beta = -\alpha_S^2 \left[\frac{33 - 2N_F}{12\pi} \right] + \dots$$

At 1-loop and 2-loops, continuous at thresholds



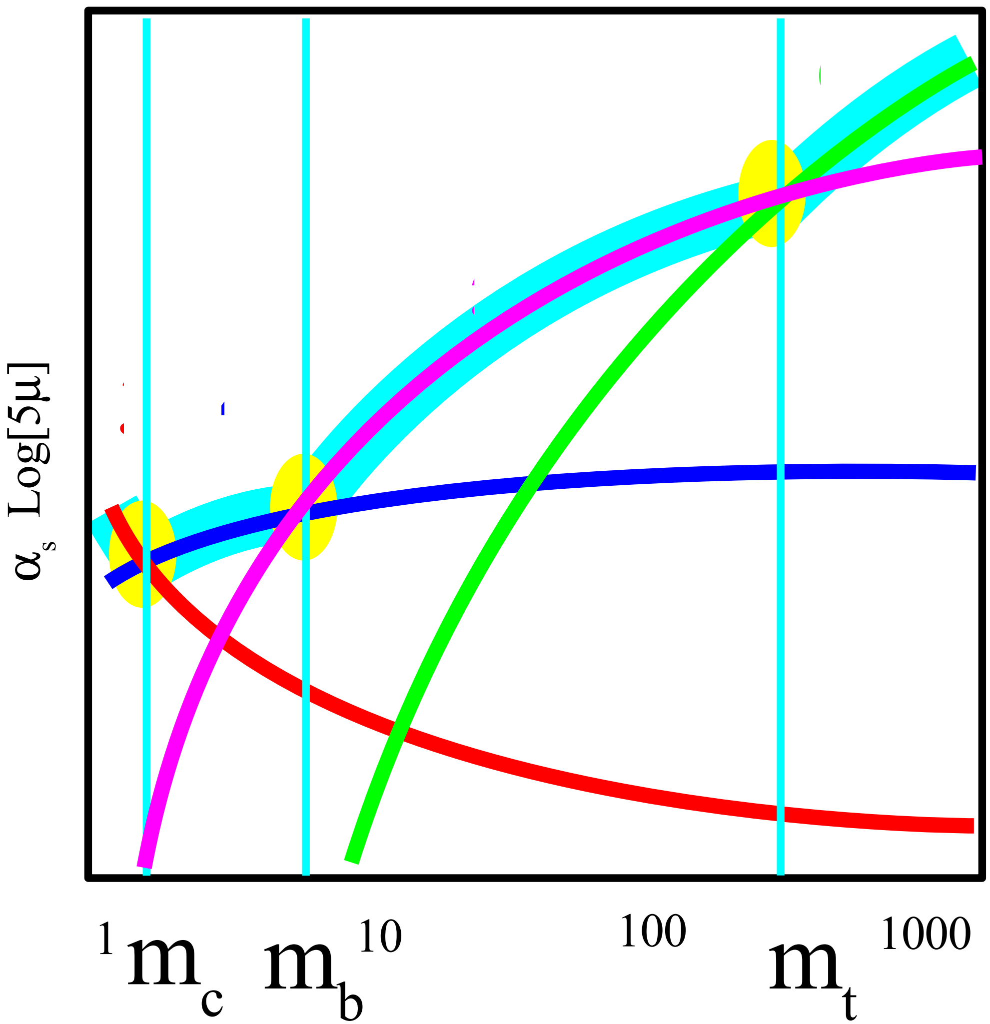
$\Lambda \sim 200\,\mathrm{MeV} \sim 1\ \mathrm{fm}$

Strong Coupling across mass thresholds

$$\alpha_S^{N_F+1}(\mu^2) = \alpha_S^{N_F}(\mu^2) \Big[1 + \alpha_s^1(c_{10} + c_{11}L^1) + \alpha_s^2(c_{20} + c_{21}L^1 + c_{22}L^2) + \ldots \Big]$$

This is zero

This is non-zero



$$L = \ln(\mu^2)$$

$$c_0 = 0$$

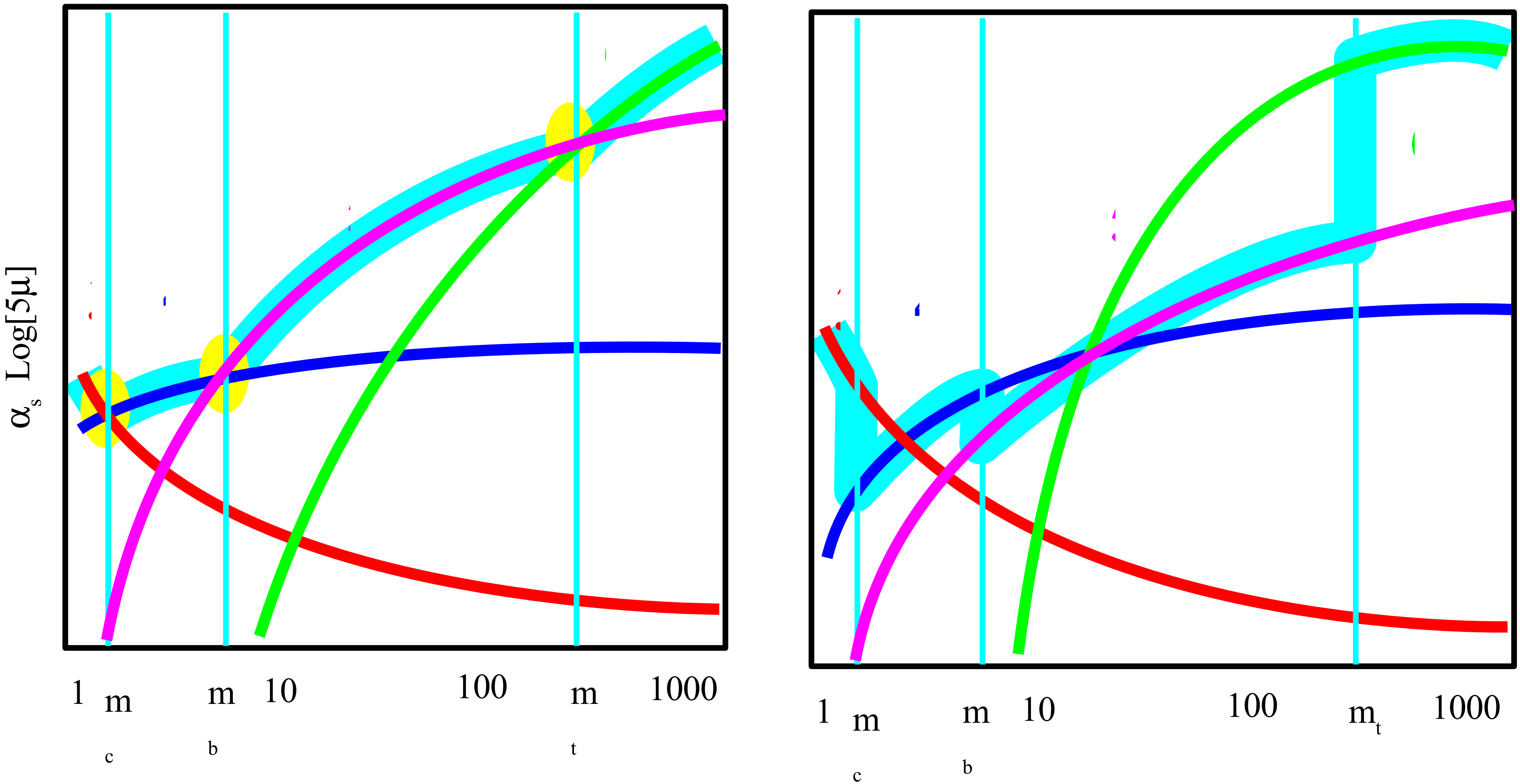
$$c_1 = \frac{-11}{72\,\pi} \neq 0$$

At $\mu = m$ $$\alpha_S^{N_F+1}(\mu^2) = \alpha_S^{N_F}(\mu^2)[1 + 0 + c_{20}\,\alpha_S^2]$$

Strong Coupling across mass thresholds

At 1-loop and 2-loops, continuous at thresholds

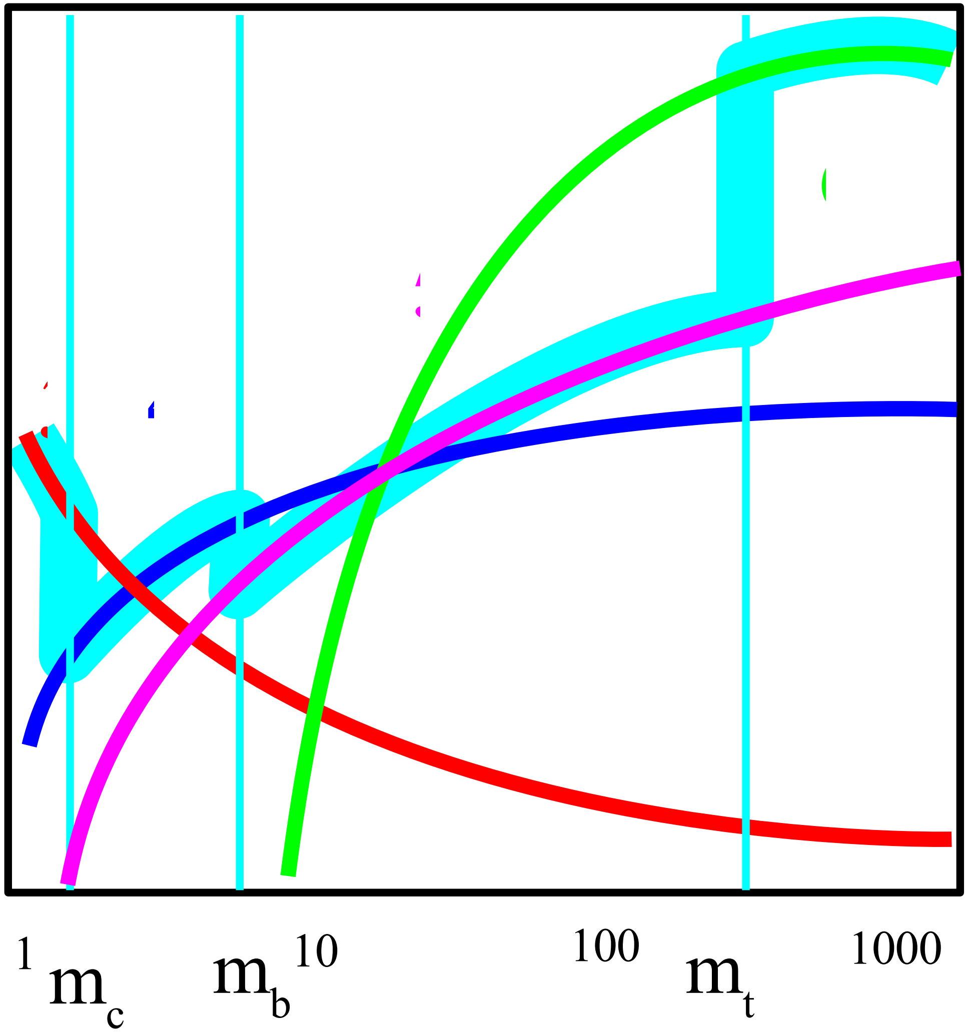
At $O(\alpha_s^3)$, not even continuous at thresholds



$$\alpha_{(n_f)}(M) = \alpha_{(n_f-1)}(M) - \frac{11}{72\pi^2}\,\alpha^3_{(n_f-1)}(M) + \mathcal{O}(\alpha^4_{(n_f-1)})$$

Strong Coupling across mass thresholds

At $O(\alpha_s^3)$, not even continuous at thresholds



Un-physical theoretical constructs:

(E.g., as, PDFs, ...)

Cannot be measured directly

Depends on Schemes

Renormalization Schemes:

MS, MS-Bar, DIS

Renormalization Scale m

Depends on Higher Orders

Physical Observables

Measure directly

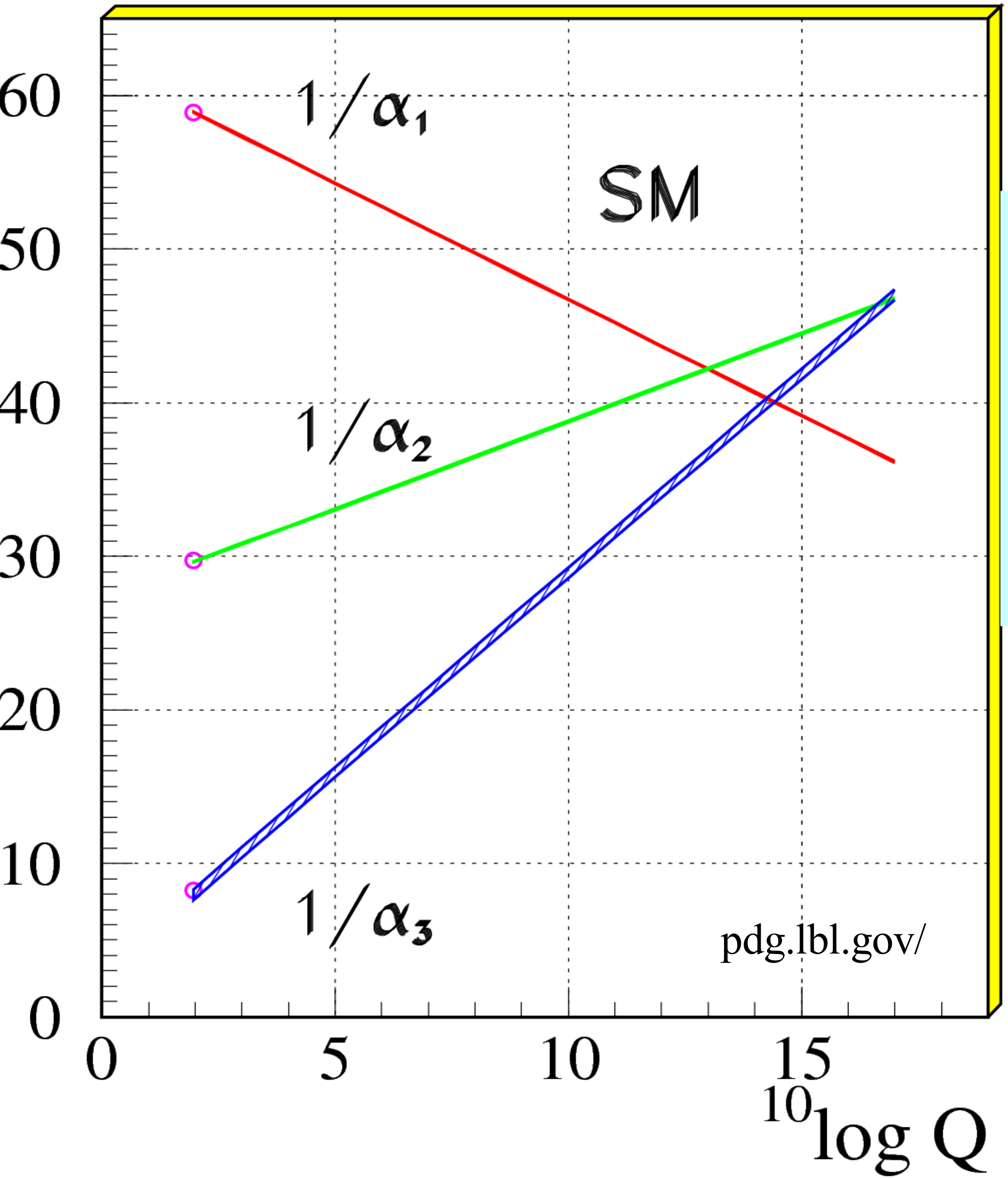
Independent of Schemes/Definitions

Independent of Higher Orders

$$\alpha_{(n_f)}(M) = \alpha_{(n_f-1)}(M) - \frac{11}{72\pi^2}\,\alpha^3_{(n_f-1)}(M) + \mathcal{O}(\alpha^4_{(n_f-1)})$$

BEYOND SM

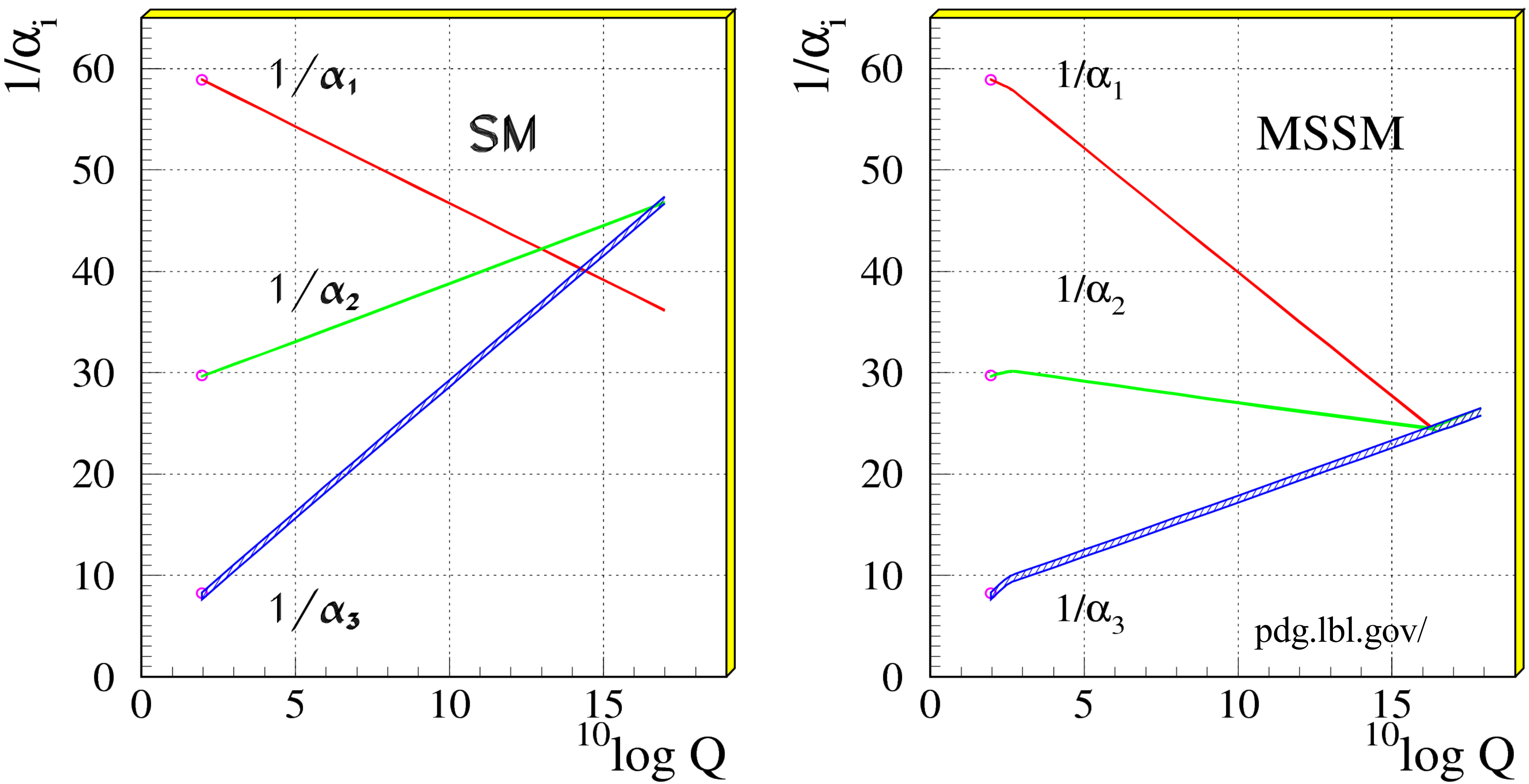
The Standard Model (SM) Running Couplings: U(1), SU(2), SU(3)



$$
\begin{aligned}
b_1 &= 0 + (2/3)N_F + \tfrac{1}{10}N_{Higgs} \\
b_2 &= -22/3 + (2/3)N_F + \tfrac{1}{6}N_{Higgs} \\
b_3 &= -11 + (2/3)N_F + 0
\end{aligned}
$$

Can we do better???

The Standard Model (SM) & SUSY Running Couplings



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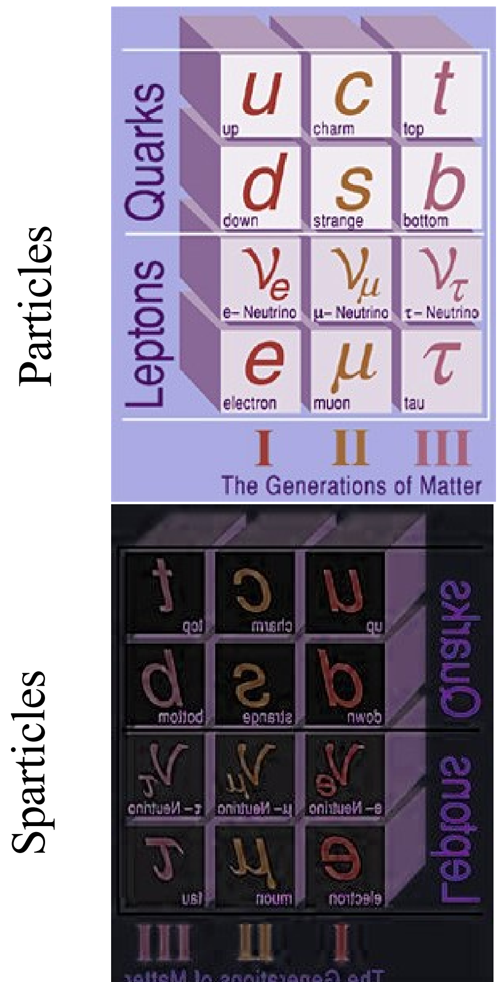
b_3 &= -11 + (2/3)N_F + 0
\end{aligned}
$$

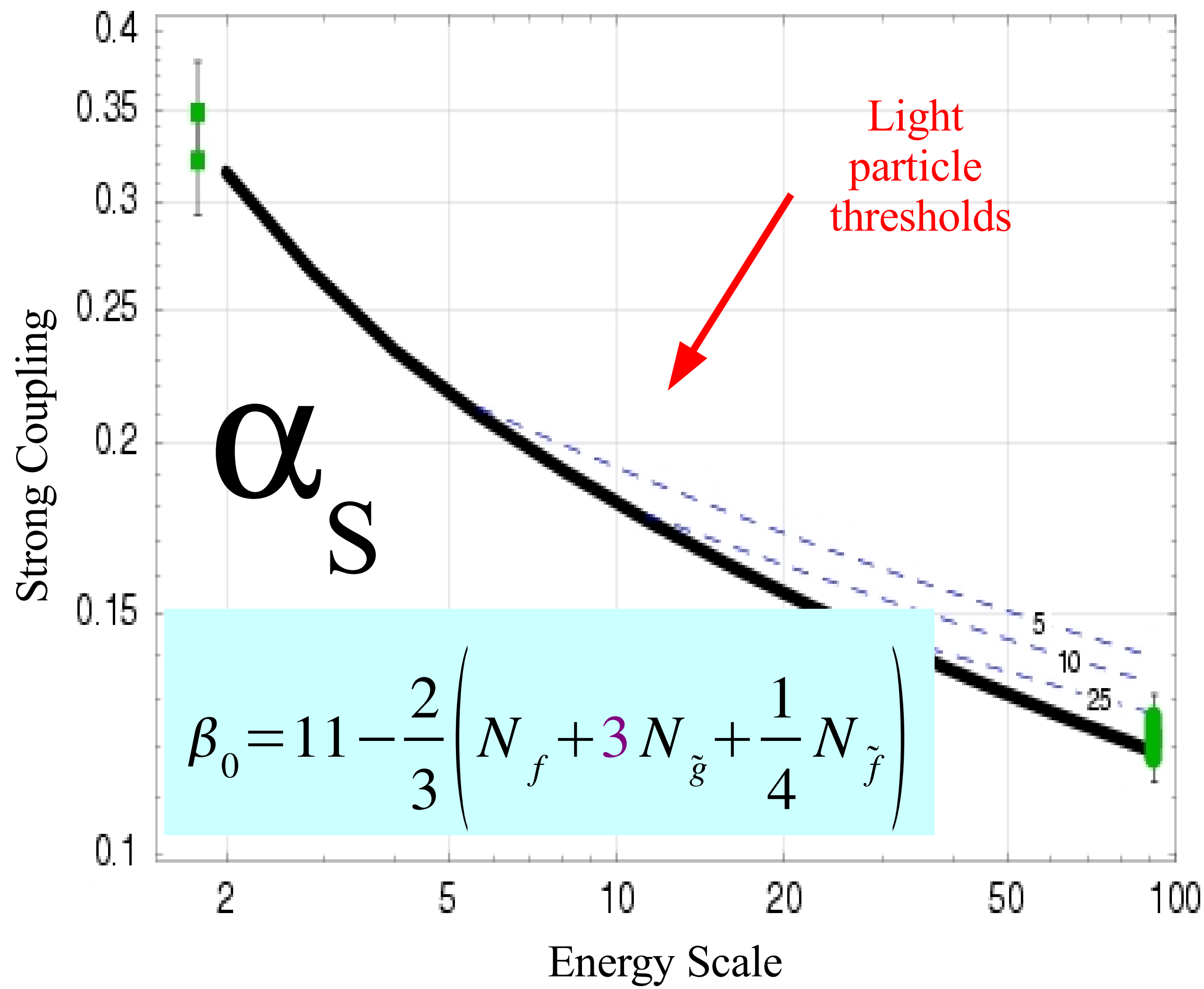
$$\beta_0 = 11 - \frac{2}{3}\left(N_f + 3N_{\tilde{g}} + \frac{1}{4}N_{\tilde{f}}\right)$$

The Standard Model (SM) & SUSY Running Couplings

We've only discovered half the particles

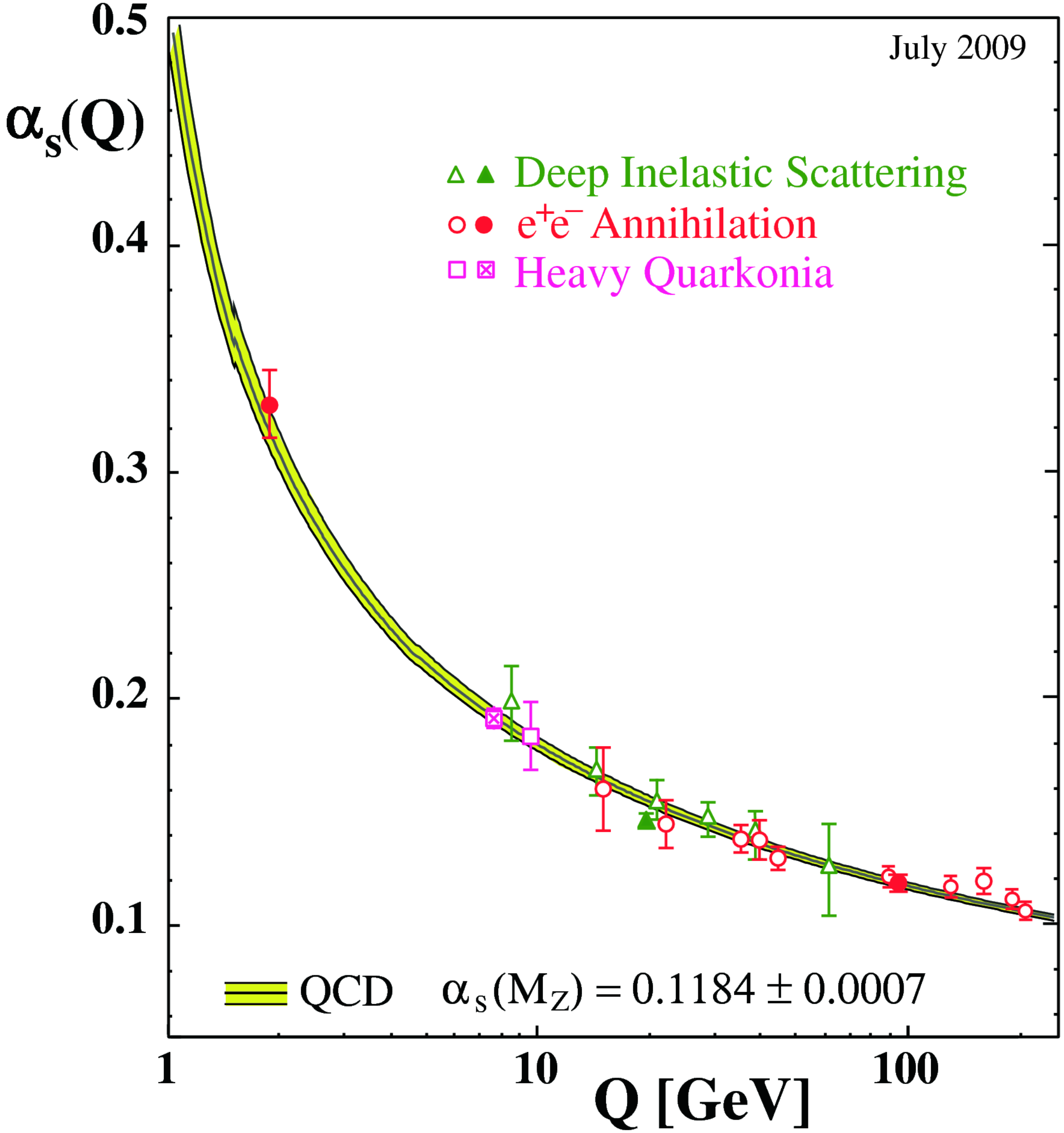


New particles effects evolution of $\alpha_s(\mu)$

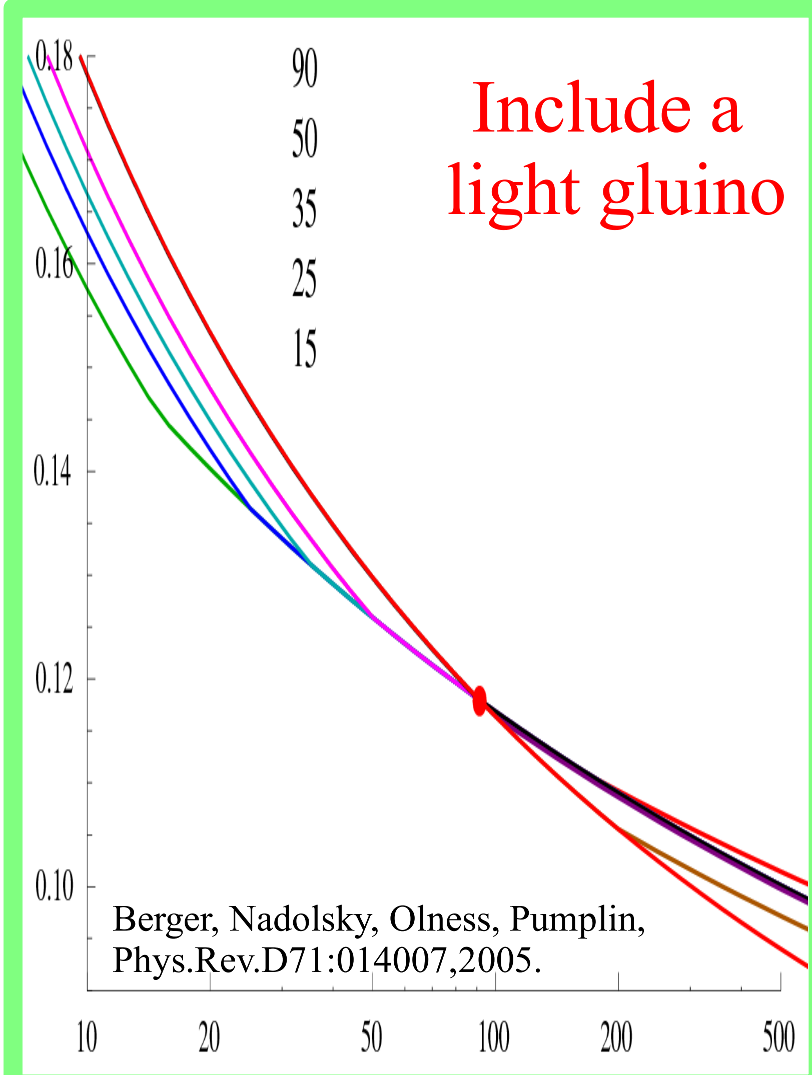


$$\beta_0 = 11 - \frac{2}{3}\left(N_f + 3N_{\tilde{g}} + \frac{1}{4}N_{\tilde{f}}\right)$$

The Standard Model (SM) & SUSY Running Couplings

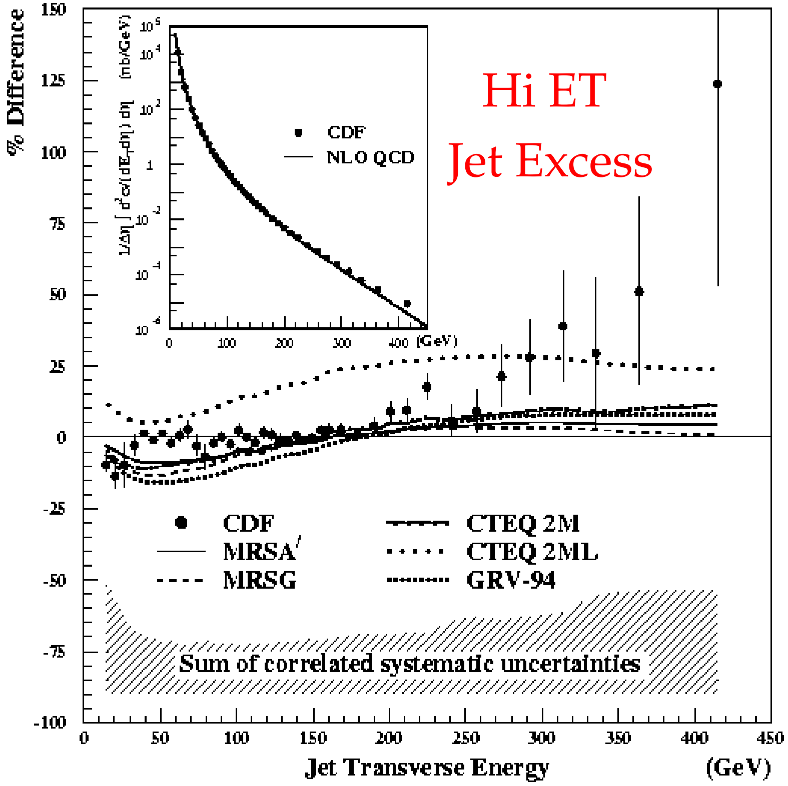


Siegfried Bethke
Eur.Phys.J.C64:689-703,2009

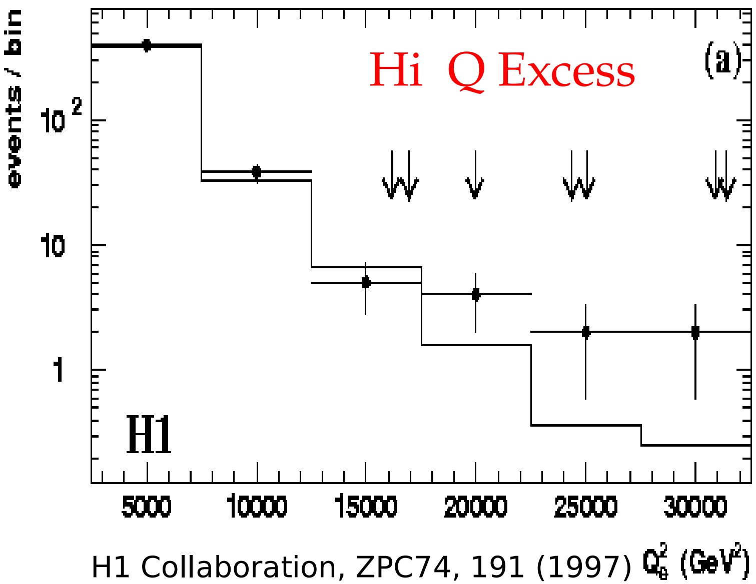


$$b_0 = \frac{1}{12\pi}\left\{33 - 2\,N_F - 6\,N_{\tilde{g}} - \frac{1}{2}\,N_{\tilde{F}} \ldots\right\}$$

GOT QCD ???



CDF Collaboration, PRL 77, 438 (1996)



H1 Collaboration, ZPC74, 191 (1997)
ZEUS Collaboration, ZPC74, 207 (1997)

Indispensable for discovery of "new physics"

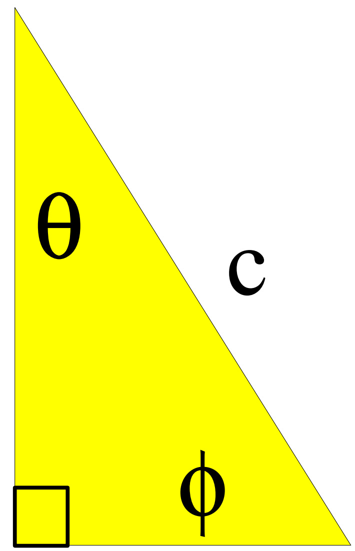
RESUMMATION

See lecture by Jeff Owens

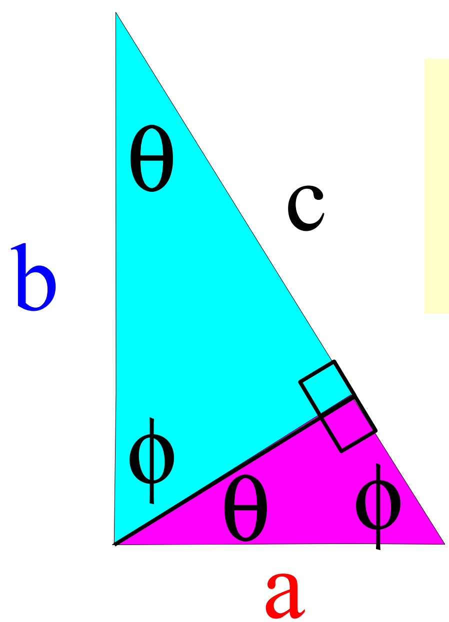
Warm up: Dimensional Analysis: Pythagorean Theorem

GOAL:
Pythagorean Theorem

METHOD:
Dimensional Analysis



$$A_c = c^2 f(\theta, \phi)$$



$$A_a + A_b =$$
$$a^2 f(\theta, \phi) + b^2 f(\theta, \phi)$$

$$A_a + A_b = A_c$$

$$a^2 + b^2 = c^2$$

Two examples to come: 1) Resummation, and 2) Scaling

Resumation: Over-Simplified

$$\left\{\mu^2 \frac{\partial}{\partial \mu^2} + \beta\left(\alpha_s(\mu)\right) \frac{\partial}{\partial \alpha_s(\mu^2)}\right\} R\left(\frac{Q^2}{\mu^2}, \alpha_s(\mu^2)\right) = 0$$

Logs can be large and spoil perturbation theory

If we expand R in powers of α_s, and we know β, we then know μ dependence of R.

$$R\left(\frac{\mu^2}{Q^2}, \alpha_s(\mu^2)\right) = R_0 + \alpha_s(\mu^2)\, R_1\left[\ln\left(Q^2/\mu^2\right) + c_1\right]$$
$$+ \alpha_s^2(\mu^2)\, R_2\left[\ln^2\left(Q^2/\mu^2\right) + \ln\left(Q^2/\mu^2\right) + c_2\right] + O\left(\alpha_s^3(\mu^2)\right)$$

Since μ is arbitrary, choose μ=Q.

$$R\left(\frac{Q^2}{Q^2}, \alpha_s(Q^2)\right) = R_0 + \alpha_s(Q^2)\, R_1\left[0 + c_1\right] + \alpha_s^2(Q^2)\, R_2\left[0 + 0 + c_2\right] + \ldots$$

We just summed the logs

QCD is non-abelian SU(3) Symmetry $\Rightarrow$ confinement

More Differential Quantities $\Rightarrow$ More Mass Scales $\Rightarrow$ More Logs!!!

$$\frac{d\sigma}{dQ^2} \sim \ln\left(\frac{Q^2}{\mu^2}\right)$$

$$\frac{d\sigma}{dQ^2} \sim \ln\left(\frac{Q^2}{\mu^2}\right) \quad and \quad \ln\left(\frac{q_T^2}{\mu^2}\right)$$

How do we resum logs? Use the Renormalization Group Equation

For a physical observable R:

$$\mu \frac{dR}{d\mu} = 0$$

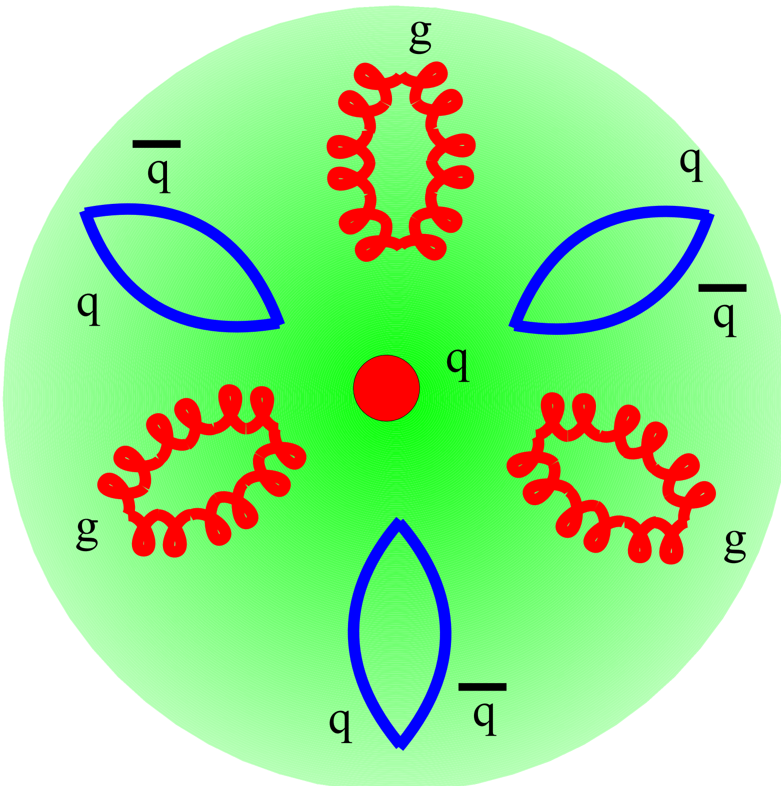
$$\mu \frac{dR}{d\ Gauge} = 0$$

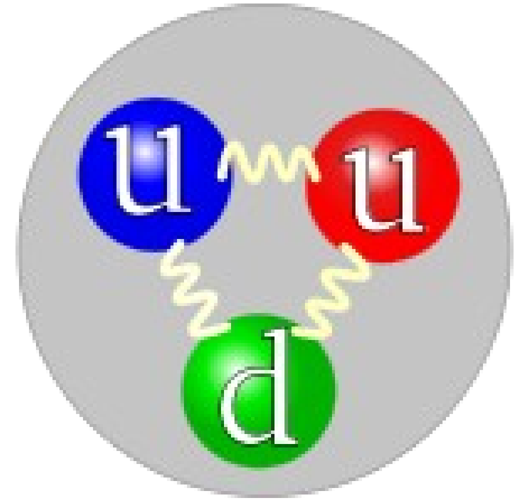
Applied to boson transverse momentum
CSS: Collins, Soper, Sterman
Nucl.Phys.B250:199,1985.

Interesting reference:
Peskin/Schroeder Text
(Renomalization ala Ken Wilson)

Scaling, and the proton structure

How do we determine the proton structure





http://en.wikipedia.org/

Quarks confined, thus we must work with hadrons & mesons

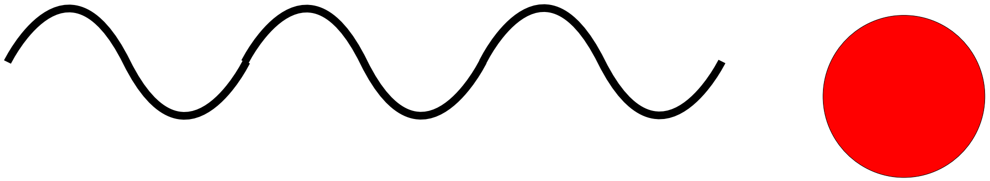
E.g, proton is a "minimal" unit

Highest energy (smallest distance) accelerators involve hadrons

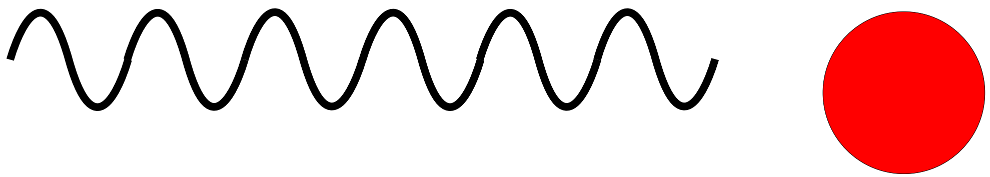
E.g., HERA, TEV, LHC

We'd better learn to work with proton

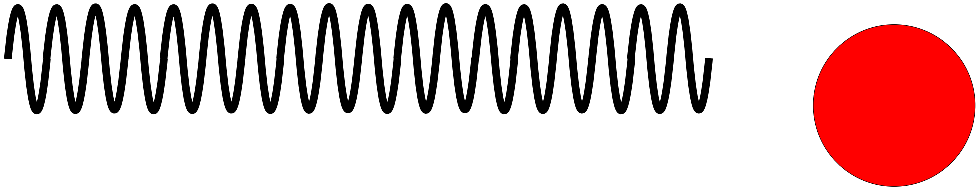
What do we expect for a point like particle



$$d\sigma \sim \frac{4\pi\alpha^2}{Q^2} \times 1$$



$$d\sigma \sim \frac{4\pi\alpha^2}{Q^2} \times 1$$

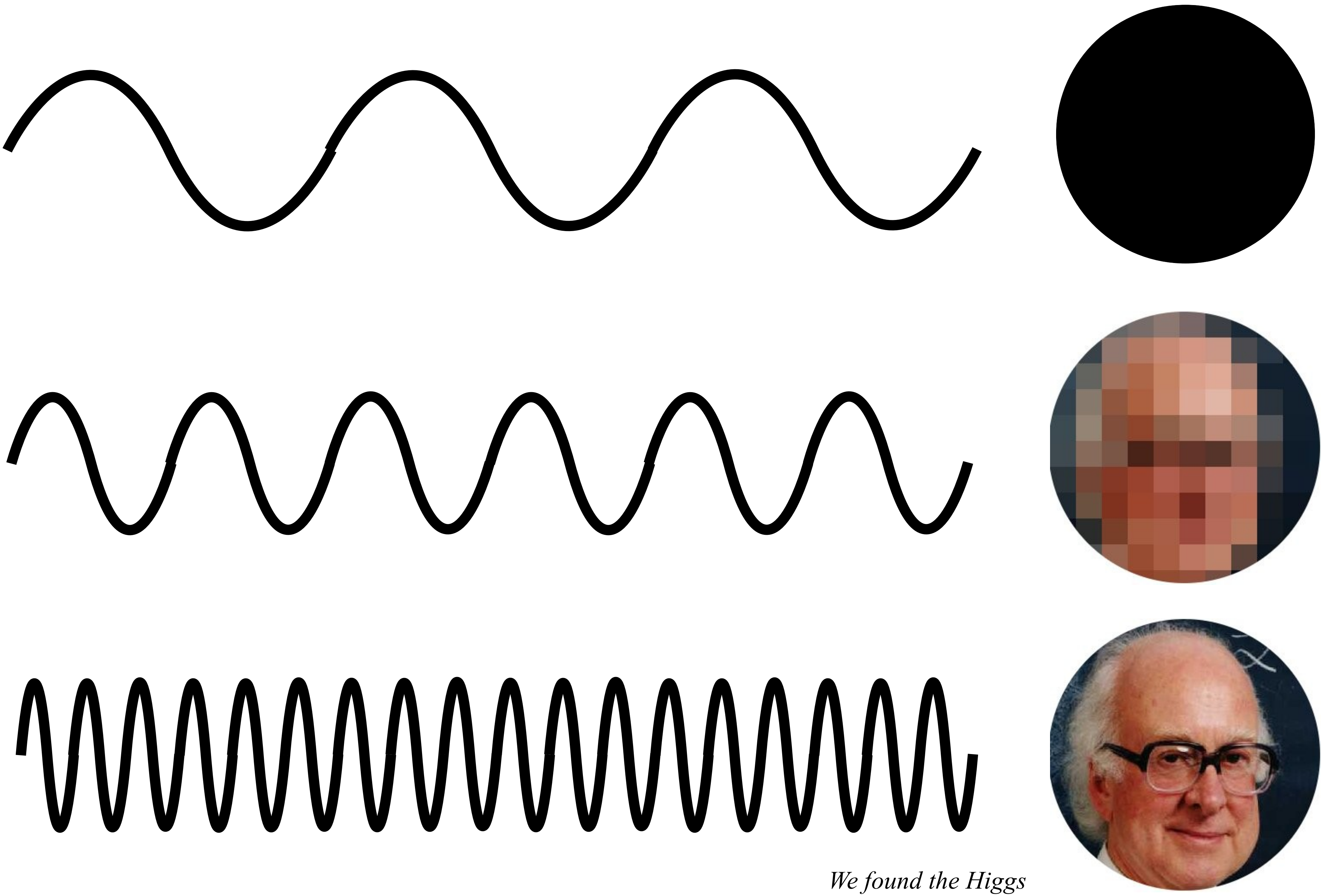


$$d\sigma \sim \frac{4\pi\alpha^2}{Q^2} \times 1$$

Dimensional considerations

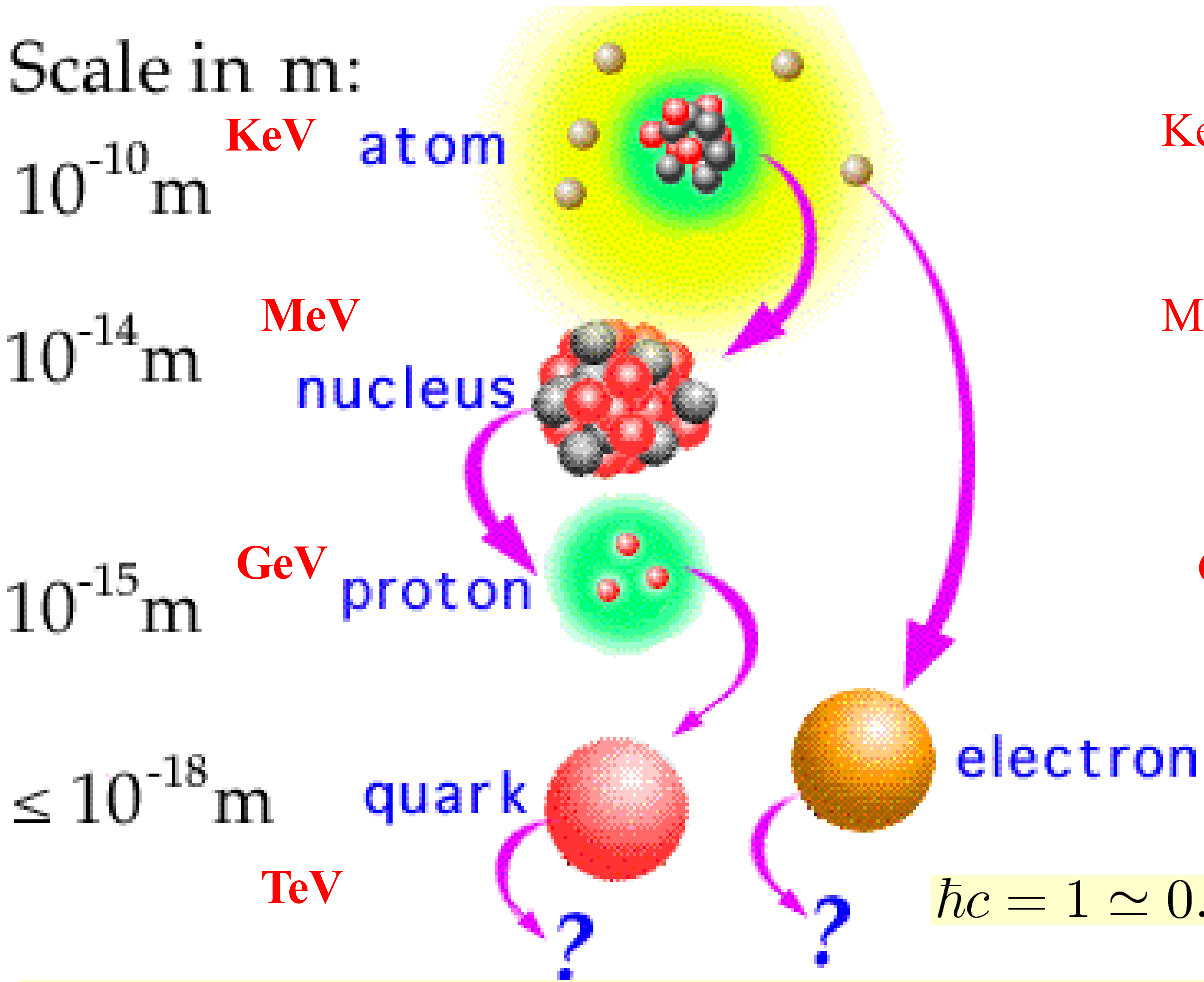
Structure Function

Is this a point like particle ???



Scaling, and the proton structure

Relative Sizes



KeV $\sim 10^{-9}$

MeV $\sim 10^{-12}$

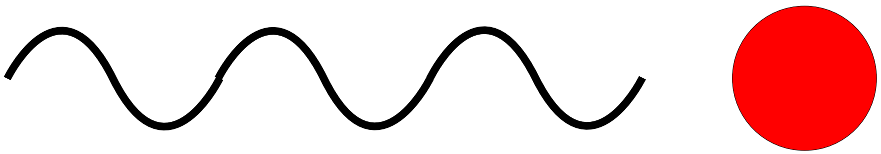
GeV $\sim 10^{-15}$

TeV $\sim 10^{-18}$

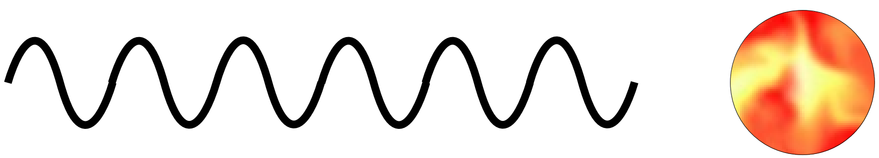
$$\hbar c = 1 \simeq 0.2 \text{ GeV fm}$$

Going to smaller scale, we get to <u>simpler</u>, more fundamental objects

Structure of the Proton

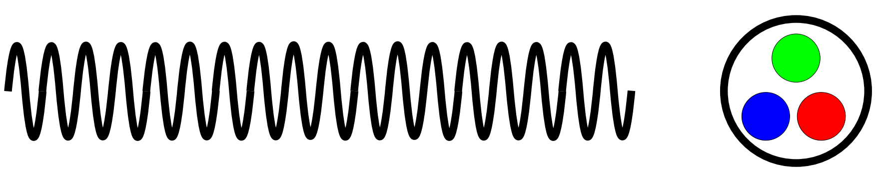


$$d\sigma \sim \frac{4\pi\alpha^2}{Q^2} \times 1$$



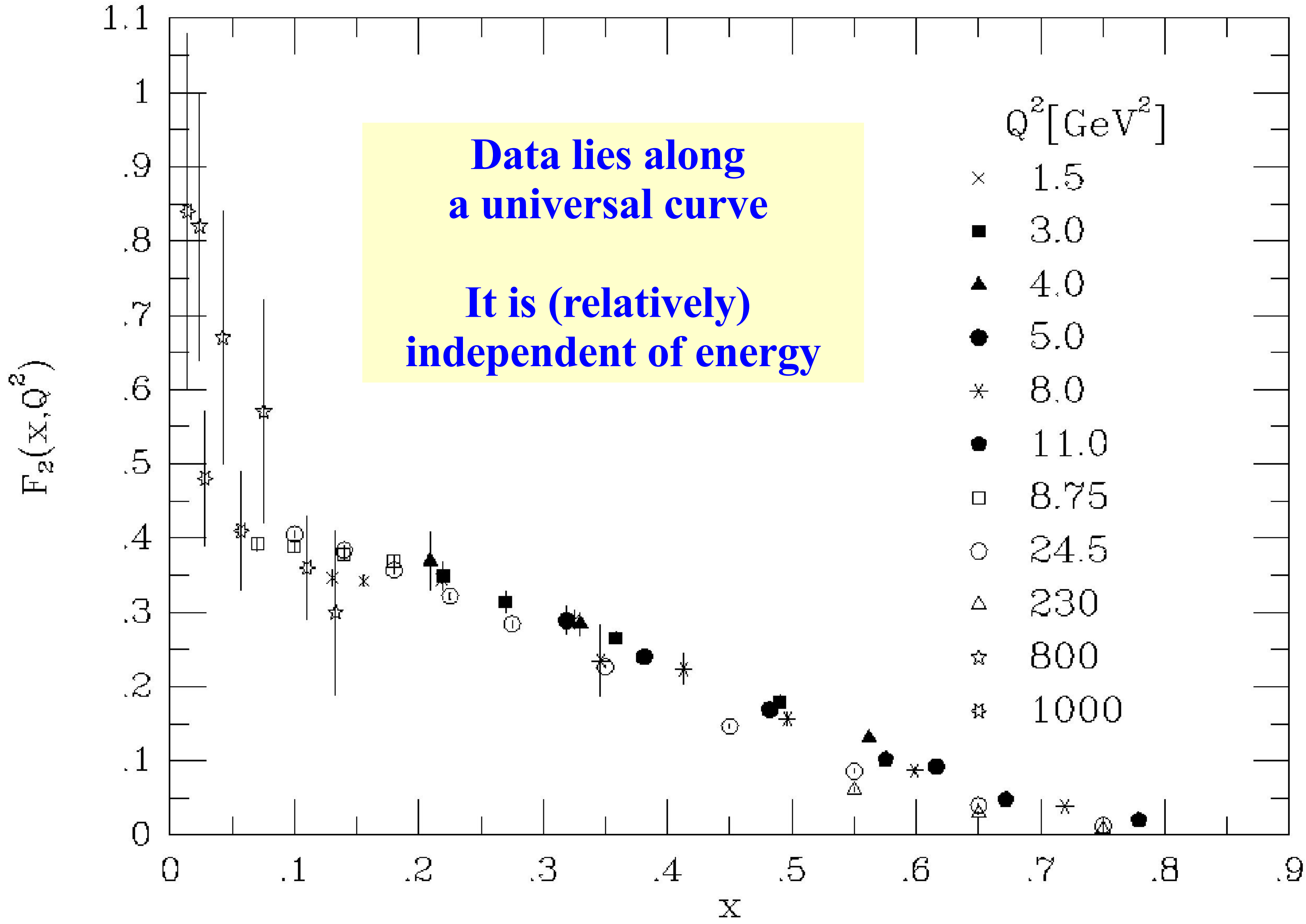
$$d\sigma \sim \frac{4\pi\alpha^2}{Q^2} \times F\left(\frac{Q^2}{\Lambda^2}\right)$$

Λ of order of the proton mass scale



$$d\sigma \sim \frac{4\pi\alpha^2}{Q^2} \times \sum_i e_i^2$$

The Scaling of the Proton Structure Function



End of lecture 1: Recap

- QCD is just like QED, ... only different
  - QCD is non-Abelian, Quarks are confined,
- Running coupling $\alpha_s(\mu)$ tells how interaction changes with distance
  - β-function: logarithmic derivative of $\alpha_s(\mu)$
  - We can compute: Negative for QCD, positive for QED
- $\alpha_s(\mu)$ is **<u>not</u>** a physical quanitity
  - Discontinous at NNLO
- New physics can influence $\alpha_s(\mu)$
  - Unification of couplings at GUT scale
- Running of $\alpha_s(\mu)$ can help us "resum" perturbation theory
- Scaling and Dimensional Analysis are useful tools

END OF LECTURE 1