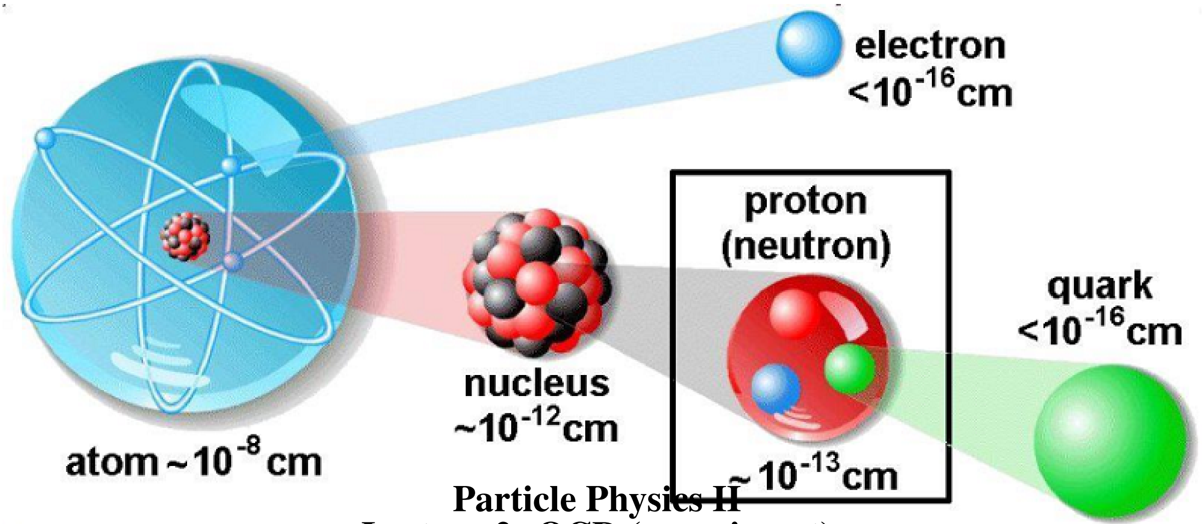


# Particle Physics II
# Lecture 2: QCD (experiment)

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February 29, 2024

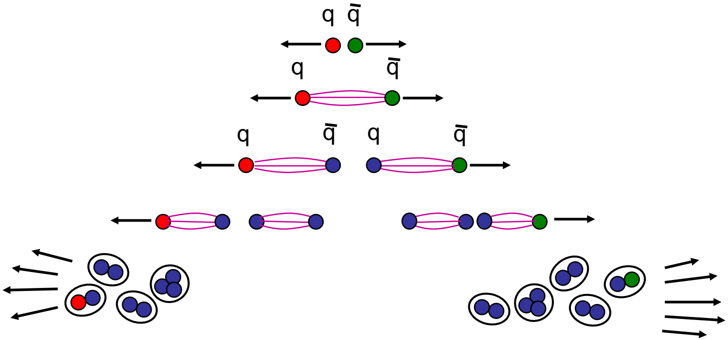
## Quantum Chromodynamics: main experimental concepts

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

# Hadronization and Jets

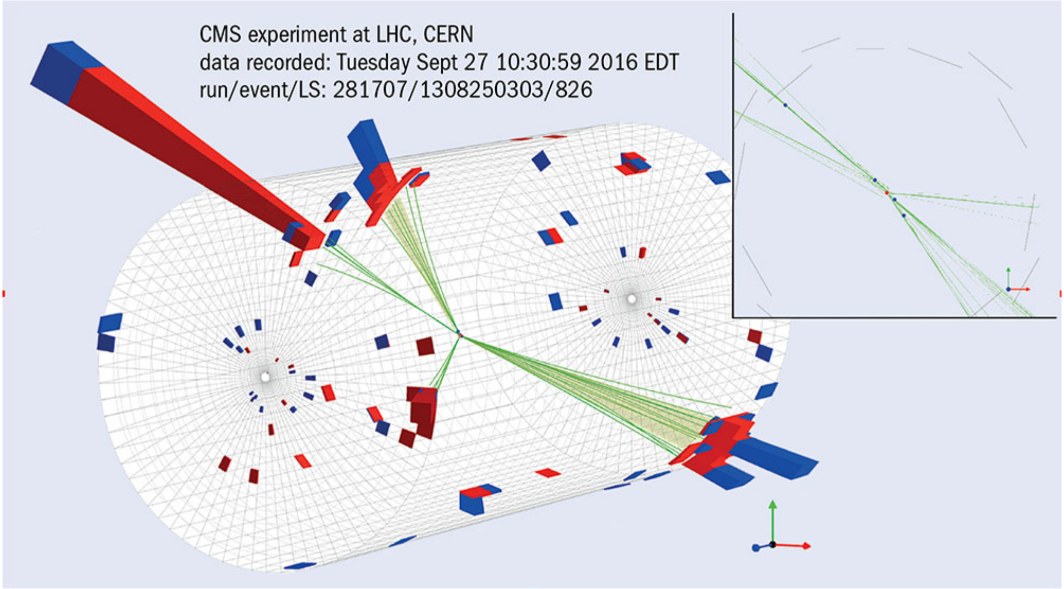
For example, take electron positron annihilation $e^+e^- \to q\bar{q}$:

- 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

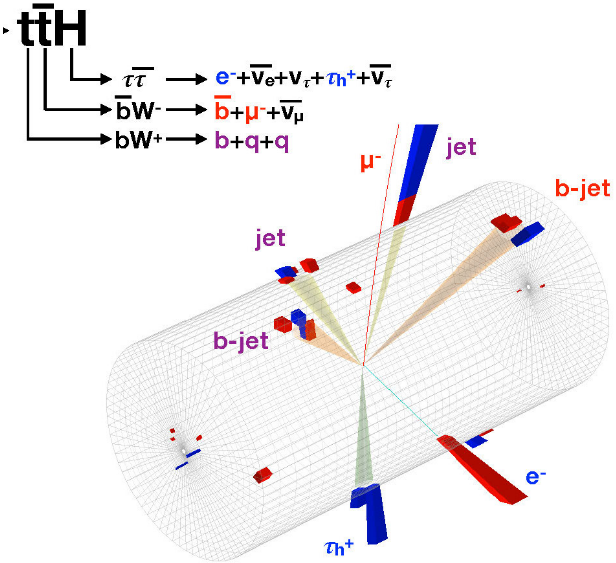


- this process is called hadronisation: it is not (yet) calculable, though reasonable numeric simulations exist
- the main consequence is that at collider experiments quarks and gluons observed as jets of particles

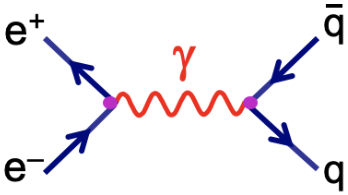
# Jets in a detector



# Jets in a detector

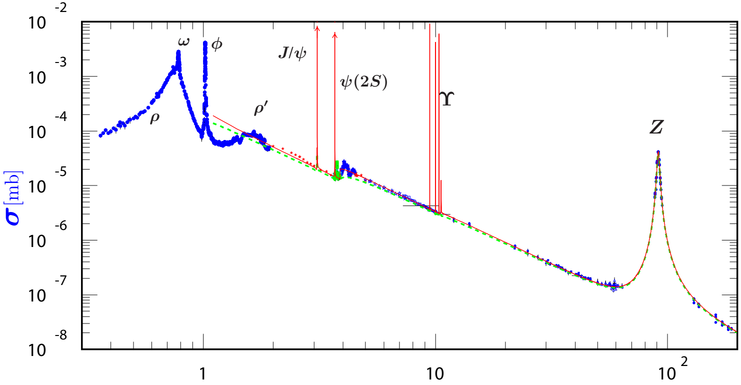


$e^+e^-$ colliders are an excellent place to study QCD:




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




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

$$\sigma = \frac{4\pi\alpha^2}{3s}, \qquad \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\alpha^2}{4s}(1+\cos^2\theta) \tag{1}$$

# Quark spin in $e^+e^-$

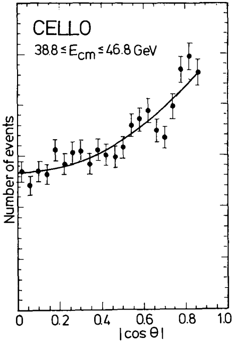



Fig. 1. Angular distribution of the corrected sphericity axis. The solid line corresponds to a fit of $1+a\cos^2\theta$ with $a=1.00\pm0.01$.

- 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 $\propto (1+\cos^2\theta)$

  $\Longrightarrow$ quarks are spin $\frac{1}{2}$

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

## 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:

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

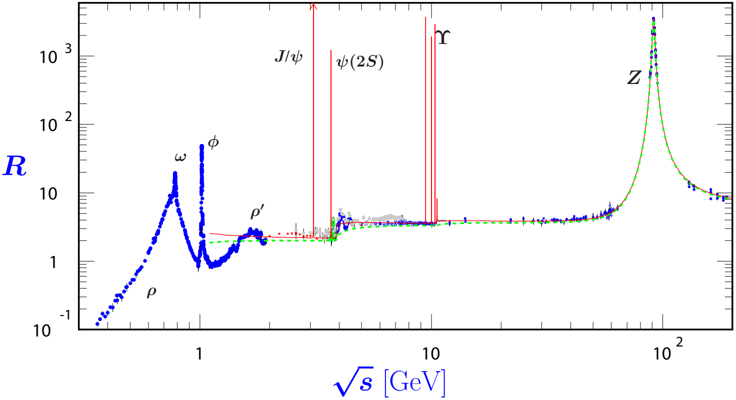
- experimentally observe jets of hadrons of all flavors (and 3 colors):

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

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

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3\sum_{u,d,s,\dots}Q_{u,d,s,\dots}^2 \tag{4}$$

# Quark color in $e^+e^-$: measurements



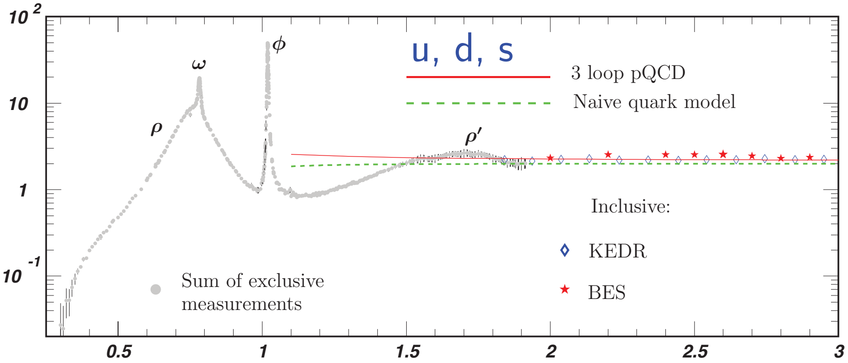

**u, d, s:** $R = 3 \times (\frac{1}{9} + \frac{4}{9} + \frac{1}{9}) = 2$

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

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

**Data are consistent with factor 3 from color!**

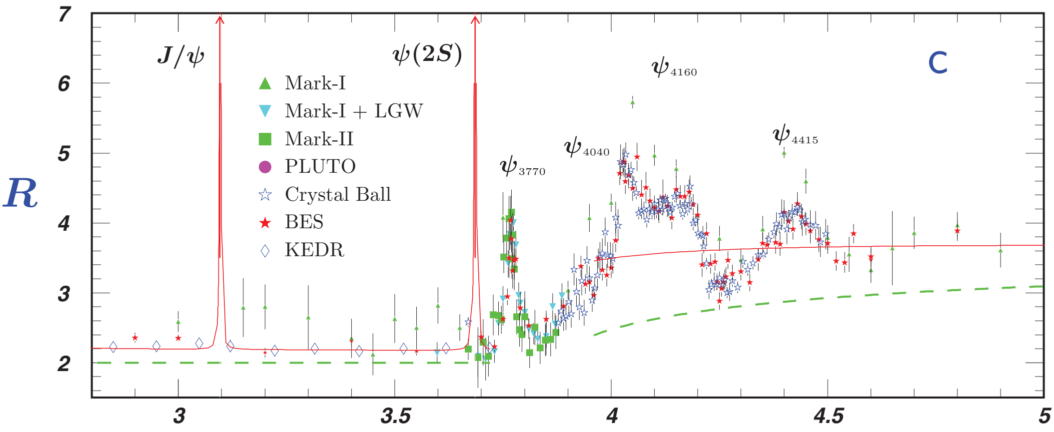
# Quark color in $e^+e^-$: zoomed-in measurements




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

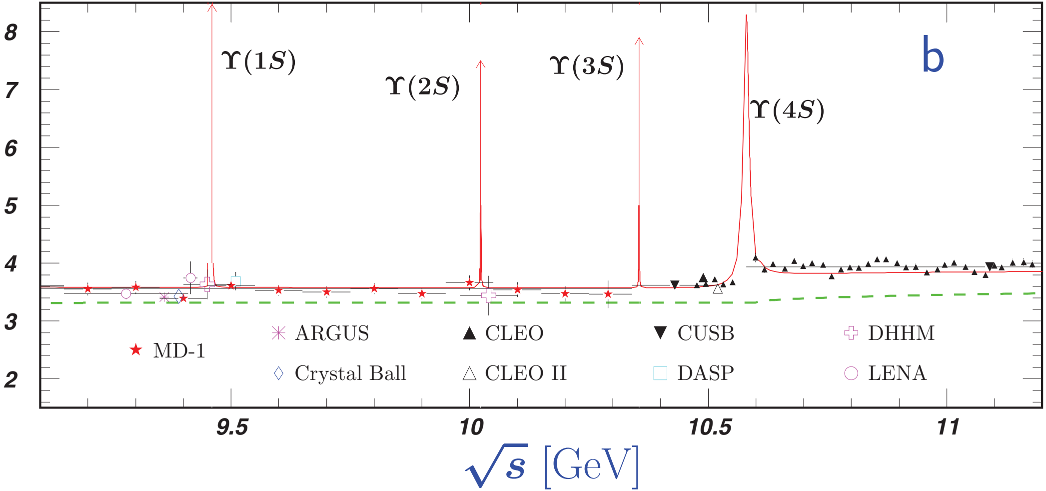
Green dashed line is the lowest order prediction assuming three colors (as shown here). The solid red lines are computed with 3-loop perturbative QCD prediction, which includes the next order contributions as e.g. $e^+e^- \to \mu^+\mu^-\gamma$, $e^+e^- \to q\bar{q}\gamma$ or $e^+e^- \to q\bar{q}g$, summing up to about 10% correction dominated by the last diagram and $\alpha_s$ value.

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




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

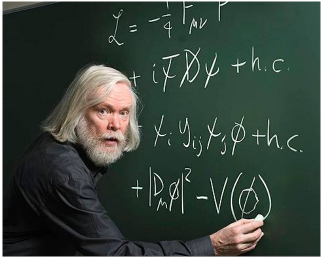
# Quark color in $e^+e^-$: zoomed-in measurements




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

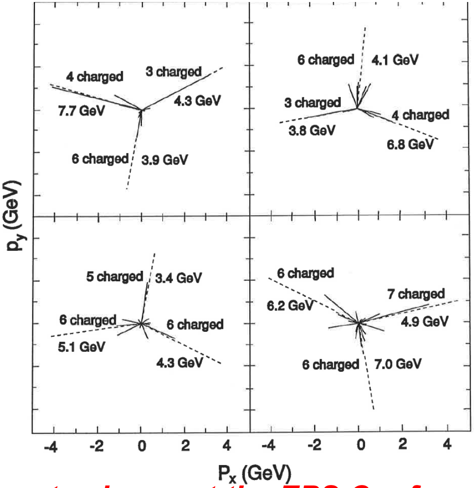
## The Discovery of the Gluon

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:* $e^+e^- \to q\bar{q}g$.
*What could be simpler?*

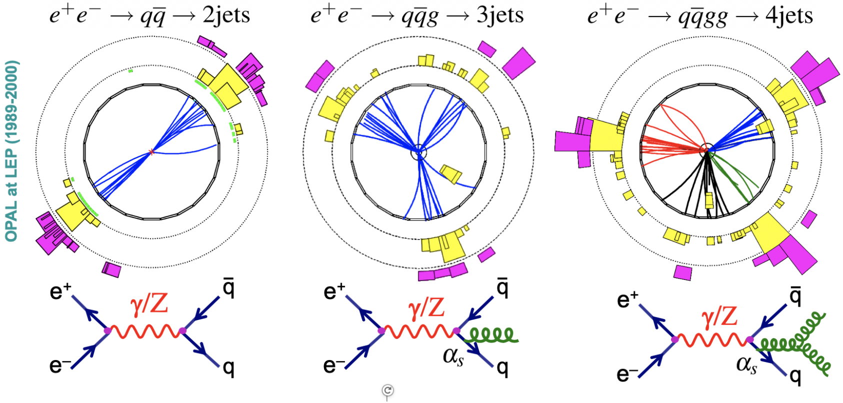



***TASSO***

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

https://indico.cern.ch/event/704471/contributions/3012502/attachments/1670841/2680256/Wu.pdf

# Four decades of gluons celebrated in 2019

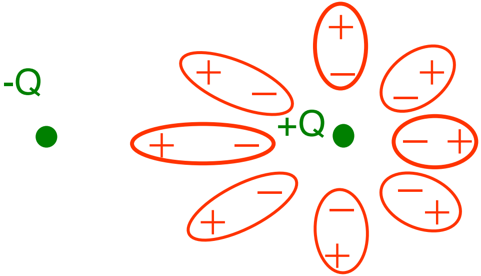



- three jet rate $\Longrightarrow$ measurement of $\alpha_s$
- angular distributions $\Longrightarrow$ gluons are spin-1
- four jet rate and distributions $\Longrightarrow$ QCD has an underlying SU(3) symmetry

https://home.cern/news/news/physics/four-decades-gluons

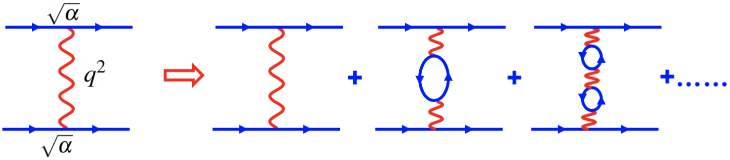
# Running coupling constants: QED

- “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 $\Longrightarrow$ add amplitudes: $M = M_1 + M_2 + M_3 + \ldots$

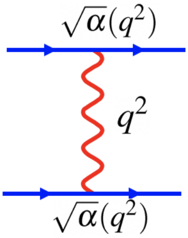
# Running coupling constants: QED

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

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

$$Q^2 \gg Q_0^2$$

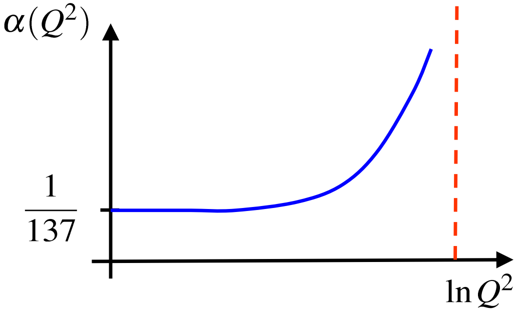
Note sign



# Running coupling constants: QED

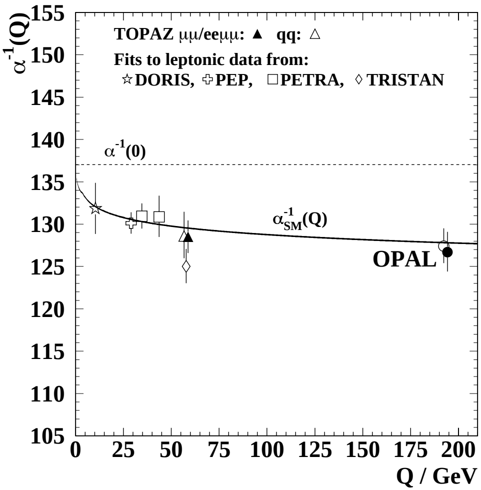
EM coupling becomes infinite at $\ln\left(\frac{Q^2}{Q_0^2}\right) = \frac{3\pi}{1/137}$, i.e. at $Q \sim 10^{26}$ GeV

- 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)

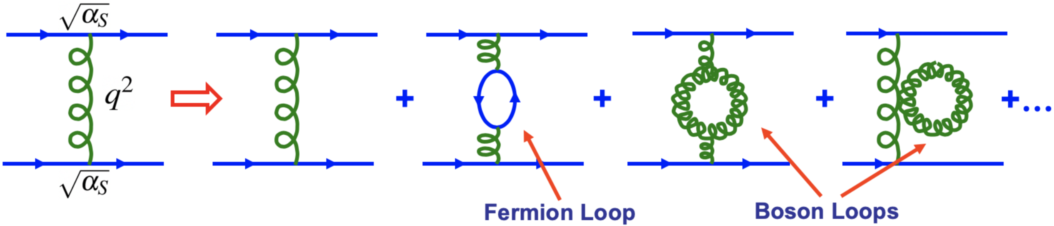



In QED, $\alpha$ increases very slowly:

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

# 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!

$$\alpha_S(Q^2) = \alpha_S(Q_0^2) \Big/ \left[1 + B\alpha_S(Q_0^2)\ln\left(\frac{Q^2}{Q_0^2}\right)\right]$$

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

$N_c$ = no. of colours

$N_f$ = no. of quark flavours

$N_c = 3;\ N_f = 6$ ➡ $B > 0$

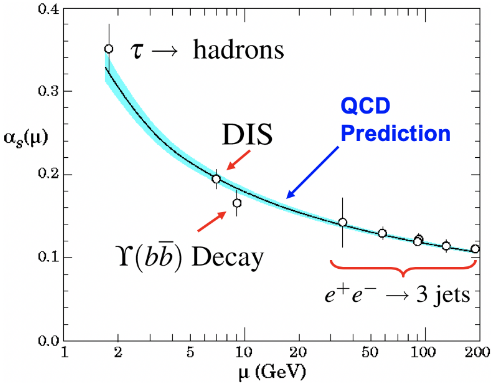
➡ $\alpha_S$ decreases with $Q^2$

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

# Running coupling constants: QCD

★ Measure $\alpha_s$ in many ways:
- jet rates
- DIS
- tau decays
- bottomonium decays
- +...

✶ As predicted by QCD, $\alpha_s$ decreases with $Q^2$




$\mu \approx Q$

EPJC 64(2009)689 arxiv:0908.1135

## Running coupling constants: QCD

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

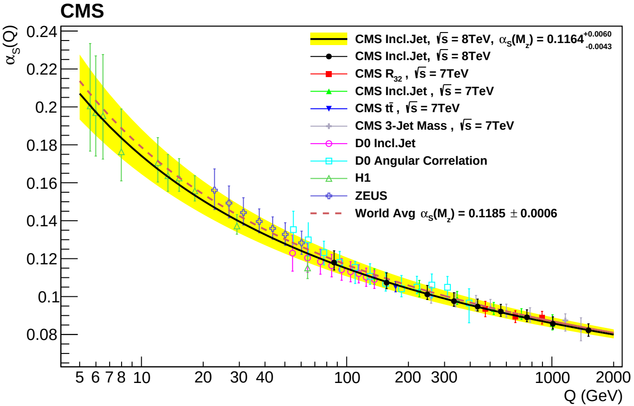
- $\Longrightarrow$ can't use perturbation theory!
- this is the reason why QCD calculations at low energies are so difficult, e.g. properties of hadrons, hadronization of quarks to jets, ...

At high $Q^2$: $\alpha_s$ 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)

*EPJC 64(2009)689* arxiv:0908.1135

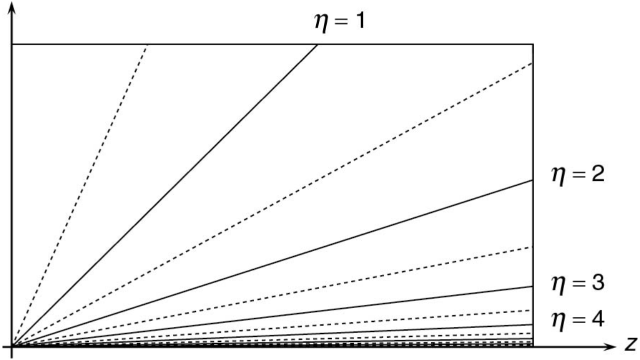
# Running coupling constants: QCD at the LHC




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 $Q = p_{\mathrm{T}}$. 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: $\mathrm{R}_{32}$: 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

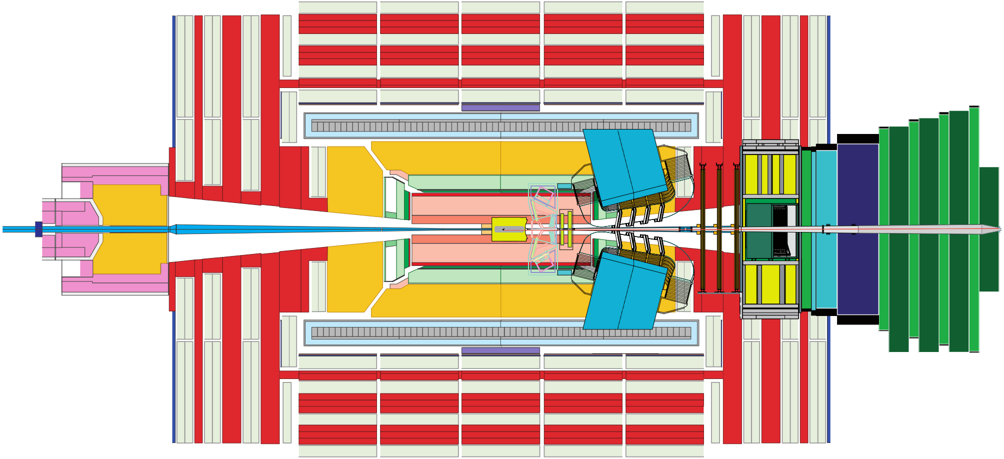
- in $e^+e^-$ collisions one angle $\theta$ is enough to parameterize event
- in $hh$ collisions there are more unknowns: $x_1$, $x_2$ of colliding partons
- for $hh$ need three variables to describe event, e.g. for $pp \to jj + X$ two angles between the jets and beam axis, and jet $p_\mathrm{T}$
  -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

- 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



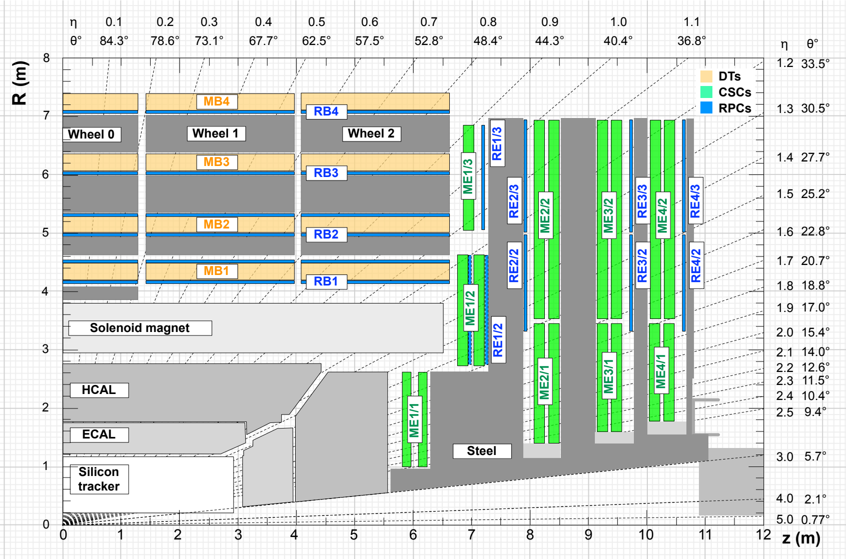
# Pseudorapidity coverage in CMS vs. LHCb

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.



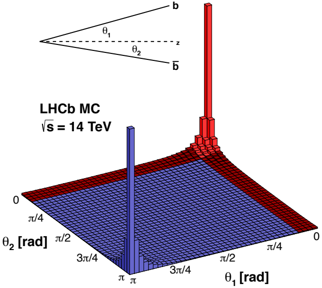
# Pseudorapidity coverage in CMS

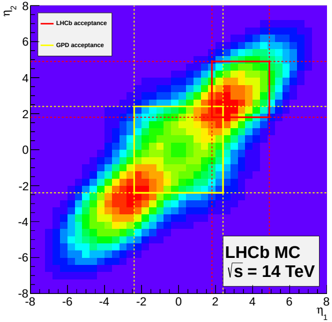
CMS is basically instrumented up to $|\eta| \approx 2.5$



# Pseudorapidity coverage in LHCb

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



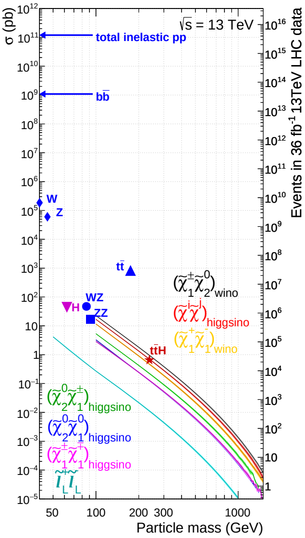




Geometry chosen to get forwardly produced $b\bar{b}$ in acceptance:

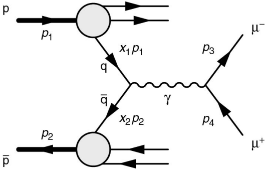
- LHCb intercepts 27% of $b$ or $\bar{b}$ quarks; 24% of $b\bar{b}$ quark pairs
- CMS intercepts 49% of $b$ or $\bar{b}$ quarks; 41% of $b\bar{b}$ quark pairs

https://lhcb.web.cern.ch/lhcb/speakersbureau/html/bb$_{P}roductionAngles.html$

# QCD cross sections not sustainable

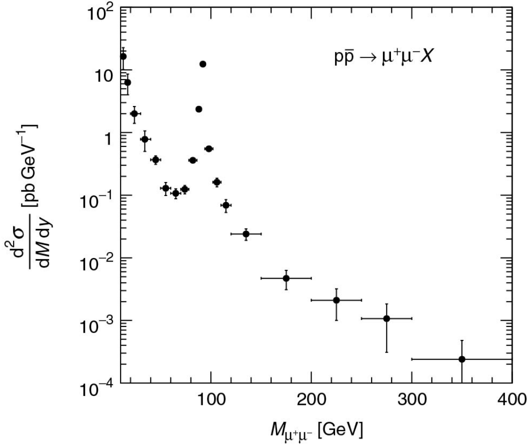



- inelastic $pp$ cross section is 6 orders of magnitude larger than those of W or Z bosons production
- $b\bar{b}$ cross section is such that a $B$ meson is produced in every collision at LHCb
- dedicated online selection strategies – triggers – are in place to record only interesting events
- more rare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




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

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



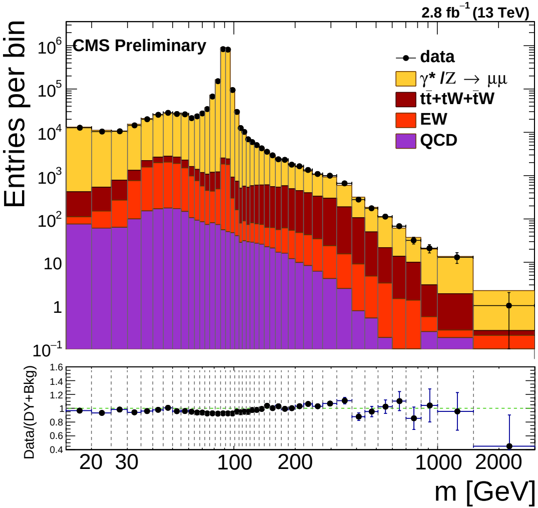

- to obtain full cross section, need to integrate over parton distribution functions (PDF) of quarks and atniquarks in a proton and an anti-proton
- using invariant mass of muon system $M^2 = x_1 x_2 s$, and its rapidity $y$ can obtain:

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

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

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

# Recent DY process measurements

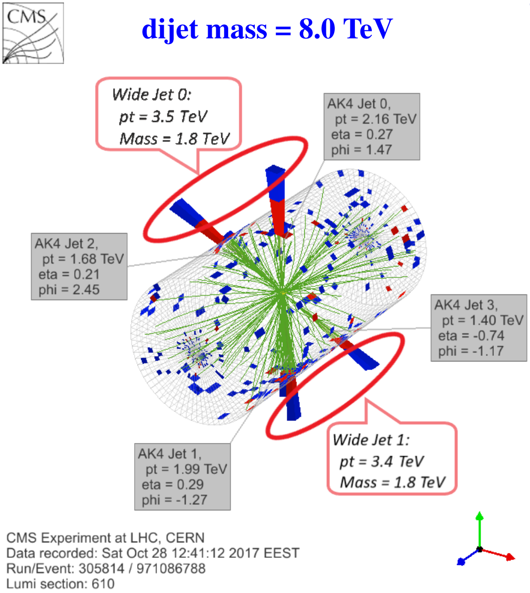



Going to invariant muon mass of 3 TeV!

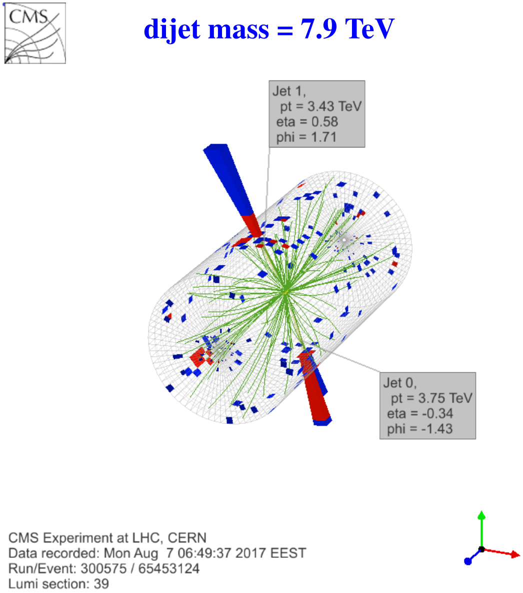
CMS-PAS-SMP-16-009

# Dijet production at CMS

**dijet mass = 8.0 TeV**

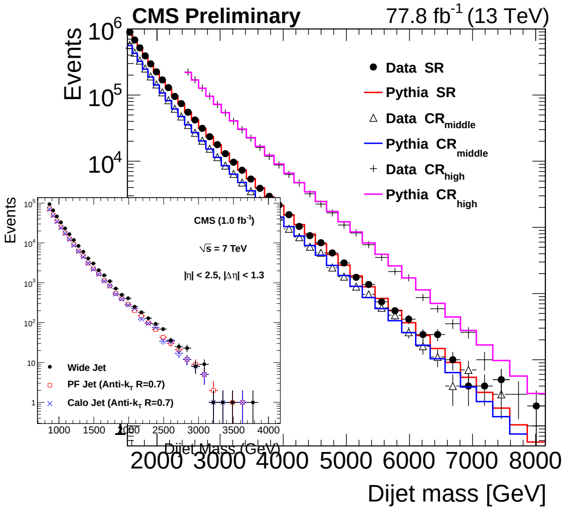


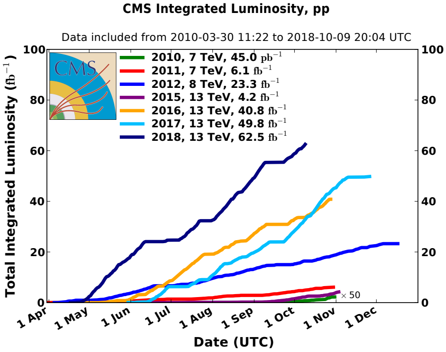

**dijet mass = 7.9 TeV**



# 7→8→13 TeV

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



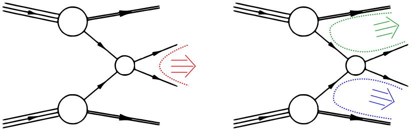




7 TeV → 13 TeV
1.0 fb$^{-1}$ → ~100 fb$^{-1}$
in m(X): 3.5 TeV → 8 TeV!

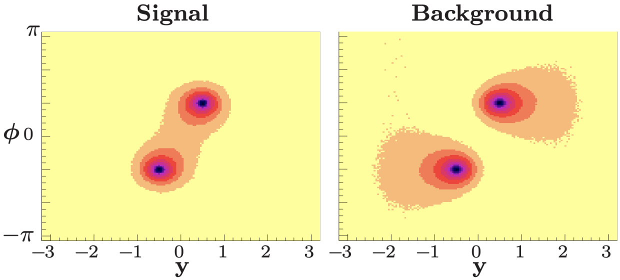
QCD is the most important process to understand and control at hadron colliders!

# Seeing color flow in detectors

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

*PRL 105(2010)022001* arXiv:1001.5027

## 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

- $\alpha_S$ 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