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QCD

(Quantum Chromodynamics)

Ivan Melo

University of Žilina

Outline

- Standard model of particle physics

- QED vs QCD at Feynman diagram level

- High energy QCD ($\sim$ 100 GeV) $\rightarrow$ jets
α_S small

- Low energy QCD ($\sim$ 1 GeV) $\rightarrow$ hadrons, confinement α_S large

- Lattice QCD (all energies) $\rightarrow$ Solving QCD numerically

Three families of fermions:

1	2	3
u (0.004)	c (1.1)	t (175)
d (0.007)	s (0.15)	b (4.2)
ν_e	ν_μ	ν_τ
e^- (0.0005)	μ^- (0.105)	τ^- (1.78)

Bosons responsible for 4 fundamental forces:

Force	Particle	Rel. strength
electromagn.	γ (0)	10^{-2}
weak	W^+, W^-, Z (80,90)	10^{-14}
strong	8 gluons (0)	1
gravitational	graviton (0)	10^{-42}

Baryons (3-quark particles)

Spin 1/2	Spin 3/2
p (0.938) uud	Δ (1.232) uuu
n (0.939) udd	Σ^* (1.385) uus
Λ (1.115) uds	...
...	...

Mesons (2-quark particles)

Spin 0	Spin 1
π^0 (0.134) $(u\bar{u} - d\bar{d})/\sqrt{2}$	ρ^0 (0.770) $(u\bar{u} - d\bar{d})/\sqrt{2}$
$\pi^\pm$ (0.139) $u\bar{d}, d\bar{u}$	$\rho^\pm$ (0.770) $u\bar{d}, d\bar{u}$
$K^\pm$ (0.493) $u\bar{s}, s\bar{u}$	ω (0.783) $(u\bar{u} + d\bar{d})/\sqrt{2}$
...	...

Pentaquarks (5-quark particles)

Θ^+ (1.54) $uudd\bar{s}$

History of quark model

1964 - Gell-Mann & Zweig $\rightarrow$ 3 quarks (u,d,s)

Every baryon composed of 3 quarks p = u u d

Every meson composed of a quark and antiquark $\pi^+ = u\bar{d}$

1970: DIS experiments $\rightarrow$ proton has sub-structure (3 lumps)

But:

- No free quarks - confinement
- Δ^{++} (spin $\frac{3}{2}$)- 3 u quarks in the same same state - violation of Pauli principle

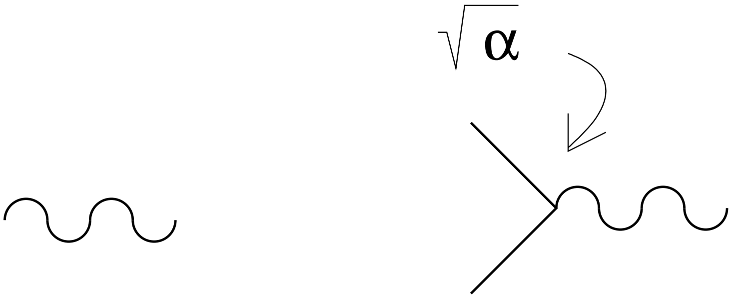
1964 O. Greenberg $\rightarrow$ 3 colors - red, blue and green:

p = u u d $\qquad$ $\pi^+ =$ u $\bar{d}$

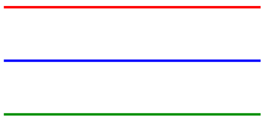
All naturally occuring particles are colorless

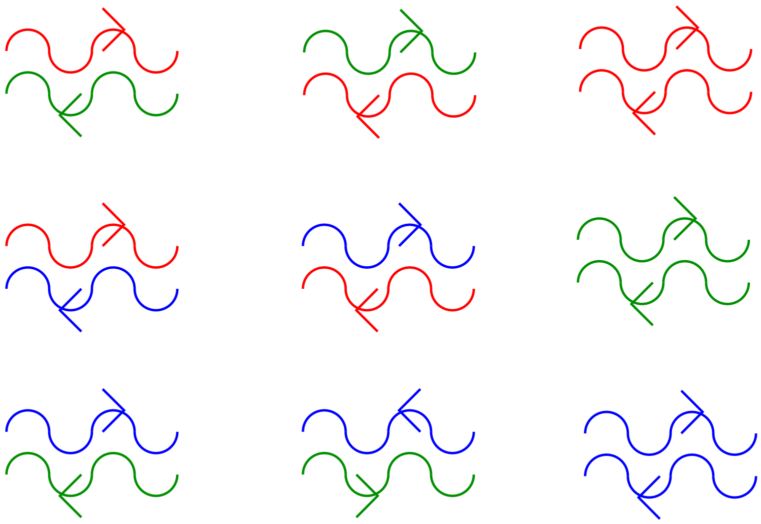
QCD vs QED

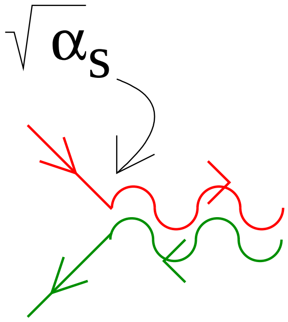
QED

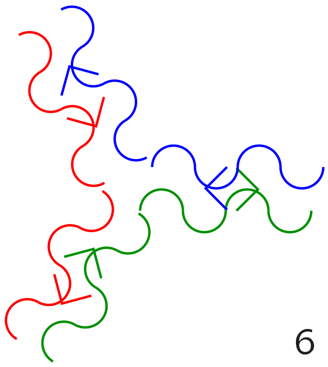


QCD









Similarities

Elmag. interactions are mediated by massless spin 1 bosons - photons

Strong interactions are mediated by massless spin 1 bosons - gluons

$\star\star\star$

Photons couple to particles with electric charge (electrons)

Gluons couple to particles with color (quarks)

$\star\star\star$

Exchange of just one gluon (photon) generates force $\frac{k}{r^2}$, $k \sim \alpha_s$ (α)

Differences

1) $\alpha_s > \alpha$

2) 1 electric charge - versus 3 colors

3) gluons can change quark color $\rightarrow$ they are (unlike photons) themselves (color) charged

4) gluons can couple to themselves

5) Nobody has ever seen quarks and qluons (colored particles) !

QED Lagrangian - $U(1)$ group

$$\mathcal{L}_{QED} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}_e \gamma^\mu D_\mu \psi_e - m_e \bar{\psi}_e \psi_e,$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu,$$

$$D_\mu = \partial_\mu + ieA_\mu$$

QCD Lagrangian - $SU(3)$ group

$$\mathcal{L}_{QCD} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a + i\,\bar{\psi}^\alpha_q \gamma_\mu (D^\mu)_{\alpha\beta} \psi^\beta_q - m_q \bar{\psi}^\alpha_q \psi_{q\alpha},$$

$$F^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g f_{abc} G^b_\mu G^c_\nu$$

$$(D^\mu)_{\alpha\beta} = \delta_{\alpha\beta} \partial^\mu - ig\frac{1}{2} \lambda^a_{\alpha\beta} G^\mu_a$$

$a = 1, 2, ...8 \qquad\qquad \alpha, \beta = 1, 2, 3$

f_{abc} are structure constants of $SU(3)$ group,

$\lambda^a_{\alpha\beta}$ are eight 3×3 Gell-Mann matrices.

Challenges:

Hadron masses & Lifetimes (low E)

Confinement (low E)

Jets at e^+e^- collisions (high E)

Quark gluon plasma (high E)

Chiral symmetry breaking

3 approaches to these challenges:

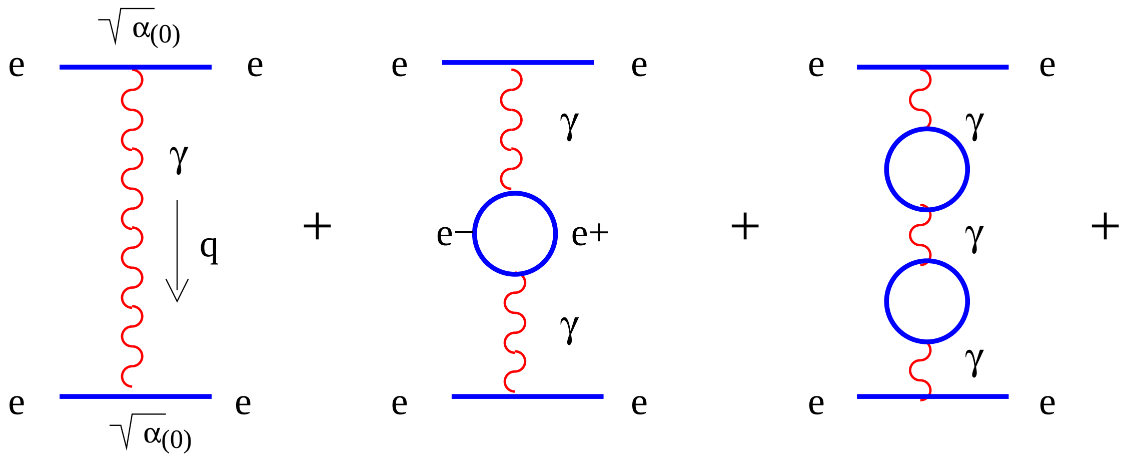
1) build models

2) simplify QCD (e.g. at high E)

3) solve equations numerically (Lattice QCD)

Running coupling constant (QED)

$\alpha(0) = \frac{e^2}{4\pi} \doteq \frac{1}{137}$



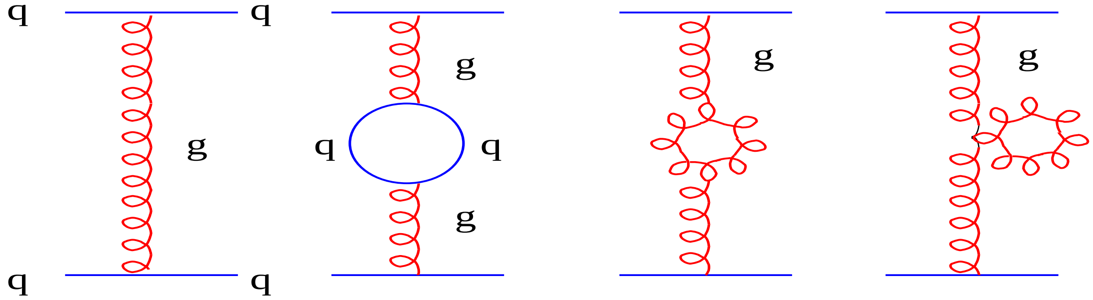
tree level $\quad$ 1-loop level $\quad$ 2-loop level

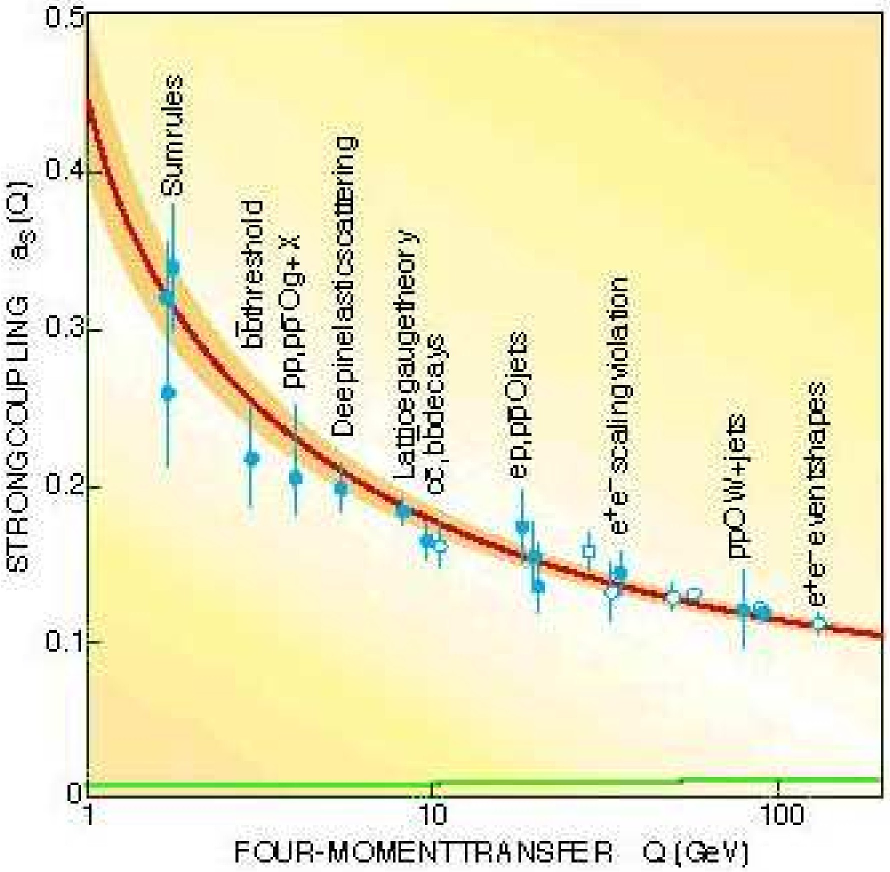
$\mathcal{M}_1 = \alpha(0)A \qquad \mathcal{M}_2 = \alpha(0)^2 B \qquad \mathcal{M}_3 = \alpha(0)^3 C$

$$\boxed{\mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2 + ... \quad = \quad \alpha(q^2)A \quad = \frac{\alpha(0)}{1+f(q^2)-f(0)}A}$$

Screening of electric charge by dielectric medium

Running coupling & Asymptotic freedom





F. Wilczek Ref. [1]

Confinement (low E, high α_s limit)

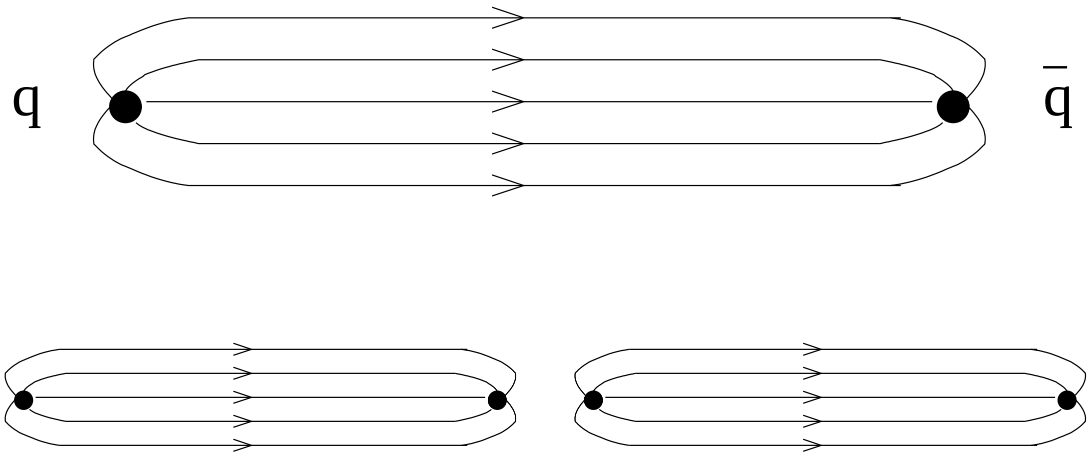
Potential between 2 quarks:

1) $r \to 0$ (high E, low α_s)

$$V(r) \sim -\frac{1}{r}$$

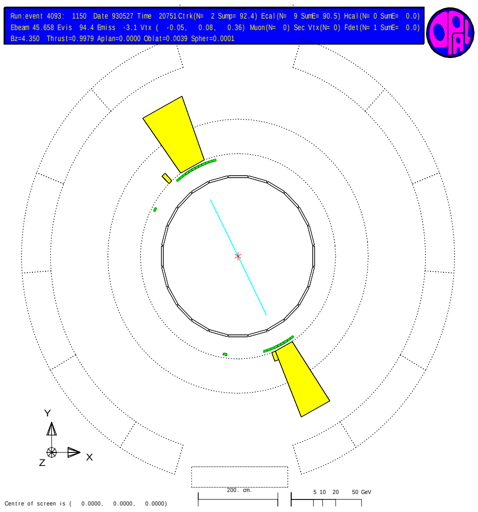
2) $r \to \infty$ (low E, high α_s)

$$V(r) \sim r \qquad \to \text{confinement}$$

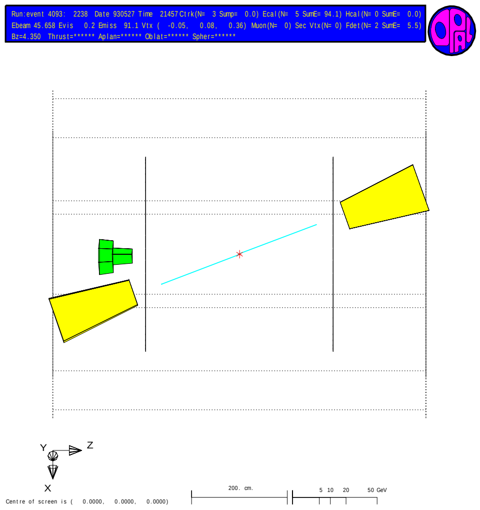


e^+e^- collisions at high energy

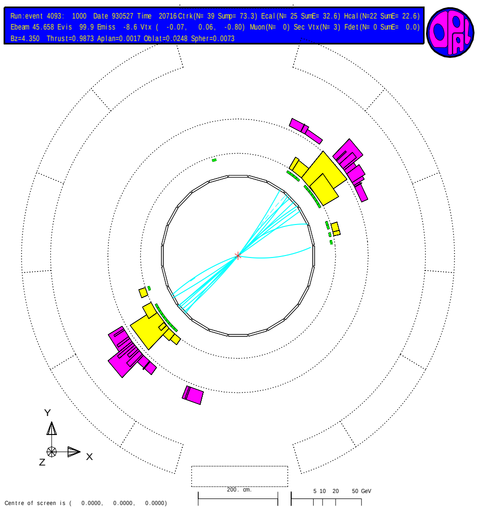
$e^+e^- \to e^+e^-$



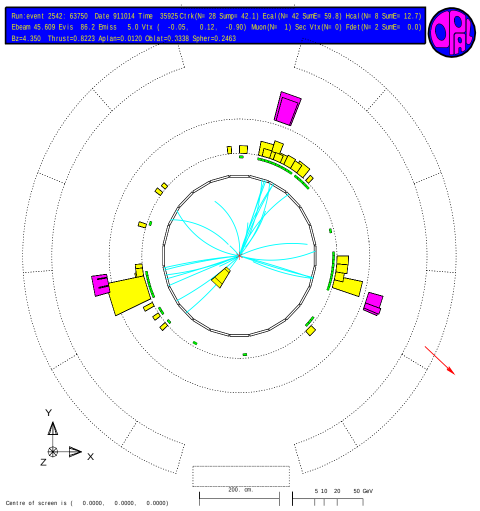
$e^+e^- \to \gamma e^+e^-$



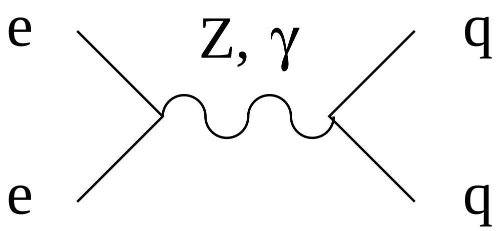
$e^+e^- \to q\bar{q}$

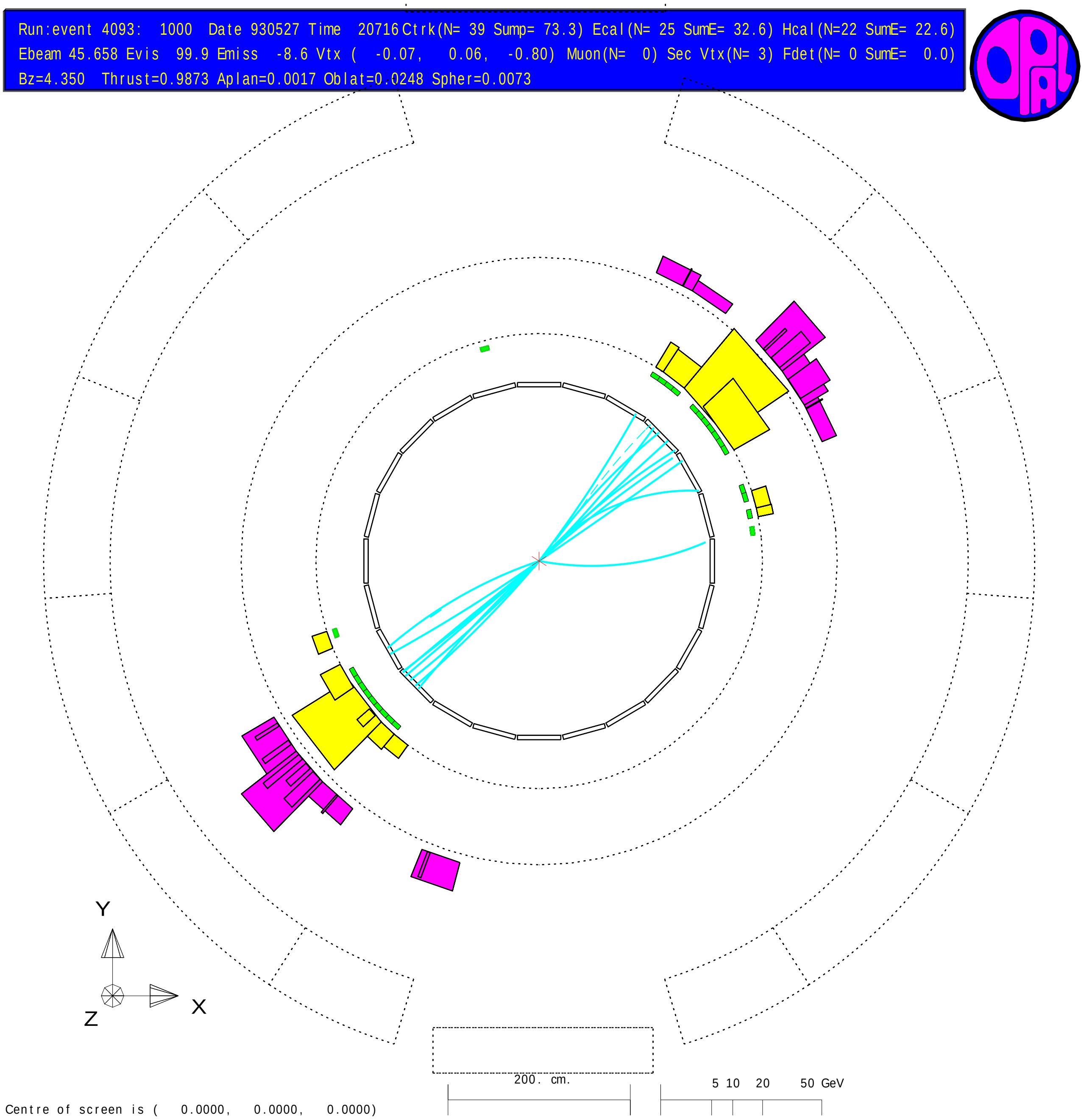


$e^+e^- \to gq\bar{q}$



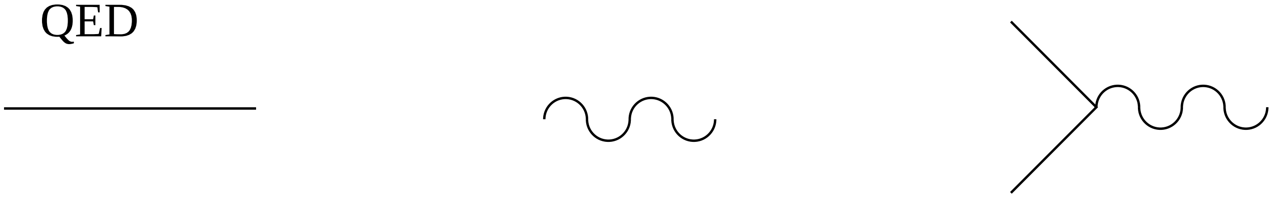
2-jet event: $e^+e^- \to q\bar{q}$



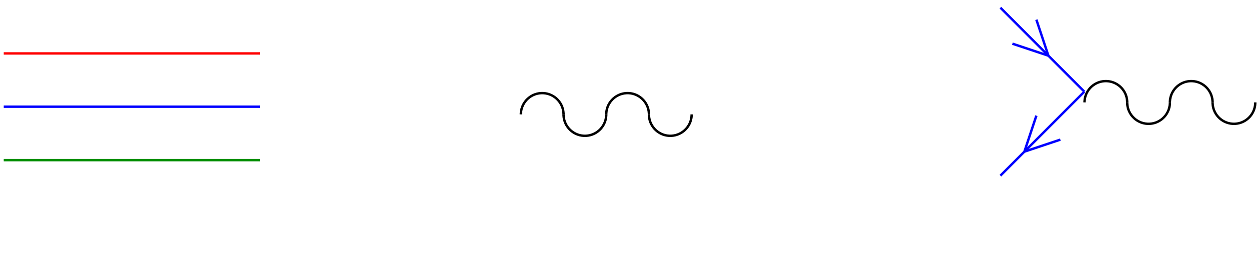


QCD of jets (high E, low α_s limit)

QED



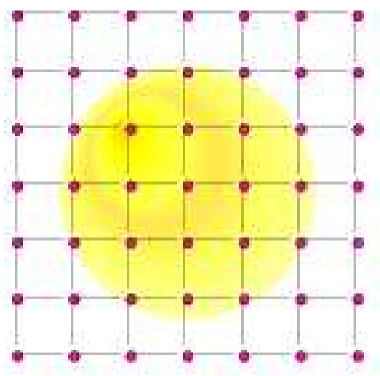
QCD



$$\alpha_s \rightarrow \frac{4}{3}\,\alpha_s$$

Lattice QCD

Size of the box $\sim$ 2 fm



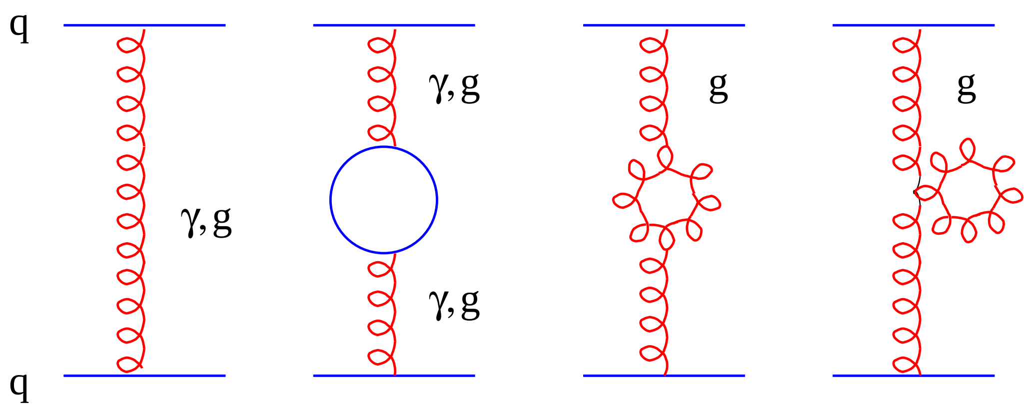
Lattice spacing $\sim$ 0.1 fm

Feynman path integral formulation:

$$\langle 0|\mathcal{O}|0\rangle = \frac{\int [d\psi][d\bar{\psi}][dG_\mu]\mathcal{O}[\psi,\bar{\psi},G]e^{-S}}{\int [d\psi][d\bar{\psi}][dG_\mu]e^{-S}}$$

where $S = \int \mathcal{L}\; d^4x$

and for a meson $\quad \mathcal{O}[\psi,\bar{\psi},G] = (\bar{\psi}\psi)_y(\bar{\psi}\psi)_x$



Vacuum computation

'Quenched Approximation' (just gluons in the vacuum) $\sim$ 10 % error

problems with quarks - 1000 $\times$ more time than QA

Supercomputers required

Baryon mass in QA requires 10^{19} operations (addition & multipl.)

World's fastest computers: few Teraflops (few $\times 10^{12}$ operations/s)

LatticeQCD Collaborations $\sim$ 50 people

- Cray, IBM, NEC
- clusters of stand. computers with Linux
- special LatticeQCD computers

Top 500 supercomputers list (www.top500.org)

1) Earth Simulator, Yokohama, NEC,
35.86 TFlops

2) Thunder, Lawrence LNL, California digital, 19.94 TFlops
1024 4-processor servers

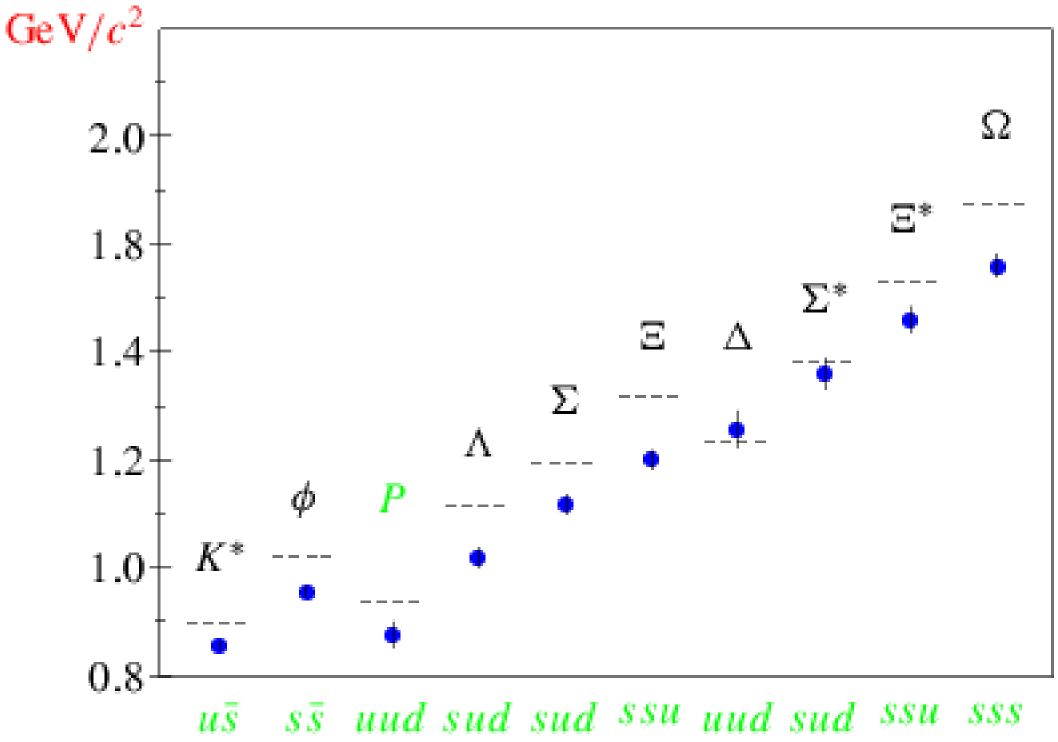
3) ASCI Q, Los Alamos, HP, 13.88 TFlops
1024 4-processor AlphaServers

...

73) Blue Gene/L, IBM , > 2 TFlops,
size: 60 inch TV
more than 1000 PowerPC processors

Plan : to interconnect 128 copies

Hadron masses (Ch. Davies, Ref.[2])



Glueballs : $\sim 1.7 m_p$

α_{QCD} computation

β decay

CP violation (weak interactions of quarks) in B mesons mixed with strong interactions

Quark-gluon plasma

What I did not talk about

Strong CP problem - axions

High density QCD (neutron stars)

High temperature QCD (Quark-gluon plasma)

References

1) Frank Wilczek "QCD made simple" Physics Today Vol. 53 (Aug 2000)

2) Ch. Davies Phys. World, pp35-40 (Aug 2000)

3) Ch. Davies Summer Lectures at the 55th Scottish Universities Summer School, St Andrews, Aug 2001

4) S. Olejnik, plenary talk at 12. konf. slovenskych fyzikov, Smolenice, Sep 2001