Heavy quark production in e^+e^- & pp collisions

Seminar talk by Bernhard Maaß

Outline

I. Introduction to heavy quark production

II. Producing quarks in e^+e^- collisions

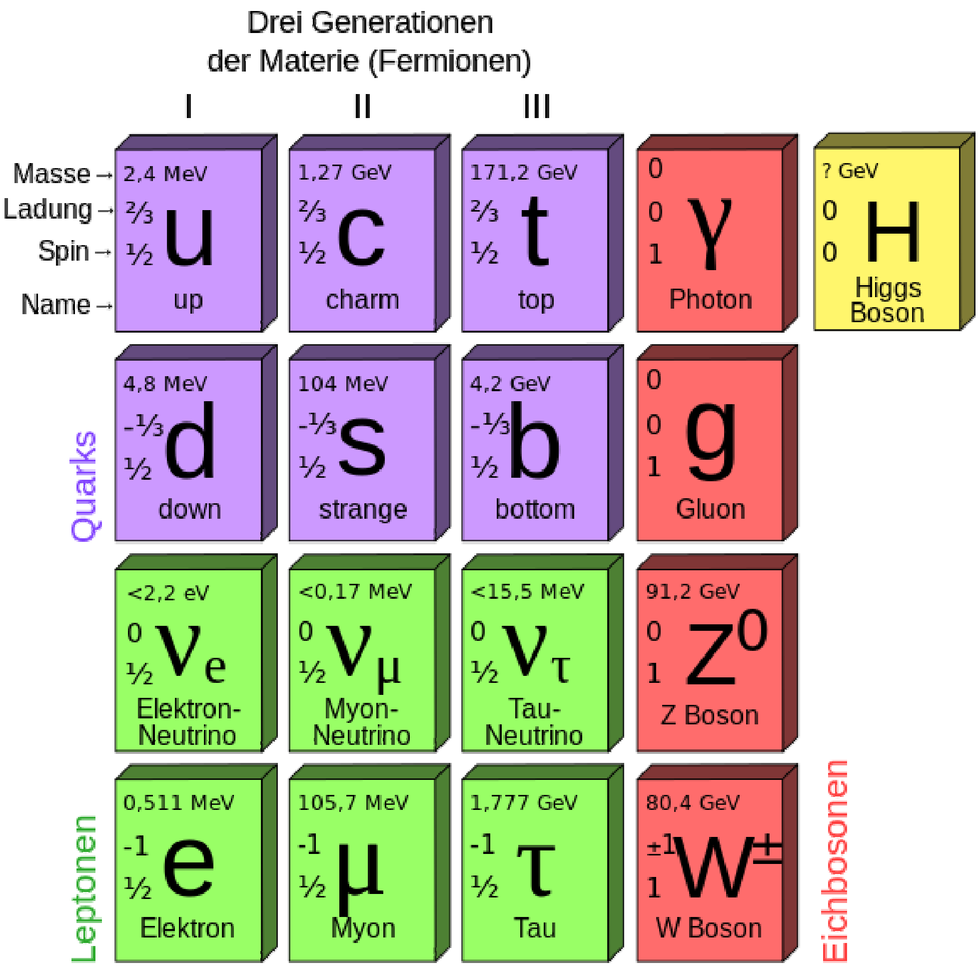
III. Hadronic structure and e^-p collisions

IV. Advanced experiments: pp collisions

Introduction to heavy quark production

I

Heavy quarks



<u>charm</u>: SLAC and Brookhaven
e^+e^- annihiliation (1974)

<u>bottom</u>: Fermilab
p-nucleus (1977)

<u>top</u>: Tevatron
p^+p^- annihilation (1995)

Source: wikipedia: quark

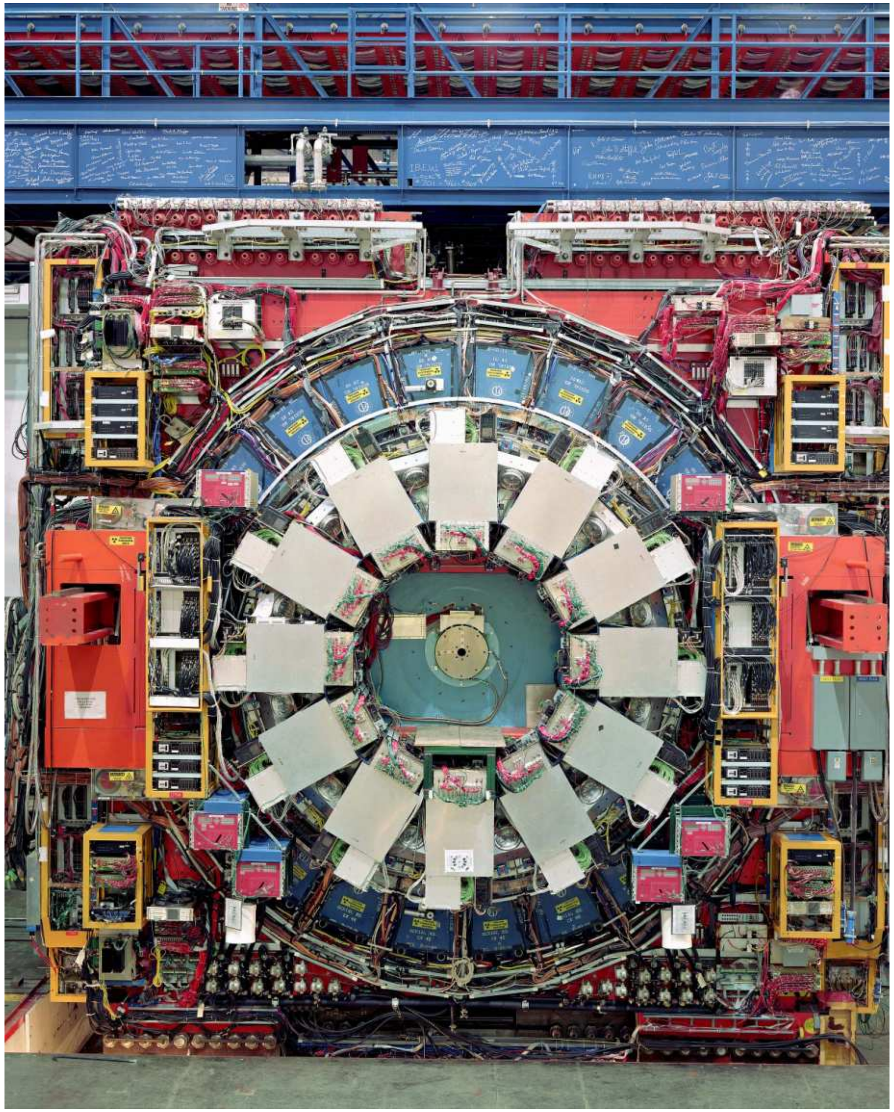
collider...

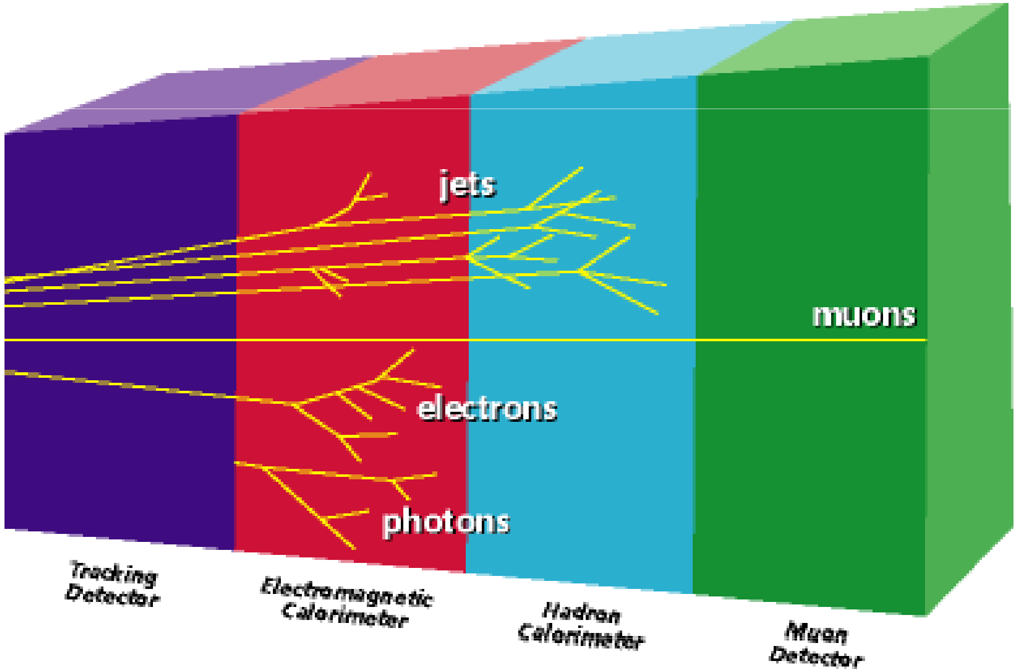
SLAC: acceleration of $e^+$and e^- up to 50 GeV

Tevatron:
acceleration of $p^+$and p^- up to 900 GeV (when discovering top-quarks)

Source: wikipedia: SLAC, Tevatron

... and particle detectors





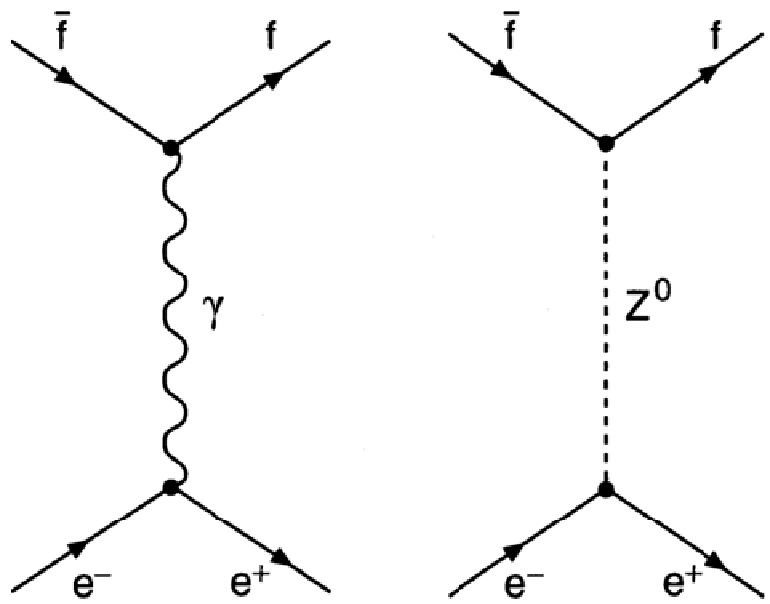
CDF-Detector from Tevatron

Source: http://www-cdf.fnal.gov/, [povh]

Producing quarks in e^+e^- collisions

II

e^+e^- annihilation



the basic process

$$e^+ + e^- \rightarrow \bar{q} + q$$

all weak/em-interacting particles can be produced

Source: [povh]

muon production as reference

Muon production

$e^+ + e^- \rightarrow \mu^+ + \mu^-$

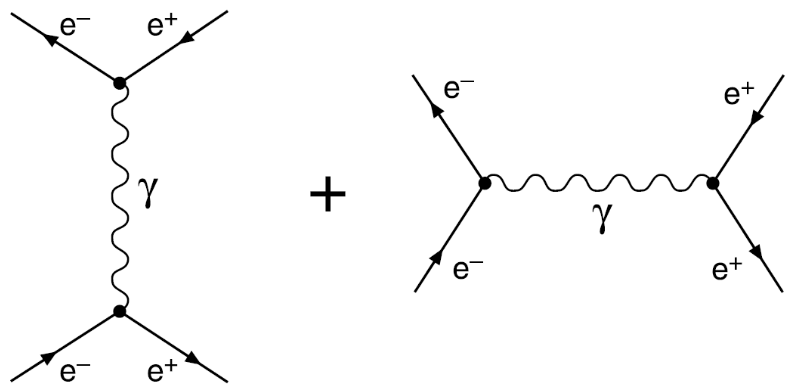
EM-process due to high Z^o mass – easy to calculate

μ-mass: 105.7 MeV
τ-mass: 1.777GeV
Z^o-mass: 91.2 GeV

reaction cross section:

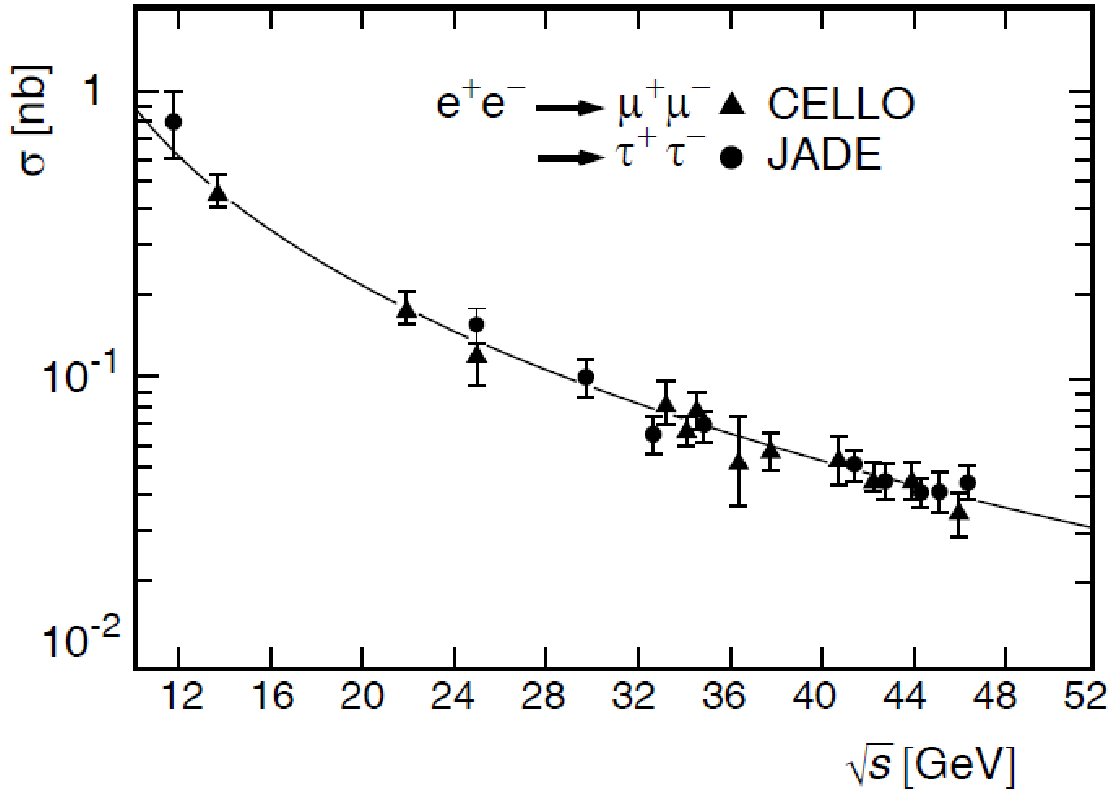
$$\sigma(e^+e^- \rightarrow \mu^+\mu^-) = 21.7 \frac{\text{nbarn}}{(E^2/\text{GeV}^2)}$$

Bhabha-Diffraction



Source: [povh]

lepton universality



lepton universality / leptons are point-masses ($< 10^{-18}$m)

Source: [povh]

Resonances and quarks

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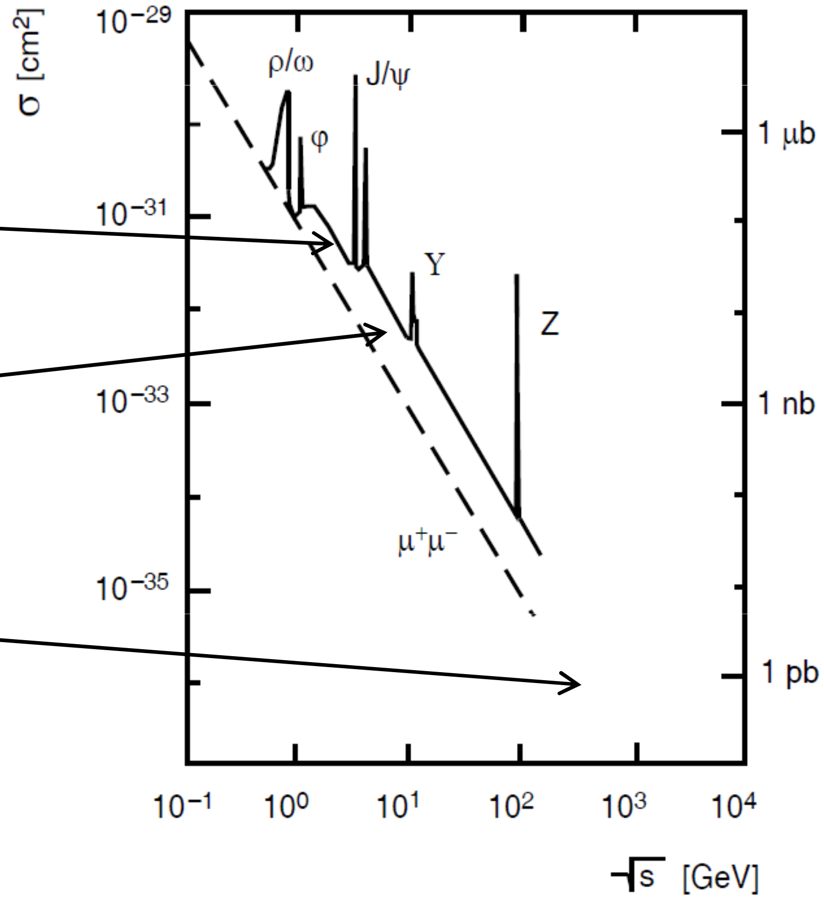
Resonances with light and heavy quarks are observed

charm

bottom

top



maximum e^+e^- collider cm-energy: ~ 172 GeV

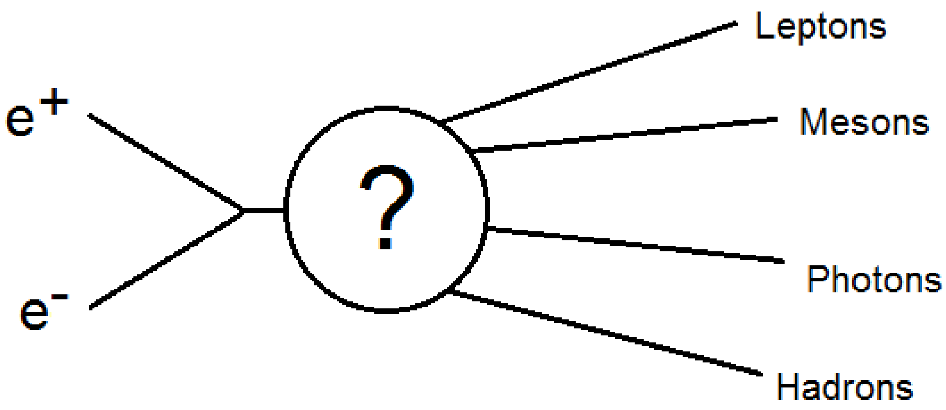
Source: [povh]

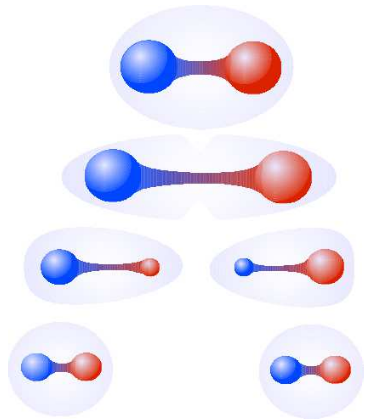
between the resonance

„<u>free quarks</u>“ can be produced between the resonances.

$e^+e^- \rightarrow q\bar{q} \rightarrow$ Hadrons

Due to color confinement, the quark/antiquark-pair will immediatly hadronize („fragmentation“)





Source: [bethke]

Fragmentation

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The (pertubative) process is on a scale of d << 1fm

$$e^+e^- \rightarrow q\bar{q} \rightarrow \text{Hadrons}$$

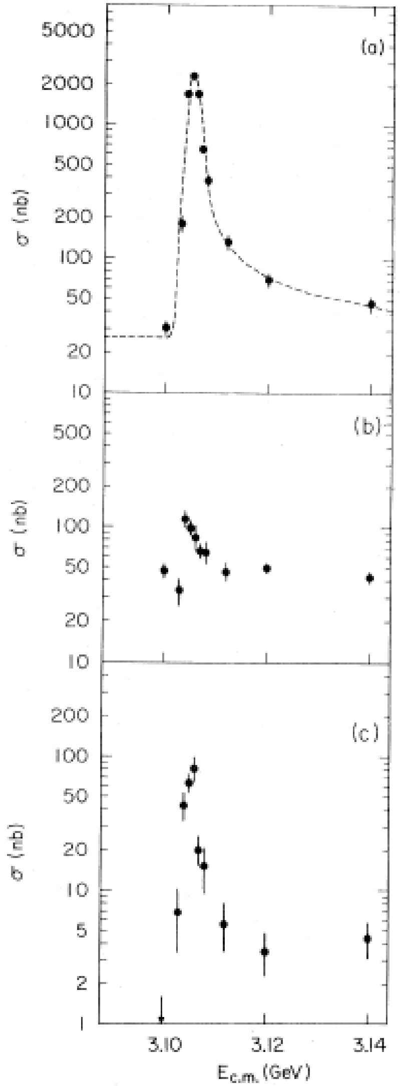
The fragmentation process occurs on much larger scales - d >> 1fm

Every quark/antiquark will hadronize and therefore:

$$\sigma(e^+e^- \rightarrow q\bar{q}) = \sigma(e^+e^- \rightarrow \text{Hadrons})$$

when $\sigma(q\bar{q} \rightarrow \text{Hadrons}) = 1$

Charm discovery



Discovery of the charm-quark:

The charm decays (mainly) into Pions and Kaons. These particles have to be detected and identified.

Decay mode	Mass Region (GeV/c^2) 1.50–1.85	1.85–2.40	2.40–4.00
$K^-\pi^+$ and $K^+\pi^-$	0.25	0.18	0.08
$K_s{}^0\pi^+\pi^-$	0.57	0.40	0.29
$\pi^+\pi^-$	0.13	0.13	0.09
K^+K^-	0.23	0.12	0.10
$K^-\pi^+\pi^+$ and $K^+\pi^-\pi^-$	0.51	0.49	0.19
$K_s{}^0\pi^+$ and $K_s{}^0\pi^-$	0.26	0.27	0.09
$K_s{}^0K^+$ and $K_s{}^0K^-$	0.54	0.33	0.09
$\pi^+\pi^-\pi^+$ and $\pi^+\pi^-\pi^-$	0.48	0.38	0.18
$K^\mp\pi^\pm$, $\bar{K}^0\pi^+\pi^-$, and $K^0\pi^+\pi^-$	1.16	0.90	0.58
K^+K^- and $\pi^+\pi^-$	0.23	0.16	0.15
$K^\mp\pi^\pm\pi^\pm$, $\bar{K}^0\pi^\pm$, and $K^0\pi^\pm$	0.64	0.51	0.30
$\bar{K}^0K^\pm$, $K^0K^\pm$, and $\pi^+\pi^-\pi^\pm$	1.10	0.76	0.29

Source: [charm], [charm2]

Production ratio

Cross section ratio:

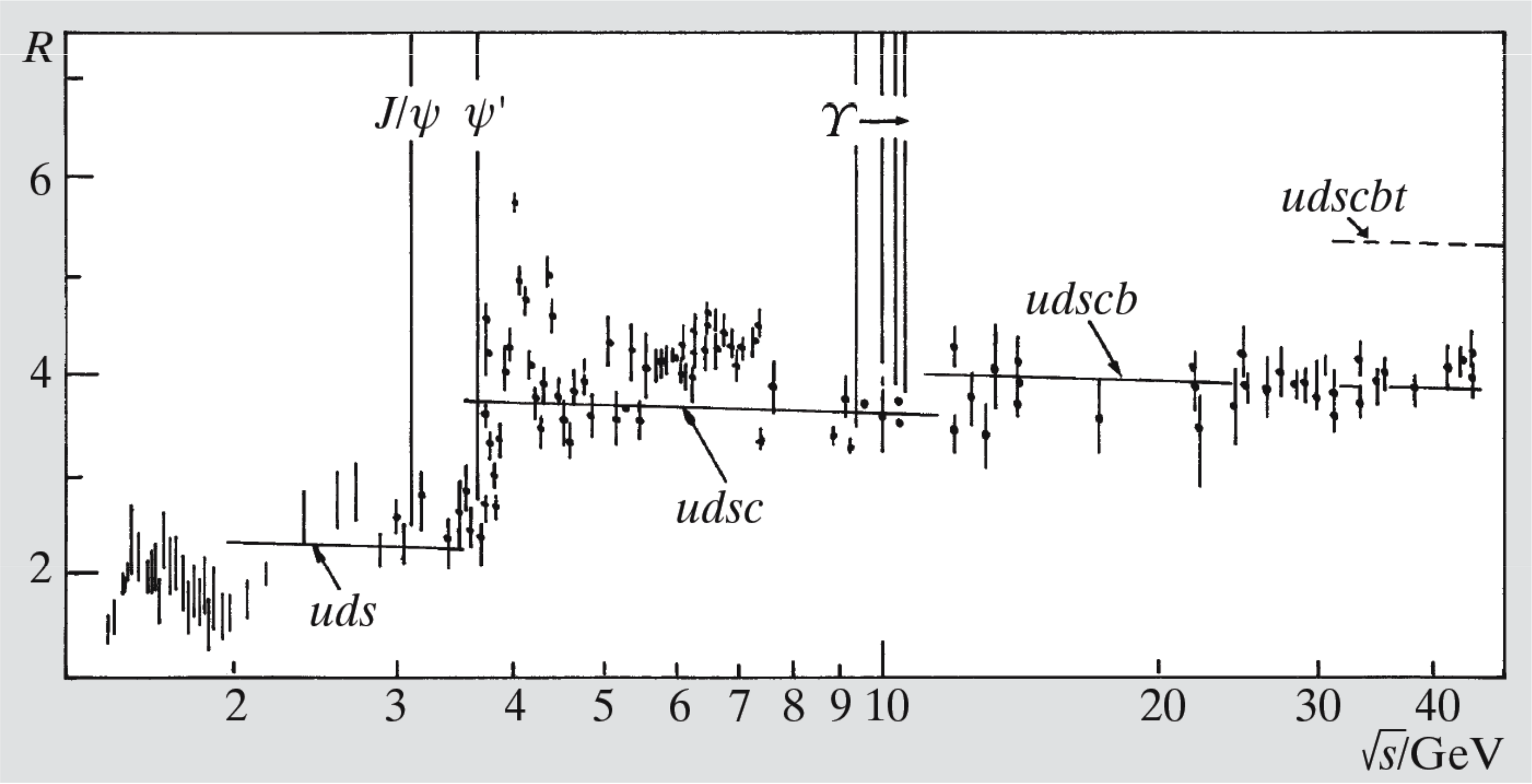
$$R = \frac{\sigma(e^+e^- \to H)}{\sigma(e^+e^- \to \mu^+\mu^-)} = \frac{\Sigma_f \sigma\left(e^+e^- \to q_f q_{\bar{f}}\right)}{\sigma(\mu^+\mu^-)}$$

The cross sections of the different quark flavours are summed up:

$$R = 3 \cdot \sum_f z_f^2 = 3 \cdot \{ \underbrace{\underbrace{\underbrace{\underset{u}{(\tfrac{2}{3})^2} + \underset{d}{(-\tfrac{1}{3})^2} + \underset{s}{(-\tfrac{1}{3})^2}}_{3 \cdot 6/9} + \underset{c}{(\tfrac{2}{3})^2}}_{3 \cdot 10/9} + \underset{b}{(-\tfrac{1}{3})^2}}_{3 \cdot 11/9} \} \, .$$

Source: [berger], [povh]

Stepwise quark production



Source: [berger]

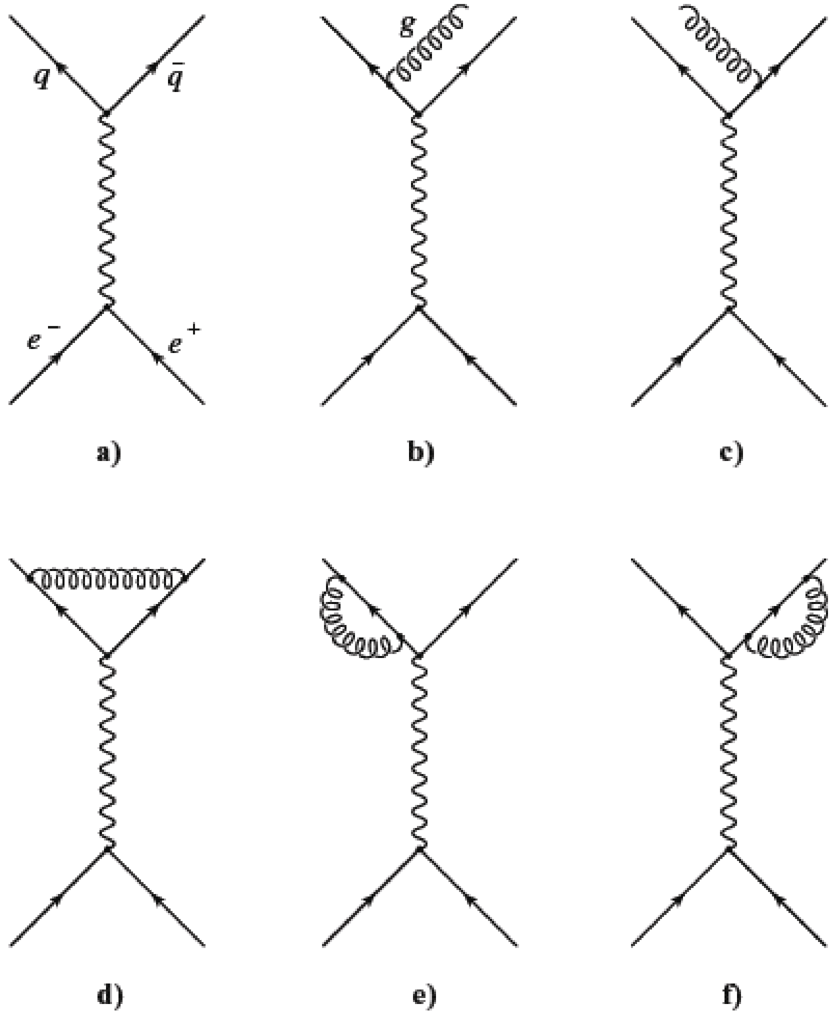
Gluons and QCD corrections

Quarks can emitt gluons
due to strong interaction:

$e^+ + e^- \rightarrow q + q + g$

A pertubative calculations yields:

$$\sigma(e^- e^+ \rightarrow \text{Hadronen}) = \sigma_0 \left(1 + \frac{\alpha_S(s)}{\pi}\right)$$

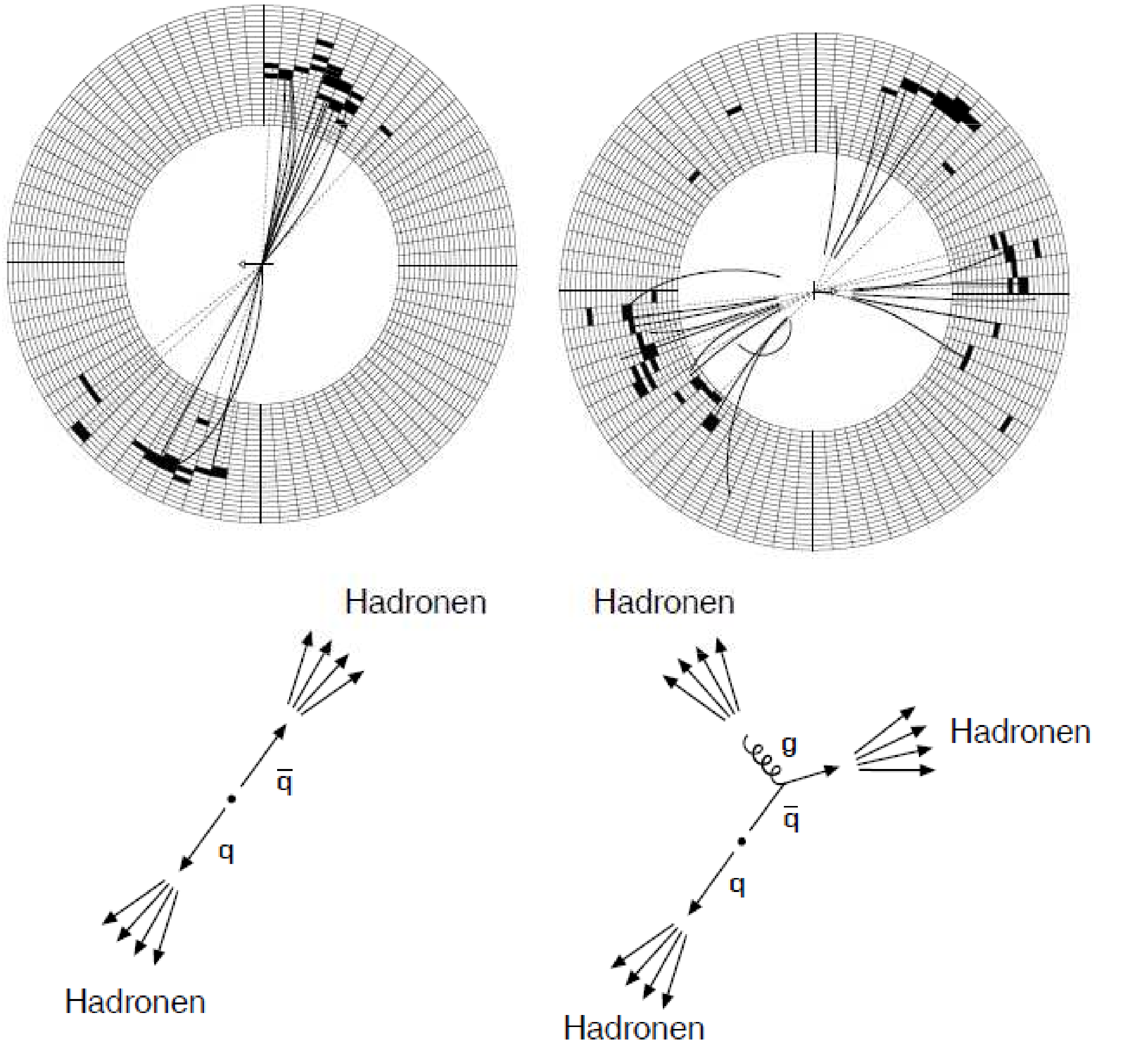


Source: [berger]

Jets

After fragmentation of the quarks, the hadrons can be detected as jets.

The ratio 2-jet/3-jet events allows the determination of the strong coupling α_s



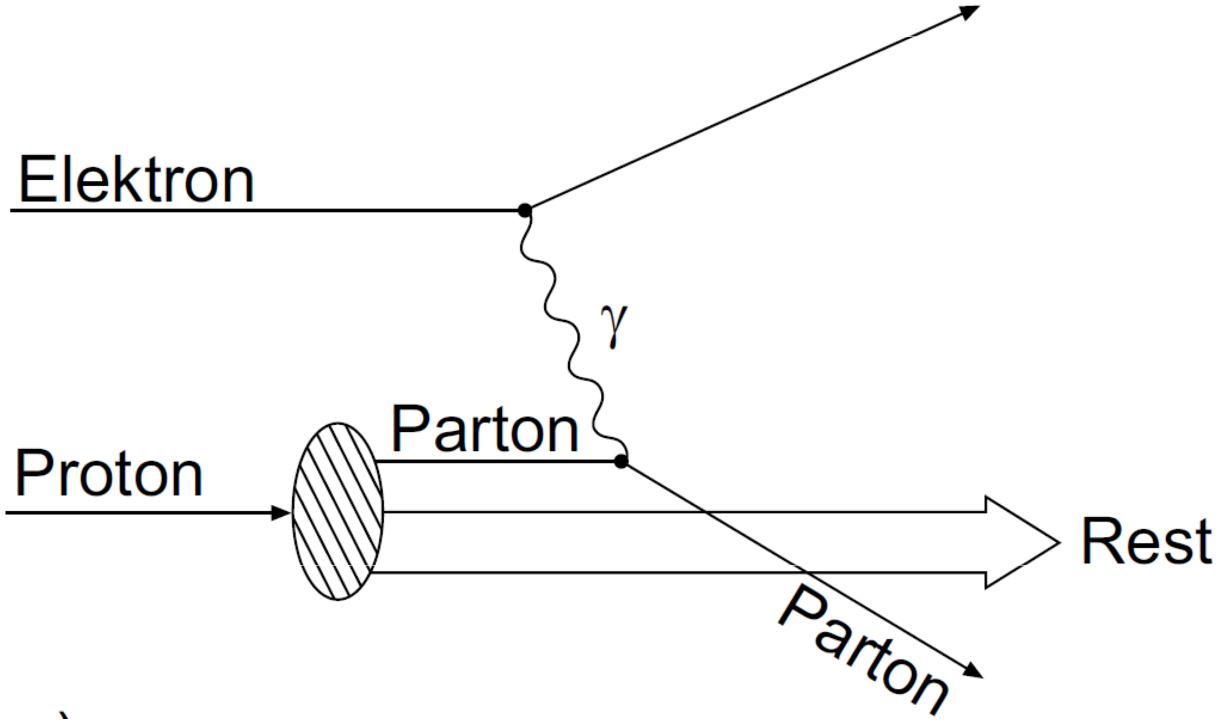
Source: [povh]

Hadronic structure and e^-p collisions

III

Parton modell

<u>Parton model</u>:
The proton consists of partons which are involved in the scattering process.



Source: [povh]

Deep inelastic scattering

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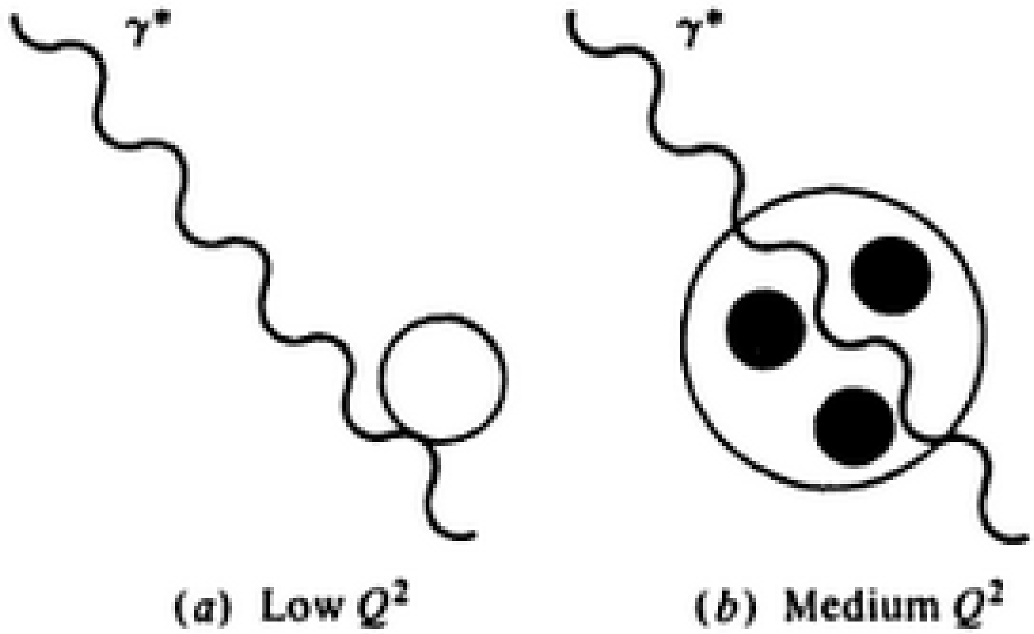
inelastic scattering:
e + p → e + X

at higher (virtual) photon energies, the proton sub-structure is revealed:

it contains three quarks.



< 1 GeV   > 1 GeV

1 GeV ~ 1.24fm

Source: [bethke]

Scaling and scaling violation

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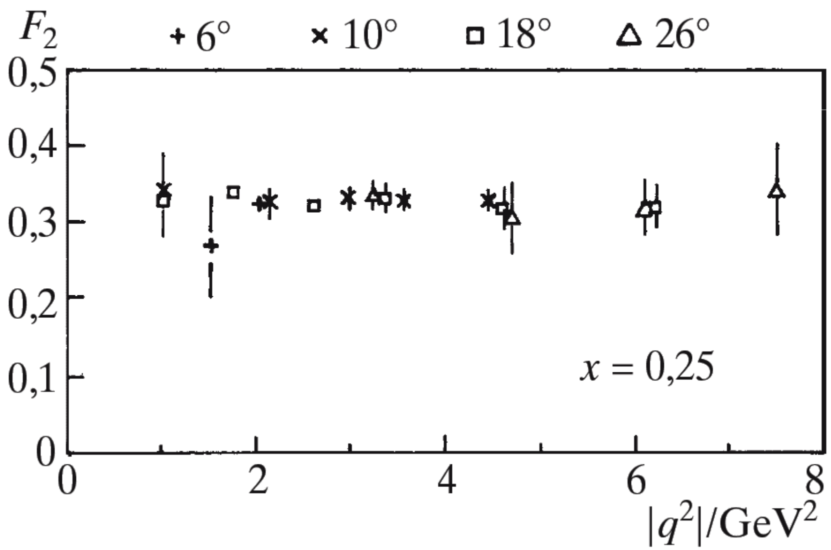
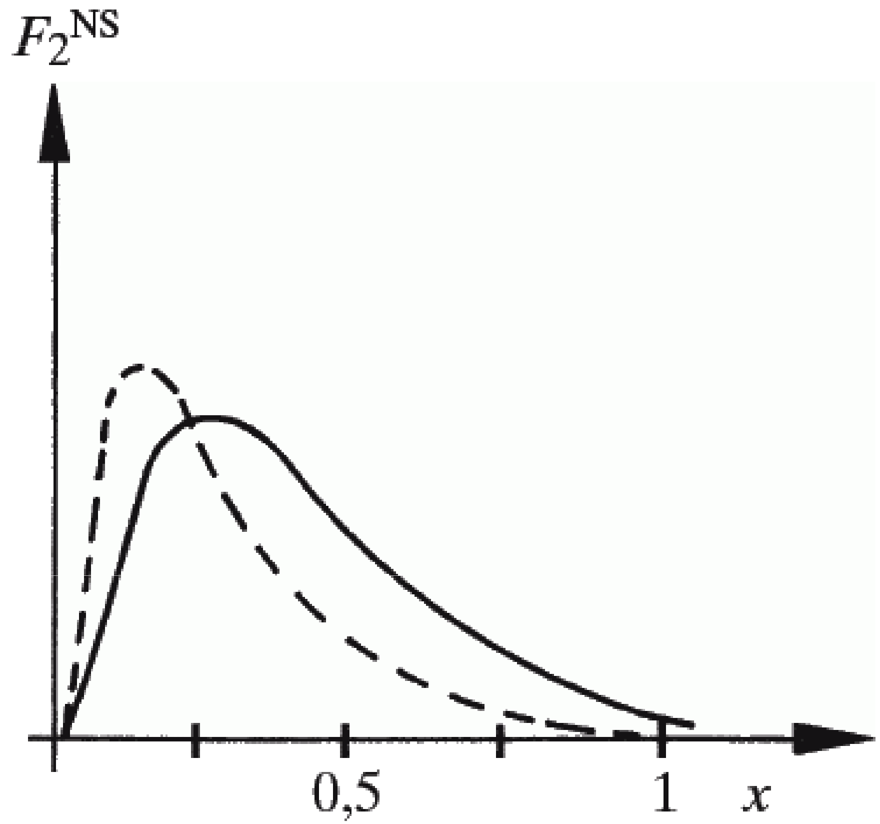


scaling of structure function...

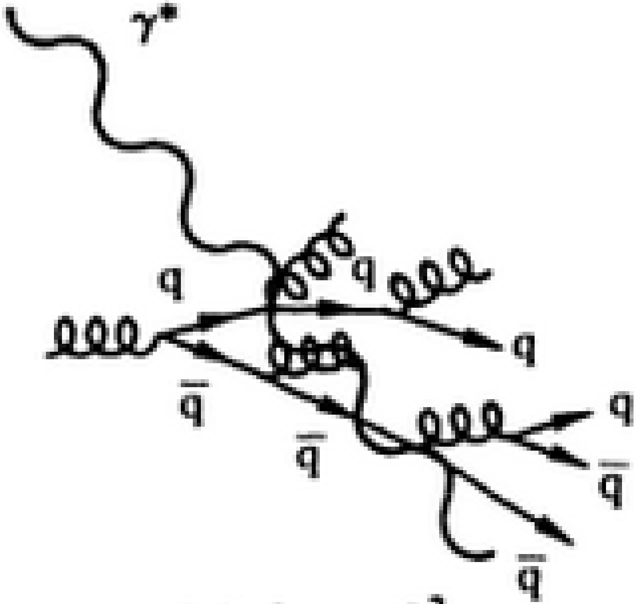


...and scaling violation

Source: [povh],[berger]

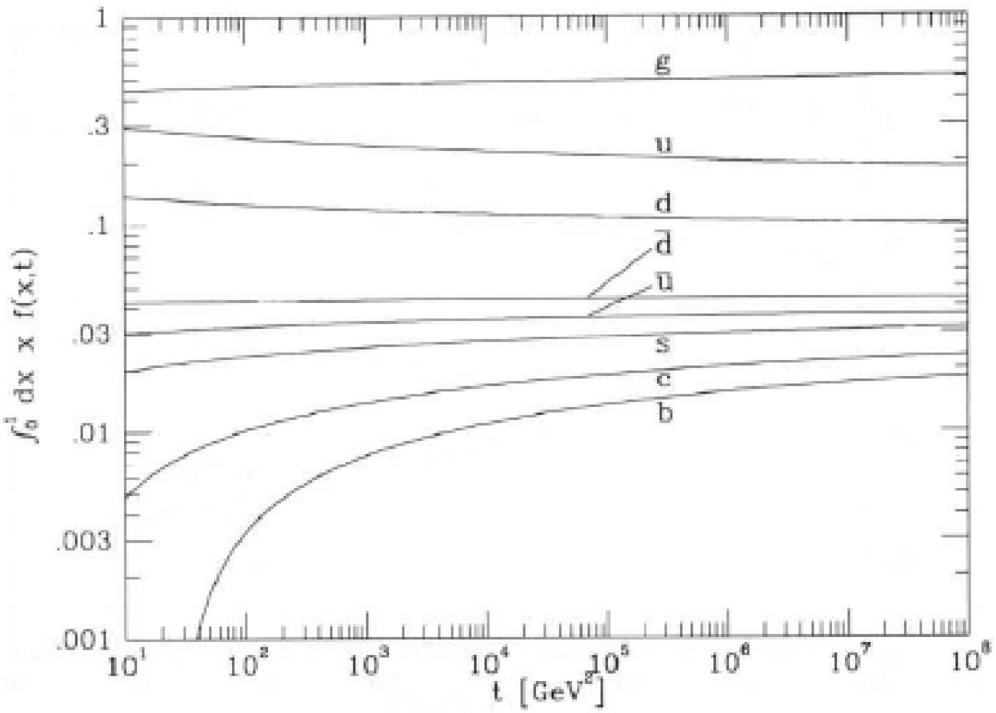
sea quarks and gluons

Sea quarks and gluons contribute to the proton structure function. They are revealed at higher scattering energies.



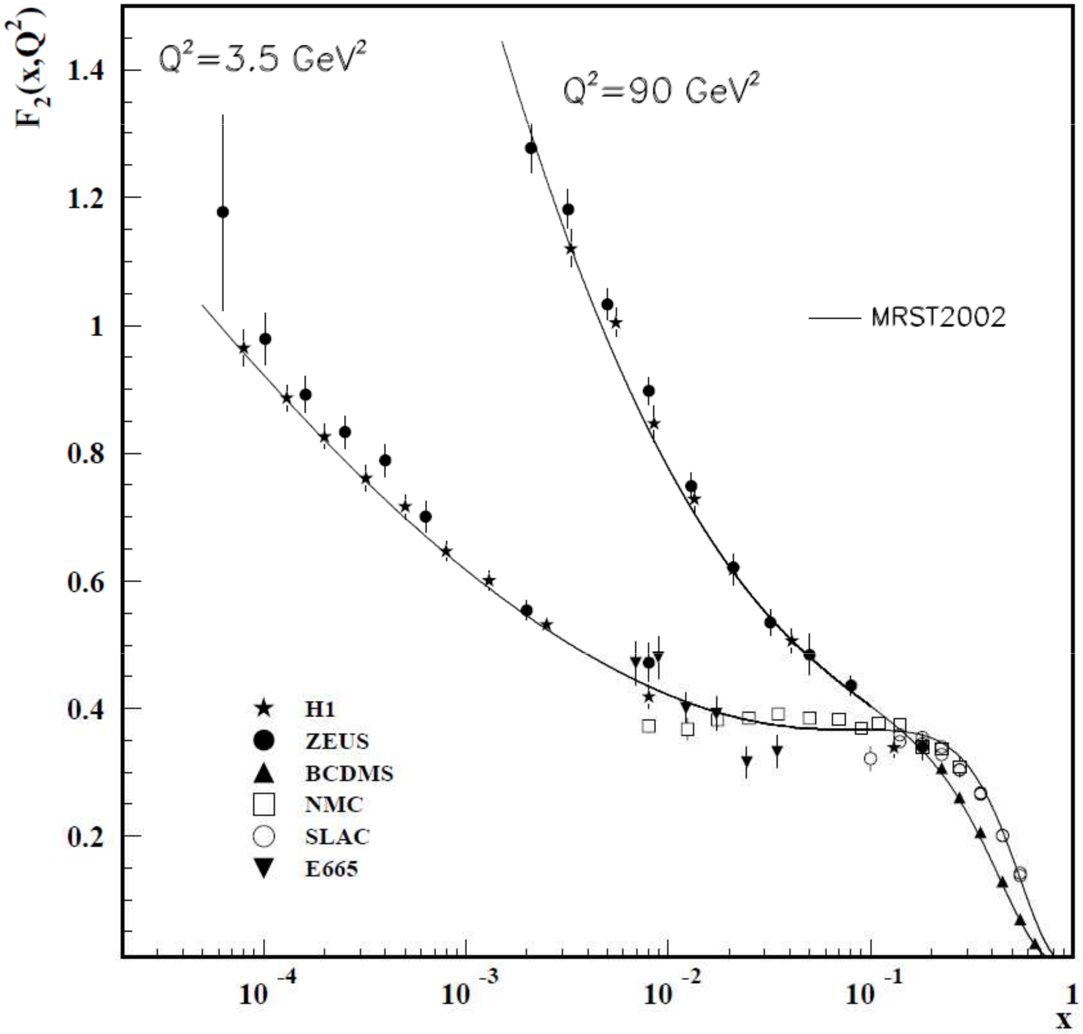
(c) Large Q^2

<< 1 GeV



Source: [bethke]

Structure function



The parton distribution function can be calculated via DGLAP-equations.

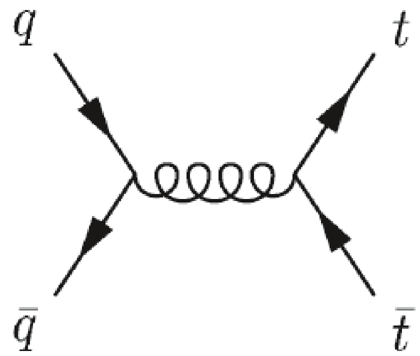
Source: [strucfunrpp]

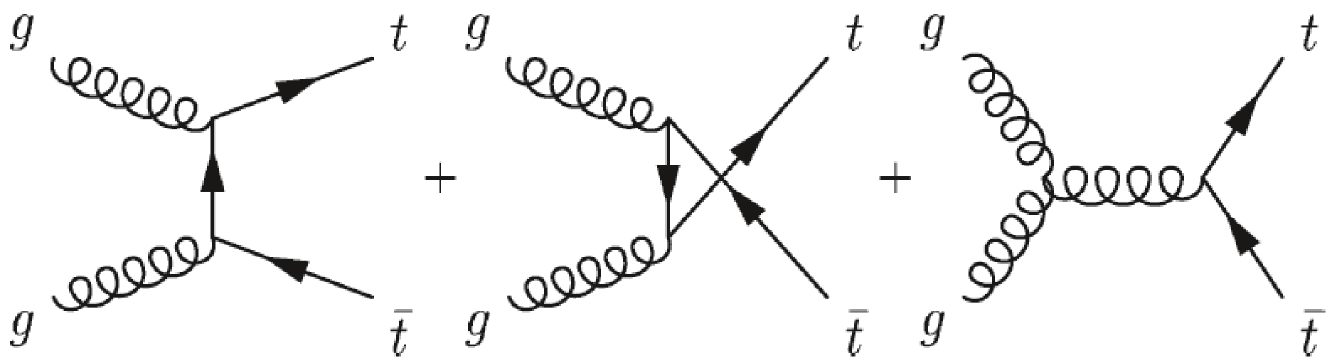
Advanced experiments: pp collisions

IV

proton-proton collisions

hard process: scattering of pointlike proton constituents.

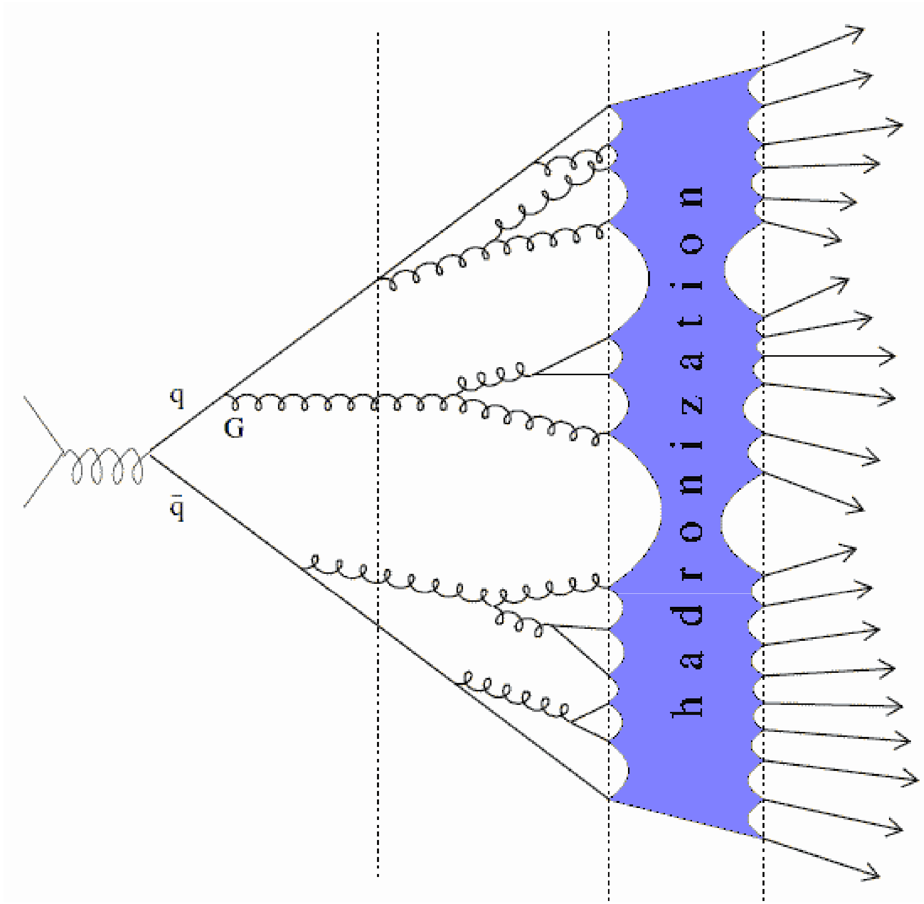




Source: [beck]

Hard and soft processes

hard process: the proton structure does not change in the time of the scattering process. It can be calculated pertubative.



soft process: in the soft reaction, the quarks fragmentize and form hadrons. This takes place in an infinite time frame.

Source: [bethke]

Factorization

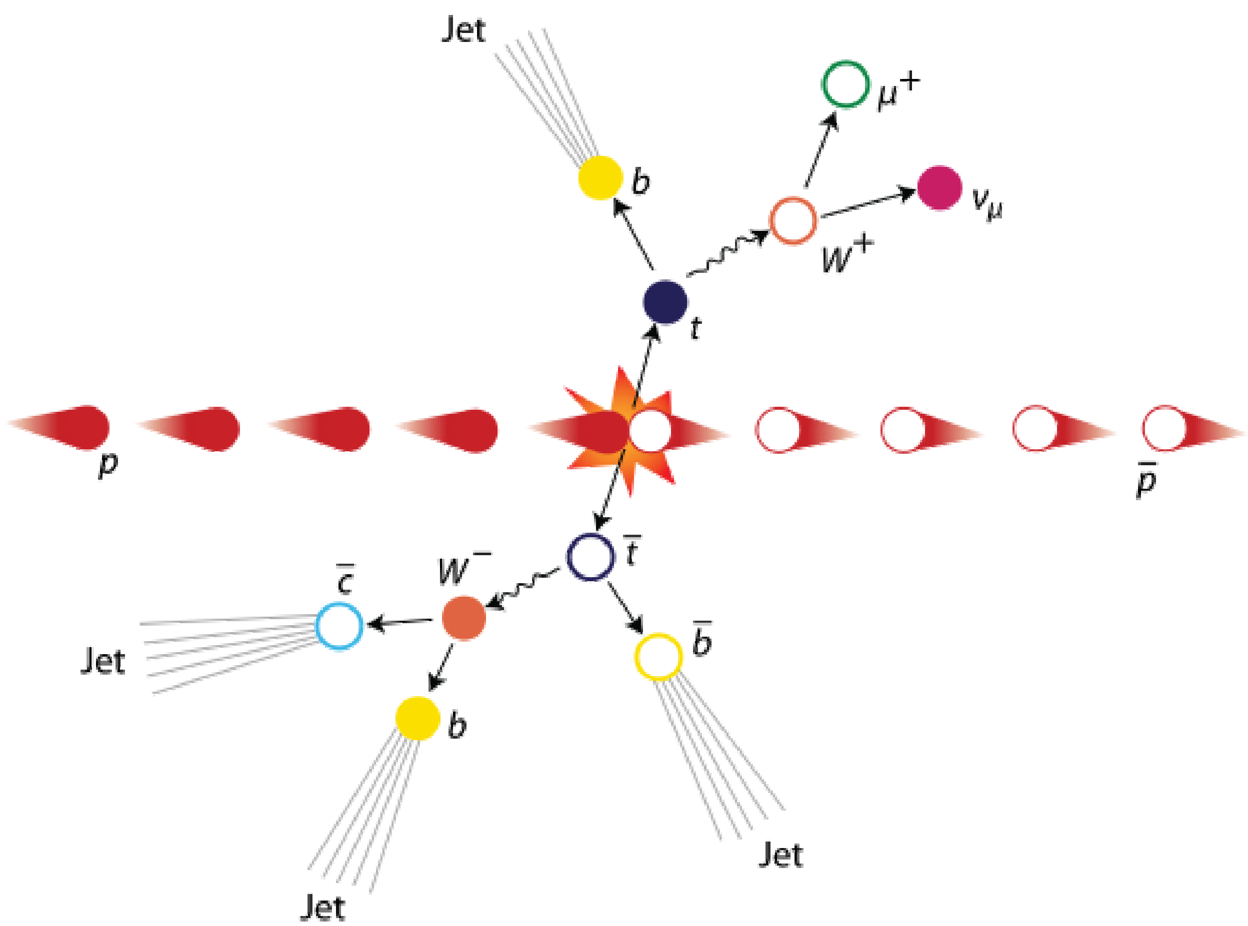
Factorization describes the total scattering cross section, which links the parton densities and the cross section of the hard process.

$$\sigma(H_1 + H_2 \to Q\overline{Q} + X) = \sum_{ij} \int \mathrm{d}x_1 f_i^{H_1}(x_1, \mu) \int \mathrm{d}x_2 f_j^{H_2}(x_2, \mu)\, \hat{\sigma}(ij \to Q\overline{Q} + X))$$

The independence of these elements are a great simplification of the model.

Source: [kraemer]

Event detection



Detectable are the particle jets which emerge from the hard scattering process.

Source: wikipedia: top antitop quark event, www-cdf.fnal.gov

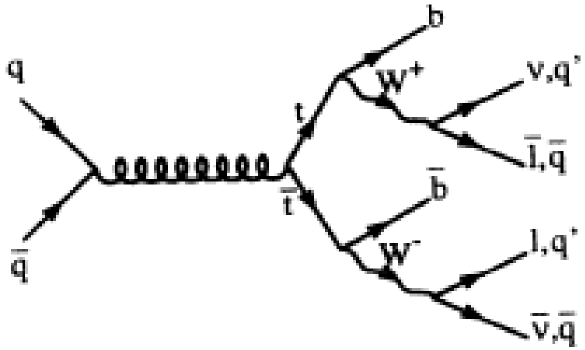
top-quark detection

TABLE I. Decay modes for a $t\bar{t}$ pair and their approximate branching ratios (to lowest order) assuming charged-current decays. The symbol q stands for a light quark: u,d,c,s.

Decay mode	Branching ratio
$t\bar{t}\to(q\bar{q}'b)(q\bar{q}'\bar{b})$	36/81
$t\bar{t}\to(q\bar{q}'b)(e\nu\bar{b})$	12/81
$t\bar{t}\to(q\bar{q}'b)(\mu\nu\bar{b})$	12/81
$t\bar{t}\to(q\bar{q}'b)(\tau\nu\bar{b})$	12/81
$t\bar{t}\to(e\nu b)(\mu\nu\bar{b})$	2/81
$t\bar{t}\to(e\nu b)(\tau\nu\bar{b})$	2/81
$t\bar{t}\to(\mu\nu b)(\tau\nu\bar{b})$	2/81
$t\bar{t}\to(e\nu b)(e\nu\bar{b})$	1/81
$t\bar{t}\to(\mu\nu b)(\mu\nu\bar{b})$	1/81
$t\bar{t}\to(\tau\nu b)(\tau\nu\bar{b})$	1/81

The decay channels can be reconstructed and their cross sections and branching ratios be determined.

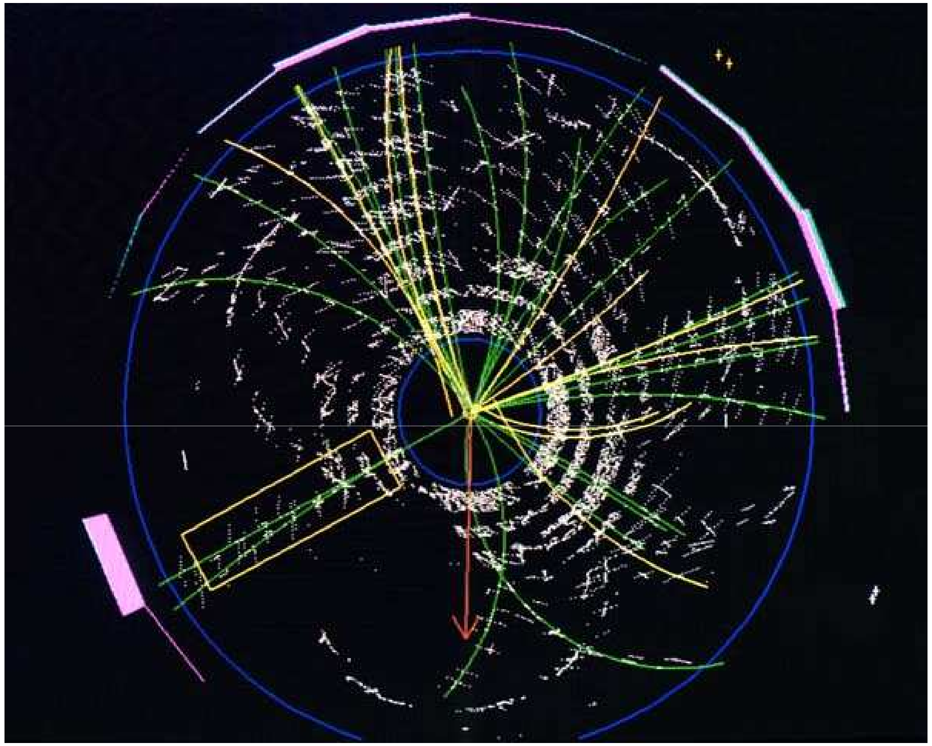
The top quark decays in bottom quarks before hadronization because of their big mass. A significant signal is a six-jet-event.

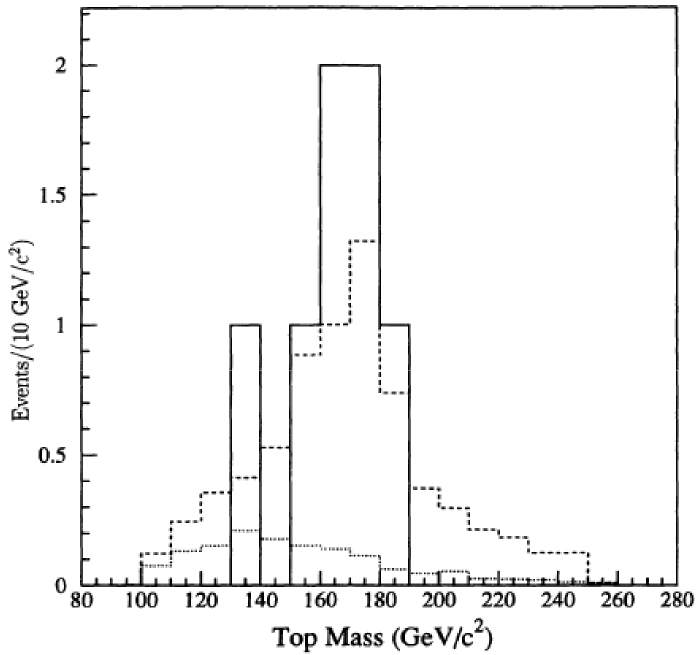


Source: [abe],[beck]

top-quark detection

The invariant mass of different decay modes can be combined to the top-quark resonance





Source: www-cdf.fnal.gov, [abe]

Summary

Depending on the c.m. energy, all quarks can be produced in e^+e^- collisions. This is easy in theory because of the point-like leptons, but it is difficult to reach sufficient energies.

pp-collisions have higher energies, but the proton sub-structure causes difficulties when extracting reaction cross sections.

This can be avoided because the hard process in which the quarks are produced occurs to be on a much smaller length and time scale than the soft hadronization (fragmentation) process – the soft and the hard process factorize. The other partons do not participate in the process as well.

Acknowledgment

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Thank you for your attention.

Also, thanks a lot to Professor Friman for the mentoring and support!

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Image sources:

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