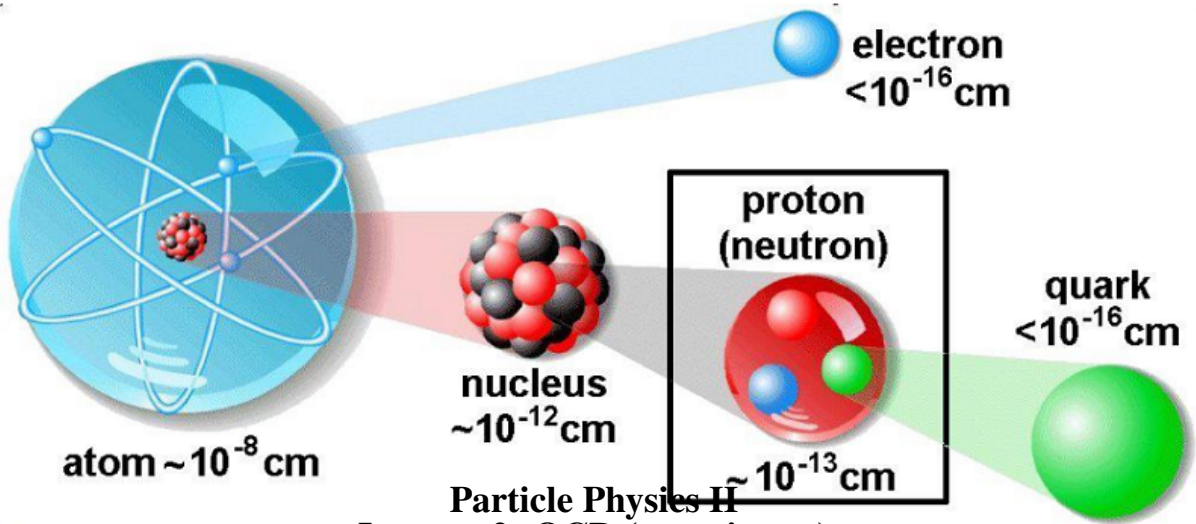




Particle Physics II
Lecture 2: QCD (experiment)

Lesya Shchutska

February 29, 2024

Quantum Chromodynamics: main experimental concepts

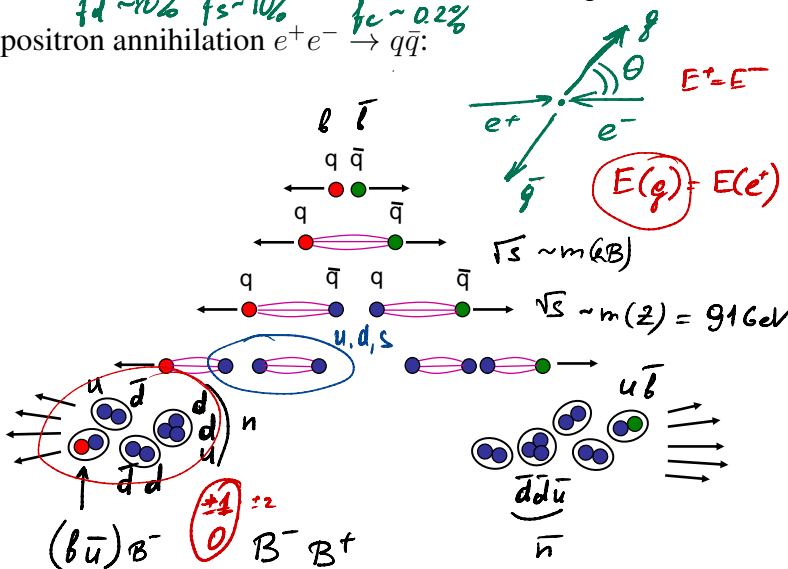
- hadronization and jets
- evidence for color existence
- gluon discovery
- α_s measurements
- importance of understanding QCD at colliders

$B_c^+ = \bar{b}c$; $B^+(\bar{b}u)$, $B^0(\bar{b}d)$, $B_s(\bar{b}s)$, $B_c^+(\bar{b}c)$, $\Lambda_b(b...)\sim 3\%$
 $f_u \sim 40\%$ $f_d \sim 40\%$ $f_s \sim 10\%$ $f_c \sim 0.2\%$

Hadronization and Jets

For example, take electron positron annihilation $e^+e^- \rightarrow q\bar{q}$:

- quarks separate at high velocity
- color flux tube forms between quarks
- energy stored in the flux tube sufficient to produce $q\bar{q}$ pairs
- continue until quarks pair up into jets of colourless hadrons



Hadronization and Jets

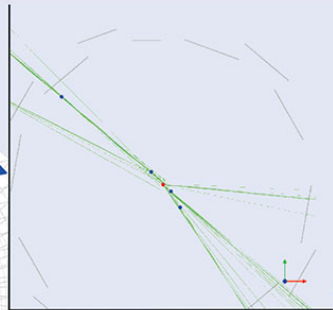
- this process is called **hadronisation**: it is not (yet) calculable, though reasonable numeric simulations exist
- the main consequence is that at collider experiments **quarks and gluons observed as jets of particles**

Jets in a detector

CMS experiment at LHC, CERN

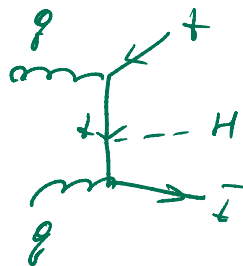
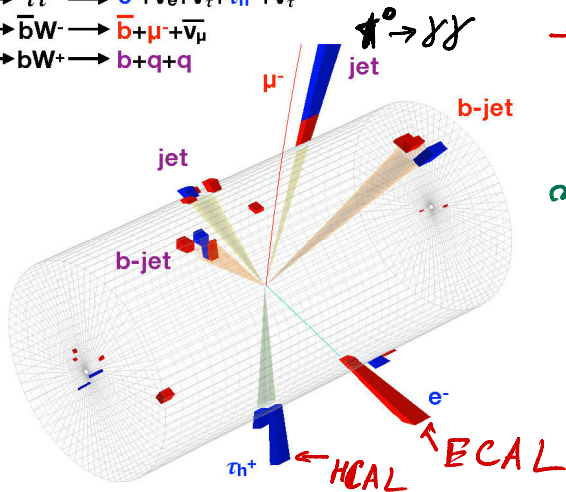
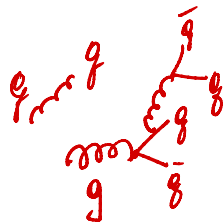
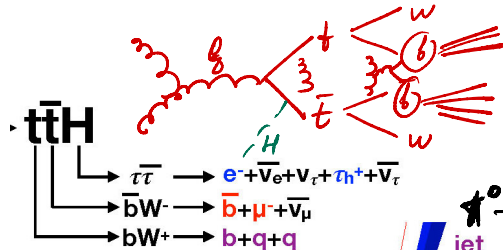
data recorded: Tuesday Sept 27 10:30:59 2016 EDT

run/event/LS: 281707/1308250303/826



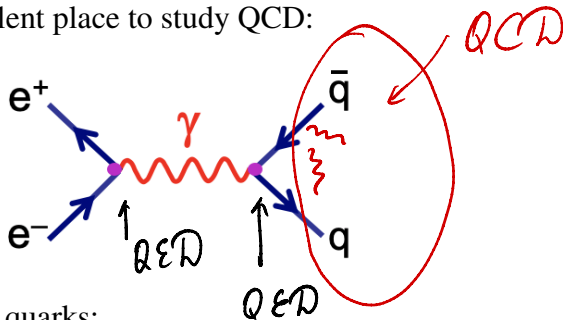
$$\vec{P}_{\text{jet}} = \sum \vec{P}_i$$

Jets in a detector



Quark studies in e^+e^-

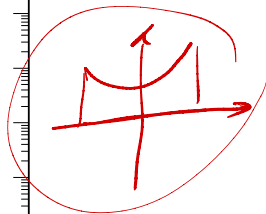
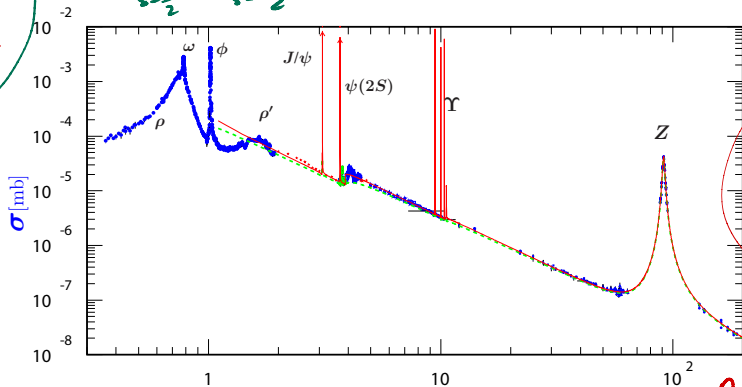
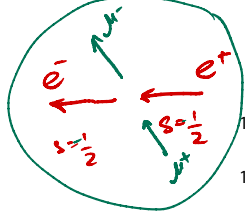
e^+e^- colliders are an excellent place to study QCD:



Well-defined production of quarks:

- QED process is well-understood
- no need to know parton structure functions of colliding particles
- experimentally very clean – no proton remnants

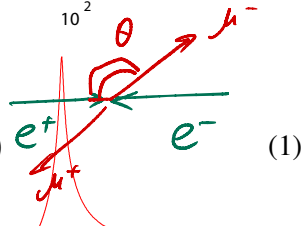
Quark spin in e^+e^-



From PPI, for $e^+e^- \rightarrow \mu^+\mu^-$ cross section:

$$\sigma = \frac{4\pi\alpha^2}{3s},$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}(1 + \cos^2 \theta)$$



(1)

Quark spin in e^+e^-

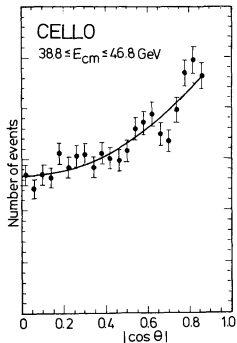


Fig. 1. Angular distribution of the corrected sphericity axis. The solid line corresponds to a fit of $1 + a \cos^2 \theta$ with $a = 1.00 \pm 0.01$.

$\sim 1 + \cos^2 \theta$

- produce all quark flavors for which $\sqrt{s} > 2m_q$
- in general, unless producing a $q\bar{q}$ bound state, produce jets of hadrons
- usually can't tell which jet comes from quark and which from anti-quark
- measured angular distribution of jets $\propto (1 + \cos^2 \theta)$
 $\Rightarrow$ quarks are spin $\frac{1}{2}$

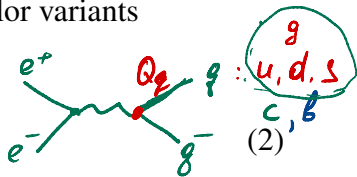
CELLO at PETRA in DESY: "Determination of α_s and $\sin^2 \theta_W$ from measurements of the total hadronic cross section in e^+e^- annihilation", *Phys. Lett. B* 183 (1987) 400

$e^+e^- \rightarrow e^+e^-$ (s,t)  $\sum_{\text{color}}$ $\sigma_{\text{tot}} = |A_1 + A_2|^2$
 $e^+e^- \rightarrow e^+e^-$ (b,u) σ_{tot}

Quark color in e^+e^-

- color is conserved, $q\bar{q}$ produced with three color/anti-color variants
- for a **single quark flavor** and **single color**:

$$\sigma(e^+e^- \rightarrow q_i\bar{q}_i) = \frac{4\pi\alpha^2}{3s} Q_q^2$$



- experimentally observe jets of hadrons of all flavors (and **3** colors):

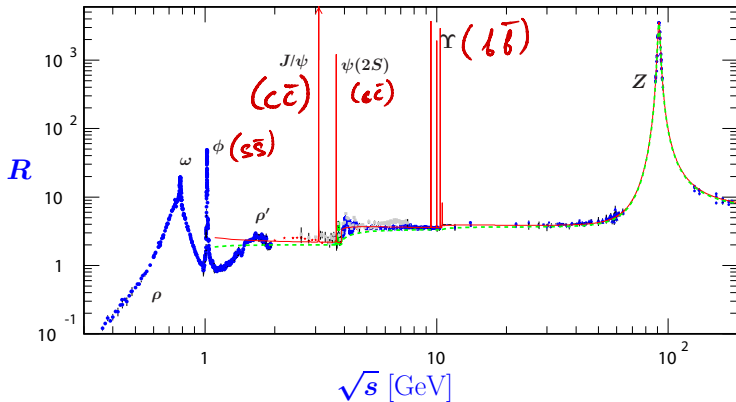
$$\sigma(e^+e^- \rightarrow \text{hadrons}) = 3 \sum_{u,d,s,\dots} \frac{4\pi\alpha^2}{3s} Q_{u,d,s,\dots}^2$$

- usually use a ratio R wrt $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$:

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = 3 \sum_{u,d,s,\dots} Q_{u,d,s,\dots}^2$$

~~$A_{\text{tot}} = A_1 + A_2 + A_3$~~
 ~~$\sigma_{\text{tot}} = |A_1 + A_2 + A_3|^2$~~
 ~~$\sigma_{\text{tot}} = |A_1 + A_2|^2 (3) = 9|A_1|^2$~~
 $\sigma \sim |A|^2$
 $\sigma_{\text{tot}} = \sigma_2 + \sigma_b + \sigma_g =$
 $3 |A|^2$ (4)

Quark color in e^+e^- : measurements



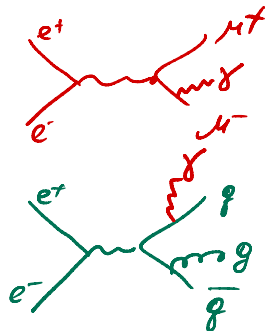
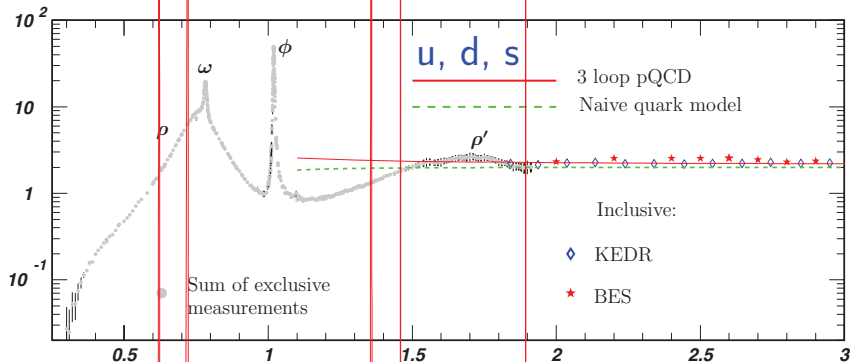
$$\mathbf{u, d, s: } R = 3 \times \left(\frac{1}{9} + \frac{4}{9} + \frac{1}{9} \right) = 2$$

$$\mathbf{u, d, s, c: } R = 3 \times \left(\frac{1}{9} + \frac{4}{9} + \frac{1}{9} + \frac{4}{9} \right) = \frac{10}{3}$$

$$\mathbf{u, d, s, c, b: } R = 3 \times \left(\frac{1}{9} + \frac{4}{9} + \frac{1}{9} + \frac{4}{9} + \frac{1}{9} \right) = \frac{11}{3}$$

Data are consistent with factor 3 from color!

Quark color in e^+e^- : zoomed-in measurements



u, d, s: $R = 3 \times \left(\frac{1}{9} + \frac{4}{9} + \frac{1}{9} \right) = 2$

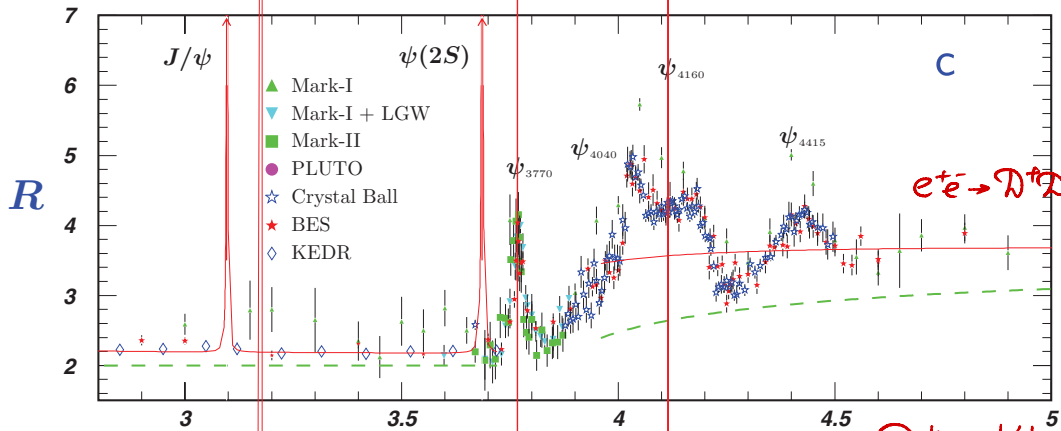
Green dashed line is the lowest order prediction assuming three colors (as shown here).

The solid red lines are computed with 3-loop perturbative QCD prediction, which includes the next order contributions as e.g. $e^+e^- \rightarrow \mu^+\mu^-\gamma$, $e^+e^- \rightarrow q\bar{q}\gamma$ or $e^+e^- \rightarrow q\bar{q}g$, summing up to about 10% correction dominated by the last diagram and α_s value.

$$e^+e^- \rightarrow J/\psi \rightarrow \pi^+\pi^-$$

Quark color in e^+e^- : zoomed-in measurements

$$D^+(c\bar{d})$$



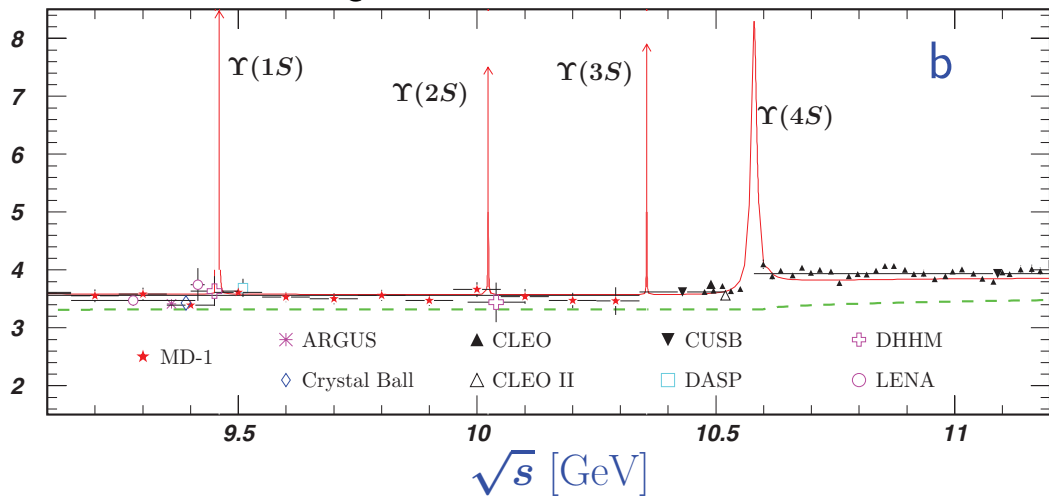
$$e^+e^- \rightarrow D^+D^-$$

$$e^+e^- \rightarrow u\bar{u} \rightarrow n\pi^+\pi^- \quad \text{u, d, s, c: } R = 3 \times \left(\frac{1}{9} + \frac{4}{9} + \frac{1}{9} + \frac{4}{9} \right) = \frac{10}{3}$$

$$D^+ \rightarrow K^+\pi^0$$

$$D^+ \rightarrow K^+K^-\pi^+\pi^-$$

Quark color in e^+e^- : zoomed-in measurements

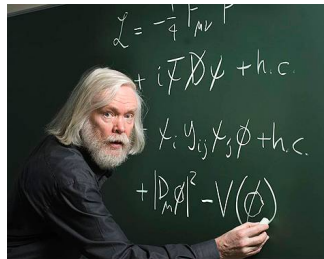


u, d, s, c, b: $R = 3 \times \left(\frac{1}{9} + \frac{4}{9} + \frac{1}{9} + \frac{4}{9} + \frac{1}{9} + \right) = \frac{11}{3}$

The Discovery of the Gluon

From John Ellis in <https://arxiv.org/abs/1409.4232>:

Abstract: “Soon after the postulation of quarks, it was suggested that they interact via gluons, but direct experimental evidence was lacking for over a decade. In 1976, Mary Gaillard, Graham Ross and the author suggested searching for the gluon via 3-jet events due to gluon bremsstrahlung in e^+e^- collisions. Following our suggestion, the gluon was discovered at DESY in 1979 by TASSO and the other experiments at the PETRA collider.”

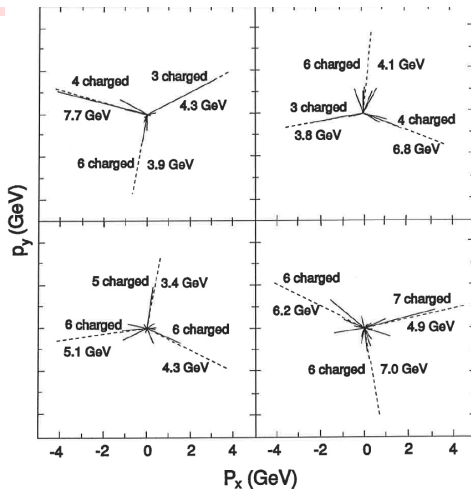


p.4: This was the context in 1976 when I was walking over the bridge from the CERN cafeteria back to my office one day. Turning the corner by the library, the thought occurred that the simplest experimental situation to search directly for the gluon would be through production via bremsstrahlung in electron-positron annihilation: $e^+e^- \rightarrow q\bar{q}g$.

What could be simpler?



The Discovery of the Gluon



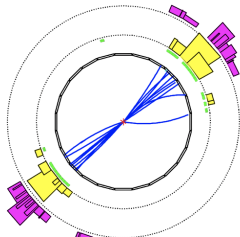
TASSO

Three-jet events shown at the EPS Conference in Geneva, June 27-July 4, 1979, by Paul Söding of TASSO.

Four decades of gluons celebrated in 2019

$$e^+e^- \rightarrow q\bar{q} \rightarrow 2\text{jets}$$

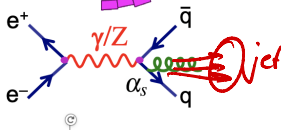
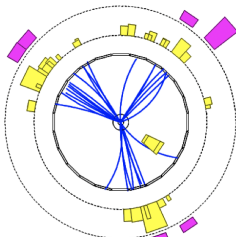
OPAL at LEP (1989-2000)



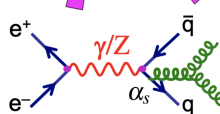
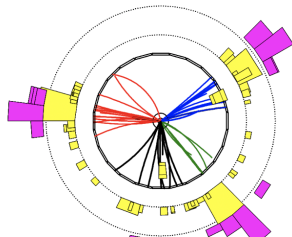
$$m = \sqrt{(q_F)^2 - (q)^2}$$

$$= 2E$$

$$e^+e^- \rightarrow q\bar{q}g \rightarrow 3\text{jets}$$



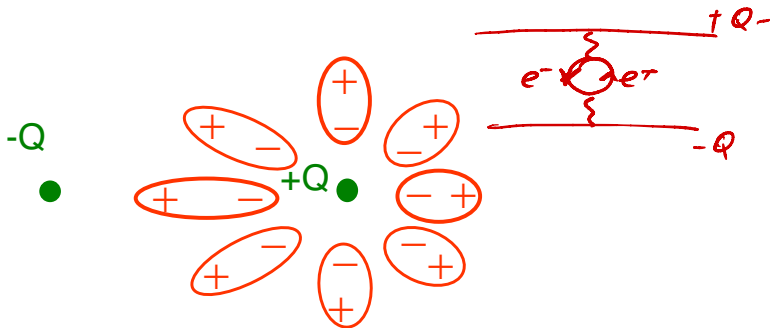
$$e^+e^- \rightarrow q\bar{q}gg \rightarrow 4\text{jets}$$



- three jet rate $\implies$ measurement of α_s
- angular distributions $\implies$ gluons are spin-1
- four jet rate and distributions $\implies$ QCD has an underlying SU(3) symmetry

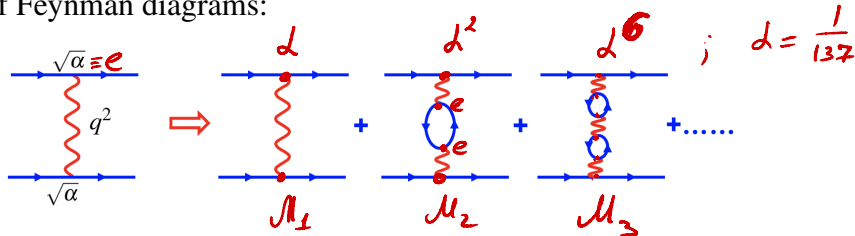
Running coupling constants: QED

- “bare” electron charge is screened by virtual e^+e^- pairs
- behaves like a polarizable dielectric



Running coupling constants: QED

- in terms of Feynman diagrams:



- same final state $\implies$ add amplitudes: $M = M_1 + M_2 + M_3 + \dots$

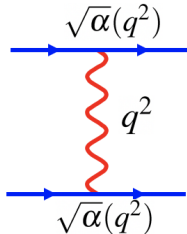
Running coupling constants: QED

- sum is equivalent to a single diagram with “running” coupling constant:

$$\alpha(Q^2) = \alpha(Q_0^2) / \left[1 - \frac{\alpha(Q_0^2)}{3\pi} \ln \left(\frac{Q^2}{Q_0^2} \right) \right]$$

$Q^2 \gg Q_0^2$

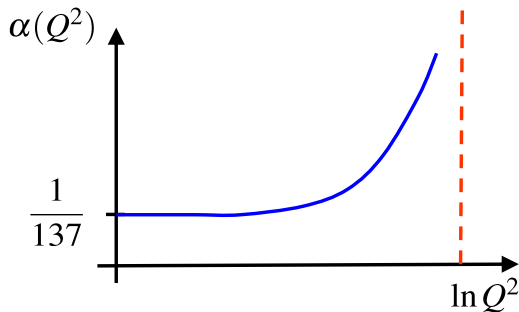
Note sign



Running coupling constants: QED

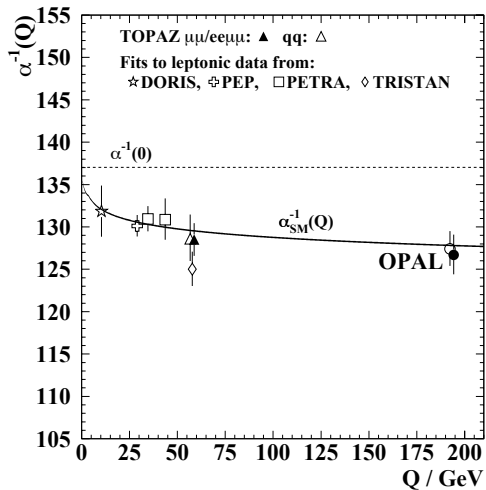
EM coupling becomes infinite at $\ln \left(\frac{Q^2}{Q_0^2} \right) = \frac{3\pi}{1/137}$, i.e. at $Q \sim 10^{26}$ GeV

- but quantum gravity effects would come in way below this energy and it is highly unlikely that QED “as is” would be valid in this regime



Running coupling constants: QED

EPJC 33(2004)173 (arXiv)



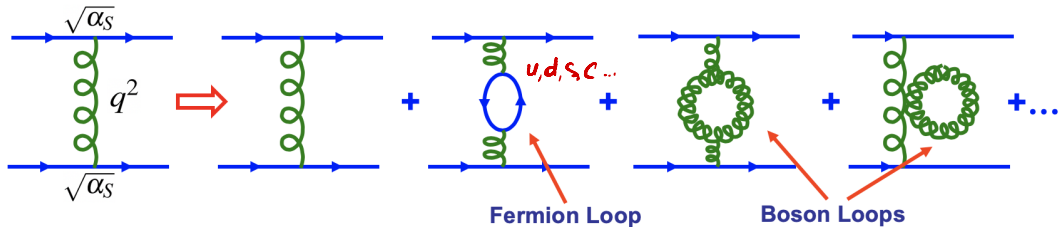
In QED, α **increases** very slowly:

- atomic physics ($Q^2 \sim 0$):
 $1/\alpha = 137.03599976(50)$
- high energy physics:
 $1/\alpha(193 \text{ GeV}) = 127.4 \pm 2.1$

H. $\oplus_p$ $\ominus_e$ $E = 13.6 \text{ eV}$

Running coupling constants: QCD

Similar to QED, but in addition have gluon loops (no photon loops in QED!):



Running coupling constants: QCD

- adding amplitudes: bosonic loops interfere **negatively**, so get a **different sign!**

$$\alpha_s(Q^2) = \alpha_s(Q_0^2) \left/ \left[1 + \underbrace{B}_{\text{negative}} \alpha_s(Q_0^2) \ln \left(\frac{Q^2}{Q_0^2} \right) \right] \right.$$

with

$$B = \frac{11N_c - 2N_f}{12\pi}$$

$$\left\{ \begin{array}{l} N_c = \text{no. of colours} \\ N_f = \text{no. of quark flavours} \end{array} \right.$$

$$N_c = 3; N_f = 6$$

$$\rightarrow B > 0$$



α_s **decreases with** Q^2

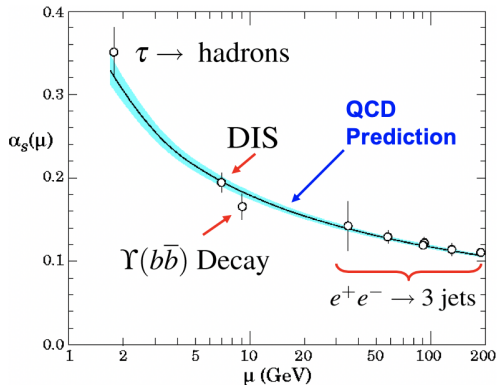
Nobel Prize for Physics, 2004
(Gross, Politzer, Wilczek)

Running coupling constants: QCD

★ Measure α_s in many ways:

- jet rates
- DIS
- tau decays
- bottomonium decays
- +...

★ As predicted by QCD,
 α_s decreases with Q^2

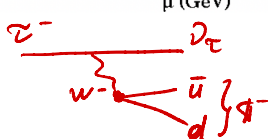


$$\mu \approx Q$$

$$\tau^- \rightarrow \mu^- \bar{\nu}_\mu$$

$$\tau^- \rightarrow e^- \bar{\nu}_e$$

$$\tau^- \rightarrow \nu_\tau \bar{\nu}_\tau$$



Running coupling constants: QCD

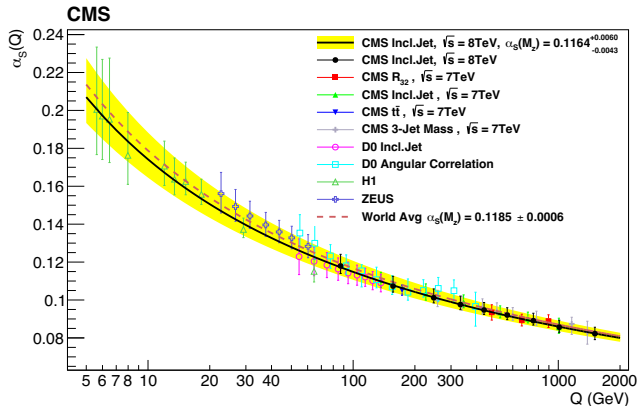
At low Q^2 : α_s is large, e.g. at $Q^2 = 1 \text{ GeV}^2$ find $\alpha_s \sim 1$

- $\implies$ can't use perturbation theory!
- this is the reason why QCD calculations at low energies are so difficult, e.g. properties of hadrons, hadronization of quarks to jets, ...

At high Q^2 : α_s is rather small, e.g. at $Q^2 = M_Z^2$ find $\alpha_s \sim 0.12$

- **asymptotic freedom**: can use perturbation theory
- this is the reason that in deep inelastic scattering (DIS) at high Q^2 quarks behave as if they are quasi-free (i.e. only weakly bound within hadrons)

Running coupling constants: QCD at the LHC

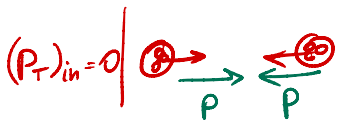


The strong coupling $\alpha_s(Q)$ (solid line) and its total uncertainty (band) as determined in [JHEP 03\(2017\)156](#) analysis using a 2-loop solution to the renormalization group equation as a function of the momentum transfer $Q = p_T$. The extractions of $\alpha_s(Q)$ in nine separate ranges of Q are shown together with results from the H1, ZEUS, and D0 experiments at the HERA and Tevatron colliders. Recent other CMS measurements are displayed as well: R_{32} : [EPJC 73\(2013\)2604](#), $t\bar{t}$ cross section: [Phys. Lett. B 738 \(2014\) 526](#), 3-jet mass: [EPJC 75\(2015\)186](#) and inclusive jets at 7 TeV [EPJC 75\(2015\)288](#)



Hadron-hadron collisions

- in e^+e^- collisions one angle θ is enough to parameterize event
- in hh collisions there are more unknowns: x_1, x_2 of colliding partons
- for hh need three variables to describe event, e.g. for $pp \rightarrow jj + X$ two angles between the jets and beam axis, and jet p_T
 - $p_T = \sqrt{p_x^2 + p_y^2}$
 - rapidity $y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$ – Lorentz-invariant wrt the boost along z

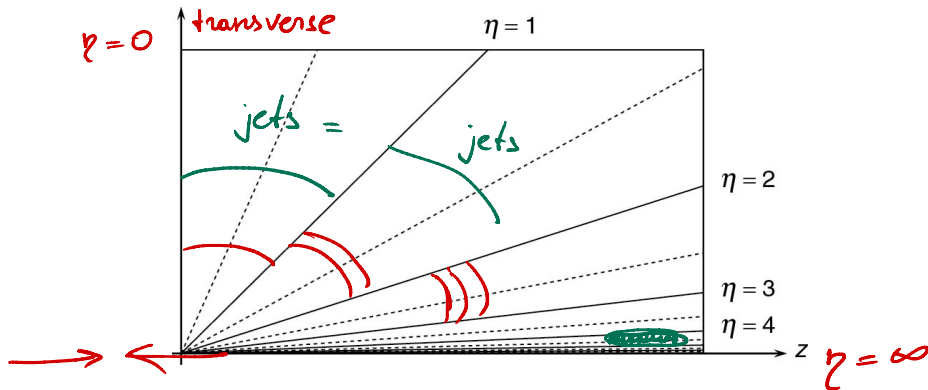


Momentum conserved
in transverse plane
 $\sum p_T^i = 0$

Hadron-hadron collisions

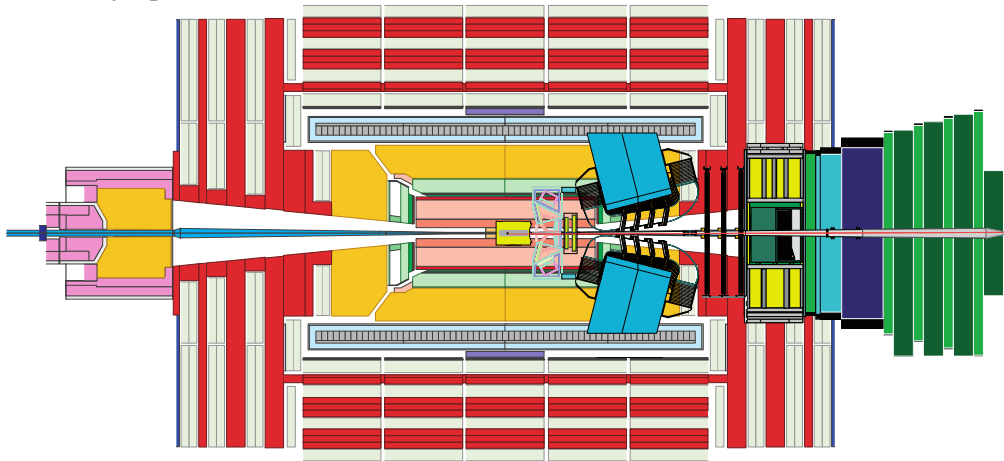
- for massless particles rapidity is the same as **pseudorapidity**

$\eta \equiv -\ln \left(\tan \frac{\theta}{2} \right)$ – depends only on the angle between the particle momentum and beam axis



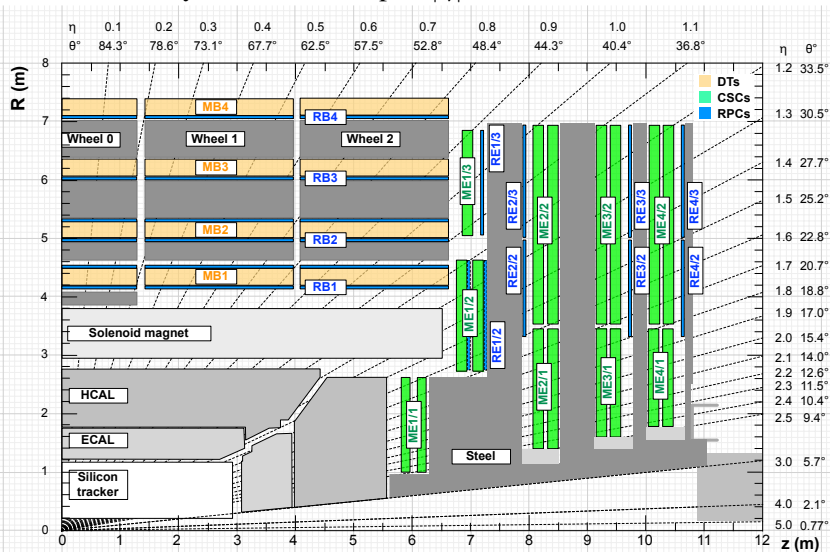
Pseudorapidity coverage in CMS vs. LHCb

Broadly speaking, the differential cross sections for jet production in hadron–hadron collisions are approximately constant in pseudorapidity, implying that roughly equal numbers of jets are observed in each interval of pseudorapidity, reflecting the forward nature of jet production in pp and $p\bar{p}$ collisions.



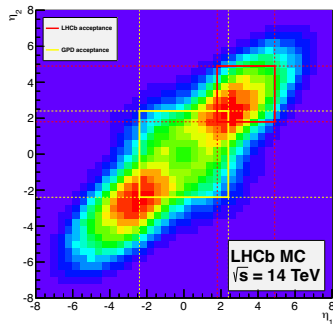
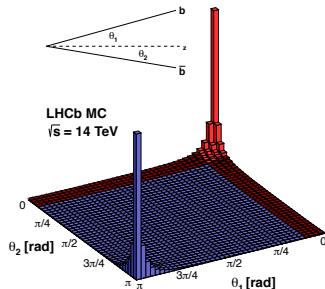
Pseudorapidity coverage in CMS

CMS is basically instrumented up to $|\eta| \approx 2.5$



Pseudorapidity coverage in LHCb

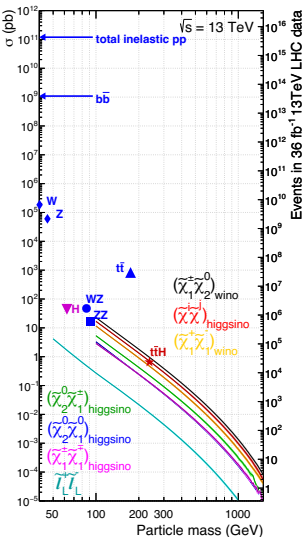
LHCb is instrumented in a region $2 < \eta < 5$:



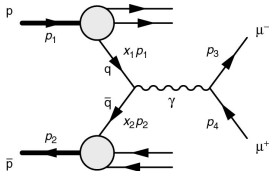
Geometry chosen to get forwardly produced $b\bar{b}$ in acceptance:

- LHCb intercepts 27% of b or $\bar{b}$ quarks; 24% of $b\bar{b}$ quark pairs
- CMS intercepts 49% of b or $\bar{b}$ quarks; 41% of $b\bar{b}$ quark pairs

QCD cross sections not sustainable

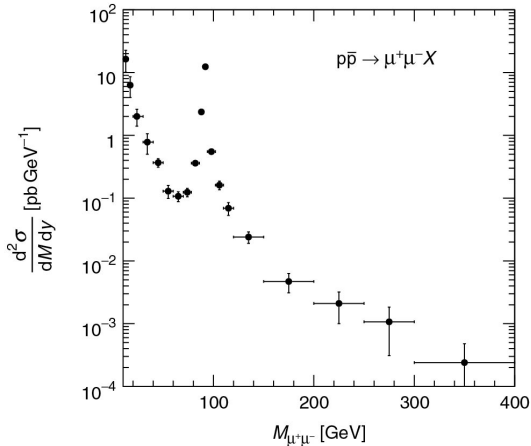


- inelastic pp cross section is 6 orders of magnitude larger than those of W or Z bosons production
- $b\bar{b}$ cross section is such that a B meson is produced in every collision at LHCb
- dedicated online selection strategies – triggers – are in place to record only interesting events
- more rare process – Drell–Yan process: QED lepton pair production



$$\sigma(q\bar{q} \rightarrow \mu^+\mu^-) = \frac{1}{N_c} Q_q^2 \frac{4\pi\alpha^2}{3\hat{s}}, \text{ where } Q_q \text{ is the quark/antiquark charge and } \hat{s} \text{ is the centre-of-mass energy of the colliding } q\bar{q} \text{ system}$$

DY production at CDF: $p\bar{p} \rightarrow \mu^+\mu^- + X$



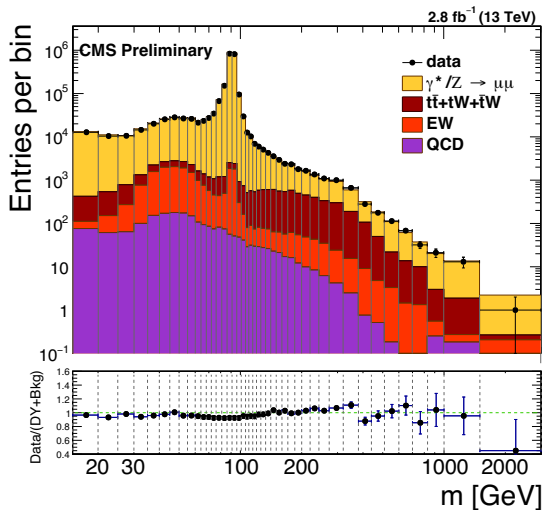
- to obtain full cross section, need to integrate over parton distribution functions (PDF) of quarks and antiquarks in a proton and an anti-proton
- using invariant mass of muon system $M^2 = x_1 x_2 s$, and its rapidity y can obtain:

$$\frac{d^2\sigma}{dy^2} M = \frac{8\pi\alpha^2}{9M_s} f(x_1, x_2),$$

$$f(x_1, x_2) = \left[\frac{4}{9} (u(x_1)u(x_2) + \bar{u}(x_1)\bar{u}(x_2)) + \frac{1}{9} (d(x_1)d(x_2) + \bar{d}(x_1)\bar{d}(x_2)) \right]$$

The cross section can grow with the collider energy as it is impacted by the PDFs of colliding partons.

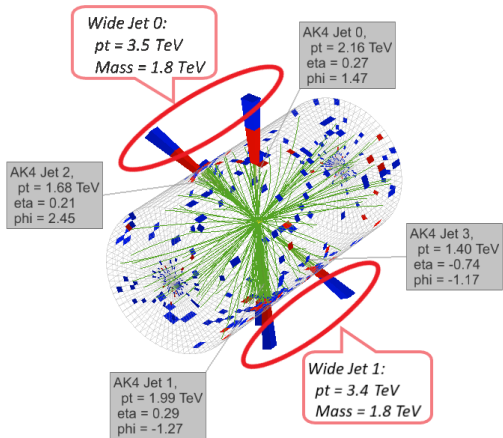
Recent DY process measurements



Going to invariant muon mass of 3 TeV!



dijet mass = 8.0 TeV

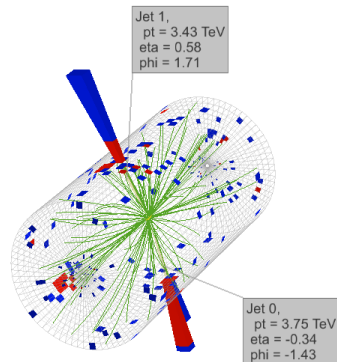


CMS Experiment at LHC, CERN
Data recorded: Sat Oct 28 12:41:12 2017 EEST
Run/Event: 305814 / 971086788
Lumi section: 610



Dijet production at CMS

dijet mass = 7.9 TeV

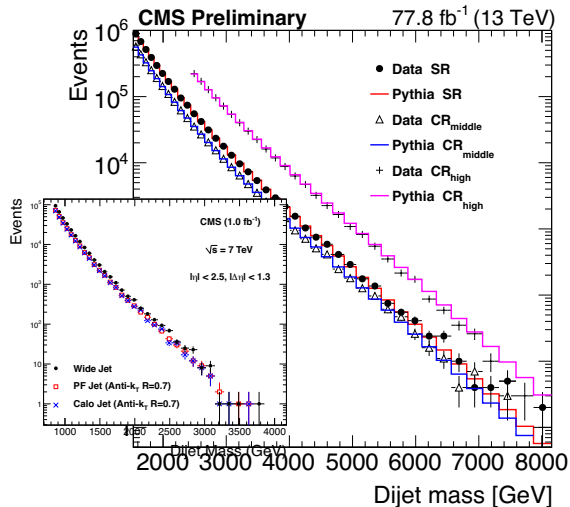


CMS Experiment at LHC, CERN
Data recorded: Mon Aug 7 06:49:37 2017 EEST
Run/Event: 300575 / 65453124
Lumi section: 39

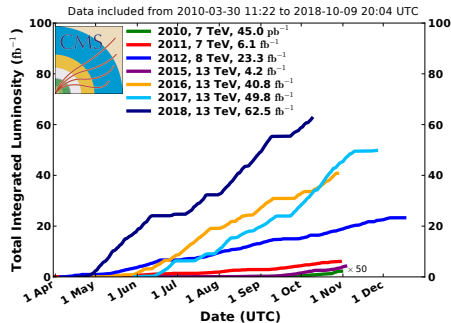


7→8→13 TeV

Dijet invariant mass shape is well described by MC generator up to highest values:



CMS Integrated Luminosity, pp

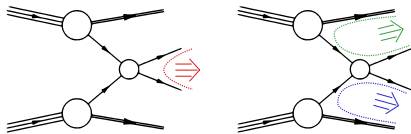


7 TeV $\rightarrow$ 13 TeV
 $1.0 \text{ fb}^{-1} \rightarrow \sim 100 \text{ fb}^{-1}$
 in $m(X)$: 3.5 TeV $\rightarrow$ 8 TeV!

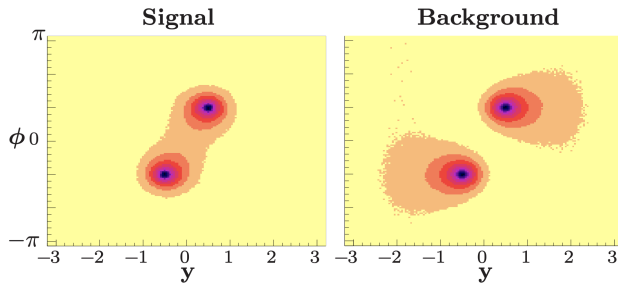
QCD is the most important process to understand and control at hadron colliders!

Seeing color flow in detectors

Color singlet ($pp \rightarrow H \rightarrow b\bar{b}$) vs. colored particle ($pp \rightarrow g \rightarrow b\bar{b}$) hadronization:



Distributions seen in the detector:



Many machine learning applications are developed to consider energy patterns in the jets in the detector, e.g. papers citing this result: [list](#)

Summary

- superficially QCD is very similar to QED
- but gluon self-interactions are believed to result in colour confinement
- all hadrons are colour singlets $\implies$ only observe mesons or baryons
- at low energies $\alpha_S \sim 1$
 - $\implies$ cannot use perturbation theory
 - $\implies$ non-perturbative regime
- α_S runs, becomes smaller at higher energy scales $\alpha_S(100 \text{ GeV}) \sim 0.1$
 - $\implies$ can use perturbation theory
 - $\implies$ asymptotic freedom
- where calculations can be performed, QCD provides a good description of relevant experimental data