How can we understand the strong force?

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Content

1. QCD Lagrangean
2. Problems
   - Running coupling
   - Vacuum condensate
3. Working methods
   - Soft processes
   - Hard processes
4. Phase transitions in the early Universe

1. QCD Lagrangean

Electrodynamics

Massless scalar particle with charge e.

Wavefunction Φ is a complex number $\sim$ vector in the 2-dimensional complex plane.

$$\mathcal{L} = \Phi^*(-iD_\mu)^2\Phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

with $D_\mu \equiv \partial_\mu + ieA_\mu, \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

Gauge invariance:

Invariant under rotations of Φ in the complex plane

$$\Phi \to \Phi e^{-ie\Lambda}, \;\; A_\mu \to A_\mu + \partial_\mu \Lambda$$

Makes QED renormalizable

Non-Abelian gauge theory

Assume Φ^a is a vector (or spinor) in an abstract 3-dim. space

$$\mathcal{L} = \Phi^*(-iD_\mu)^2\Phi - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

$$D_\mu \equiv \partial_\mu + ieA_\mu, \qquad G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g\epsilon^{abc}A^b_\mu A^c_\nu$$

Invariant under rotations in the abstract space
(allow spin 1/2: invariance under SU(2))

The quadratic term in G needed for invariance,
because rotations do not commute.

Makes equations of motion non-linear

Used by Nature for the weak force. Quarks and leptons are two-component spinors in the abstract “isospin” space.

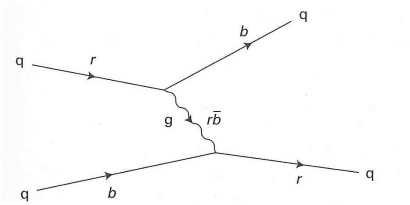
Chromo Dynamics (QCD)

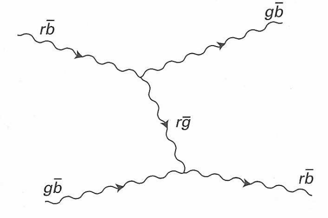
Wavefunctions for quarks have three components.
called *red*, *blue*, and *green*

Invariance under SU(3) $\sim$ rotations in an 8-dimensional abstract space.

ϵ^{abc} for SU(2) replaced by f^{abc}, $\quad a, b, c = \{1, 2, \ldots 8\}$

Cubic and quadratic terms in $\mathcal{L}$ imply couplings beteen gluons:

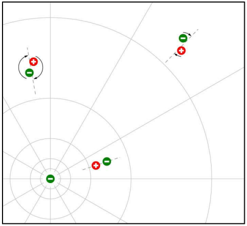




2. Problems

a) Running coupling

QED



Virtual e^+e^- pairs screen the charge

Small distances: high momentum probe penetrates through the screening

$\Rightarrow$ larger effective charge

Problem only far beyond Planck scale

QCD

Emission of virtual gluons spread out the colour charge

Small distances
(high momentum probe):

$\Rightarrow$ smaller effective charge

Large distance: large charge

Pert. th.: charge diverges for $r \sim 1$ fm

Pert. th. breaks down for soft processes

b) Vacuum condensate

The vacuum state is unknown

gluon − *gluon* interaction attractive for some colour combinations

$\Rightarrow$ bound states with $E < 0$

Gluon condensate $< G_{\mu\nu} G^{\mu\nu} >_0 \neq 0$; *cf.* superconductor

Quark condensate $< \bar{q}q >_0 \neq 0$; *cf.* suprafluidity

Superfluid helium

Bose condensation for $T < T_c = 2.17\,\mathrm{K}$

Macroscopic number of atoms in a common ground state

Common wavefunction Ψ, with $|\Psi| = \Psi_0$

Arbitrary phase $\Rightarrow$ ground state degenerate

$\Rightarrow$ exist massless particle (Goldstone boson)

Cf. spinwaves in ferromagnet

Superconductivity

Hg is superconducting for $T < T_c = 4.2\,\mathrm{K}$

Bose condensate of bound $e^- e^-$ pairs

Degenerate ground state Ψ, with $|\Psi| = \Psi_0$

But: el. pairs charged $\Rightarrow$ photons cannot pass unperturbed: move synchronized with electron pair vibrations

photon velocity $< c$: effective photon mass

Goldstone boson “eaten” by the EM field $\rightarrow$ long. pol. photon

Photon mass $\Rightarrow p^2 = \omega^2 - m^2$: $\quad \omega < m \Rightarrow p$ imaginary

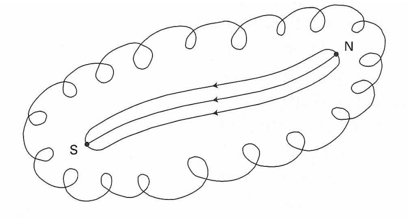
$e^{ipx} \rightarrow e^{-|p|x}$

$\Rightarrow$ Meissner effect: magnetic field expelled from the s.c.

Vortex lines

Assume magnetic monopoles exist

They would be connected by a flux tube or a “vortex line”

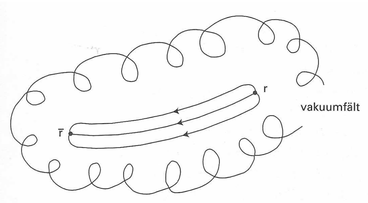


Force between endpoints prop. to distance

QCD

Gluon condensate

$\Rightarrow$ Vacuum a colour electric superconductor



Confinement: only colour neutral systems can be isolated

$\bar{q}q$ condensate is colour neutral $\Rightarrow$ Goldstone boson π

(*cf* superfluidity)

But degeneracy broken by $m_u \neq m_d \Rightarrow \pi$ mass small but $\neq 0$

Phase transition in the early Universe?

Is the condensate destroyed at high temperature,

with a transition to a “quark-gluon” plasma?

If so, can the properties of the plasma be revealed

in high energy nucleus collisions?

3. Working methods

- Soft processes; α_s blows up

  a) Models for hadronization

  b) Pert. th. around true vacuum;
  includes free parameters tuned to data
  ”Chiral pert. th.”

- Hard processes; α_s small

  Pertubation theory; neglect vacuum

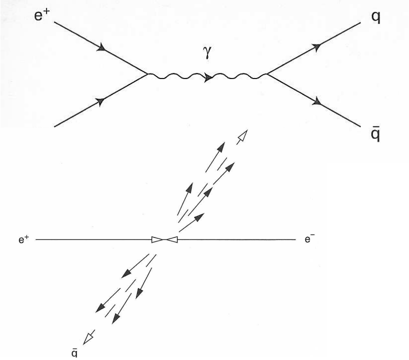
  - Higher order calculations quite complicated
  - High orders of α_s associated by high powers of large logs
  $\sim \alpha_s^n \ln^n(Q^2/M^2)$

  Approximations needed

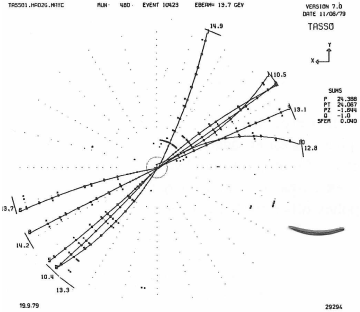
A. Soft processes, Hadronization

e^+e^--annihilation

$e^+e^- \rightarrow q\bar{q} \rightarrow$ "jets" of hadrons



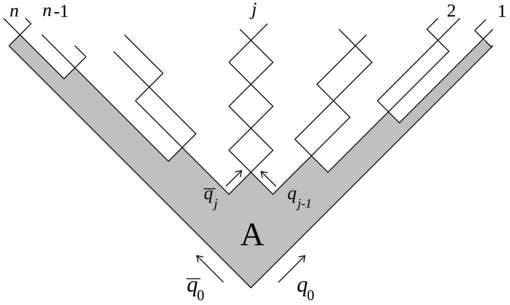
Experimental result



Lund String Hadronization Model

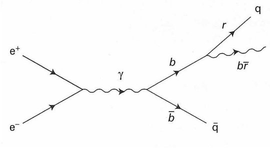
Approx. the force field by an infinitely thin "massless relativistic string"

Breakup of $q\bar{q}$ system in $x - t$ diagram

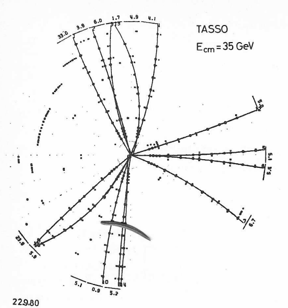


Gluon radiation

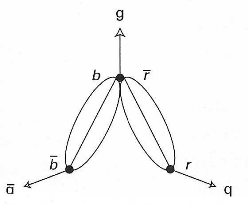
The quark and antiquark can radiate off a gluon.
Coherent “dipole” emission.



The gluon is coloured:
gives a third jet

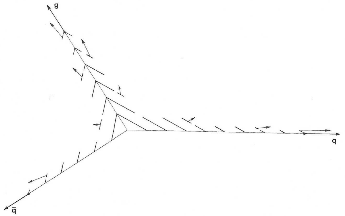


Colour field stretched
between quark and gluon, and
between gluon and antiquark

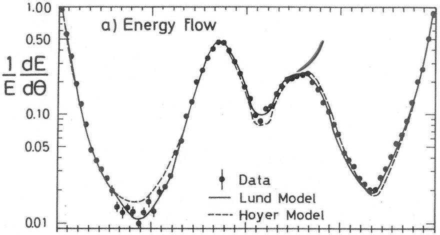


Lund model: The gluon is treated as a “kink” on the string

Predicted asymmetry among hadrons



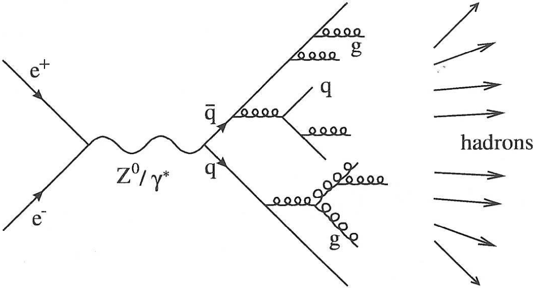
Confirmed by experiments (JADE 1980)



B. Higher energy. Pertubation theory

High energy: Many gluons emitted

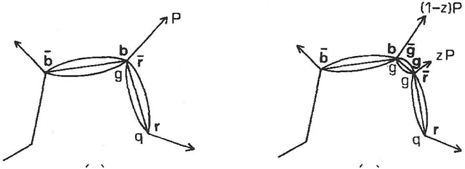
Hard perturbative phase, followed by soft hadronization phase



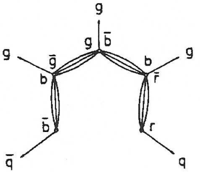
High order calculations very complicated:
Approximations needed

”Dipole cascade model”

Colour in one gluon associated with anticolour in a partner.
Radiate softer gluons as a colour dipole



Semiclassical approximation: Cascade with gradually softer and softer gluons
Colour connection gives chain of colour neutral “colour dipoles”

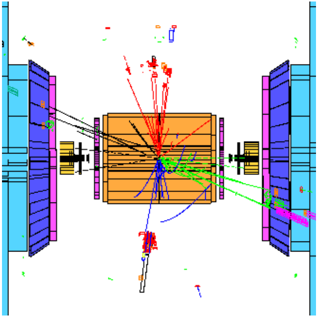


Stretch a string,
which breaks up into hadrons

The Dipole Model gives a smooth transition between the perturbative and non-perturbative phases

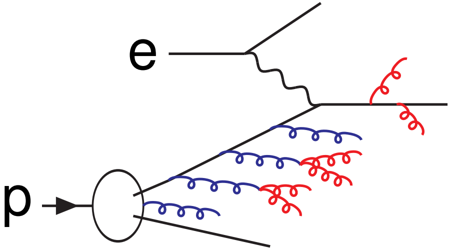
ARIADNE MC gives very good agreement with exp.

Event in the DELPHI detector at LEP

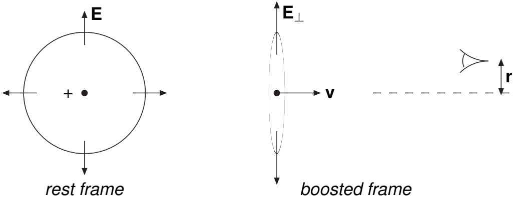


Proton structure, *ep* scattering

Both initial and final state radiation



Bremsstrahlung à la Weizsäcker-Williams in QED



A Coulomb field in a boosted frame is a flat pancake

Energy density $\sim \alpha \frac{1}{r^2}\delta(t)$

Analysis in Fourier series gives bremsstrahlung spectrum

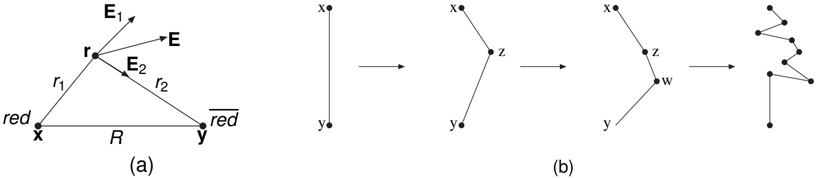
$$dn \sim dE/\omega \sim \alpha \frac{d^2k_\perp}{k_\perp^2}\frac{d\omega}{\omega}$$

Bremsstrahlung in QCD

A colour charge never alone: assume an initial *red-antired* pair, a colour dipole

Emission of a first gluon changes the charges:

Transverse corordinate space



A second emission from two dipoles, etc. gives a dipole cascade
where gluons have smaller and smaller energy,
and mostly smaller and smaller size,
meaning higher transverse momentum

Summation of large logarithms

What is the probability to find a gluon with high $k_\perp$ (a small dipole with $r \sim 1/k_\perp$) and small fraction x of total energy?

Direct emission: Prob. $= \bar{\alpha}\, \frac{dk_\perp^2}{k_\perp^2} \frac{dx}{x} \equiv \mathrm{P}_0$, with $\bar{\alpha} = 3\alpha_s/\pi$

2 steps: Emit first gluon with $k_{\perp 1} < k_\perp$ and fraction $x_1 > x$:

$$\bar{\alpha}\, \frac{dk_\perp^2}{k_\perp^2} \frac{dx}{x} \int^{k_\perp^2} \bar{\alpha} \frac{dk_{\perp 1}^2}{k_{\perp 1}^2} \int_x^1 \frac{dx_1}{x_1} = \mathrm{P}_0\, \bar{\alpha} \ln(k_\perp^2) \ln(1/x)$$

3 steps: first $(k_{\perp 1}, x_1)$ and then $(k_{\perp 2}, x_2)$

$$\mathrm{P}_0\, \bar{\alpha}^2 \frac{\ln(k_\perp^2)^2}{2} \frac{(\ln(1/x))^2}{2}$$

Sum up: $\mathrm{P}_0 \sum_n \bar{\alpha}^n \frac{\ln(k_\perp^2)^n}{n!} \frac{(\ln(1/x))^n}{n!} =$

$$= \mathrm{P}_0\; I_0(2\sqrt{\bar{\alpha} \ln(k_\perp^2) \ln(1/x)}) \;\; \sim \mathrm{P}_0\; \exp(2\sqrt{\bar{\alpha} \ln(k_\perp^2) \ln(1/x)})$$

An accelerated proton looks like a swarm of colour dipoles

The initial dipoles in the proton cannot be directly calculated from QCD,

but the dipoles in the cascade become on average smaller and smaller,

and experiments are most sensitive to the large number of small dipoles

Tune distribution of large dipoles, and calculate the small ones

$\Rightarrow$ good description of data for *ep* scattering

Unitarity constraints

Fast growth for small energy fractions x

$k_\perp$ not very large: cascades with non-ordered $k_\perp$ also important
Summation gives growth $\sim 1/x^\lambda$, with λ a constant

Probability must be smaller than 1: Corrections needed

Depends on geometric structure, no pert. th.

pp collisions

Complicated process

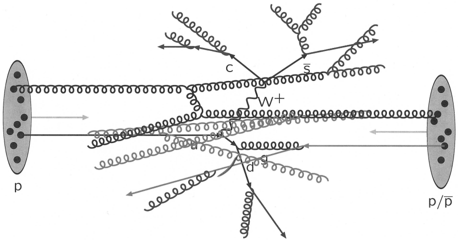


fig. from TS

- Calculate all hard subcollisions with pert. QCD (correlations needed)
- Add final state radiation
- Determine how the quarks and gluons are coulor-connected
- Draw strings which break up into hadrons

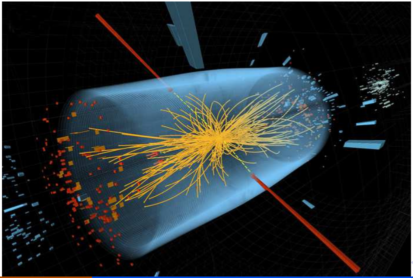
PYTHIA MC
(Torbjörn Sjöstrand)

The most widely used simulation program

Soft input from *ep* collisions

Cascades for initial and final state radiation,
and exact matrix elements for hardest interactions

Gives high precision, essential for e.g. Higgs search



DIPSY model

(Now active: GG, Leif Lönnblad, Christian Bierlich)

Can the long dipoles (gluons with small transv. mom.) be estimated?

After long evolution the result is not sensitive to the start

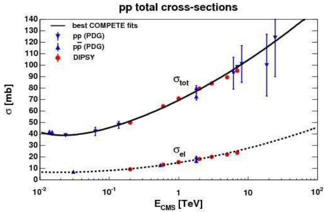
Less input and less precision for hard processes

Advantages: Can give information about

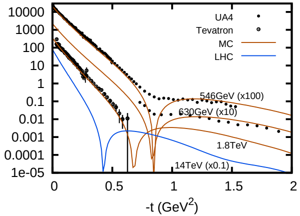
- Evolution dynamics of the large dipoles (soft partons)
- Correlations
- Fluctuations and diffraction
- Unitarity constraints
- Collisions with nuclei

Some results

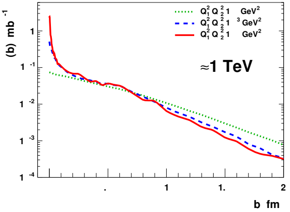
σ_{tot} and σ_{el} in *pp* coll.



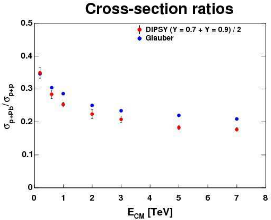
$d\sigma/dt$ (*pp*)



2-gluon correlations



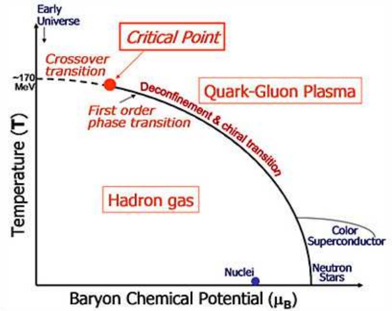
Shadowing in *pPb* coll.



4. Phase transition in nucleus collisions?

When does the above picture break down?

Expected phase diagram: Temperature *vs.*
baryon chemical potential $\propto$ density of (quarks – antiquarks)

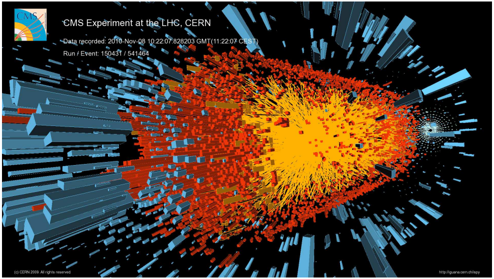


Relevant for the early Universe

Lattice QCD: Cross over at $\approx$ 170 MeV ($= 1.7 \cdot 10^{12}$ K)

Critical point?

PbPb collision in LHC (CMS)



Many features may be understood as result from hydrodynamic expansion of quark-gluon plasma, acting as an "ideal fluid":

short meanfree path and extremely low viscosity

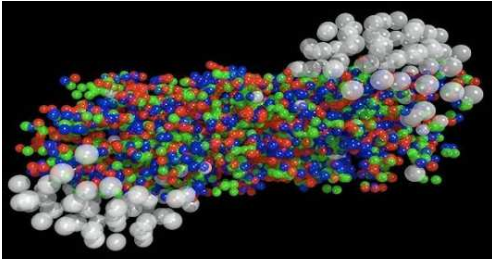
Plasma expansion gives *e.g.* flow effects, more strange quarks, more baryons

Is this necessarily the true picture?

Can the data only be explained by a plasma?

Similar effects observed in *pp* collisions, where no plasma is expected

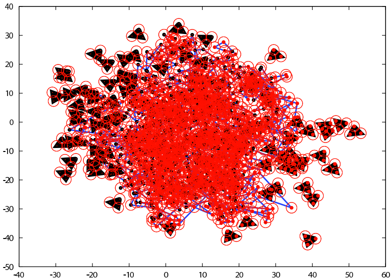
Non-homogeneous and non-static system makes the interpretation very non-trivial



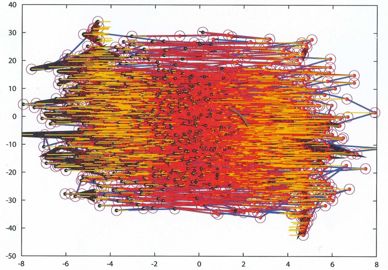
Also non-plasma explanations have to be examined

AA collisions in DIPSY

Front view



Side view



Can give energy density and particle distribution,
if NO plasma formation

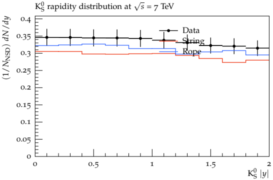
Gives initial condition for hydrodynamical expansion,
IF a plasma is formed

Many strings on top of each other:

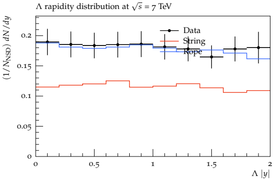
High density $\Rightarrow$ expansion, more strange quarks, more baryons

Prel. results from toy model implementation. *pp* data from CMS

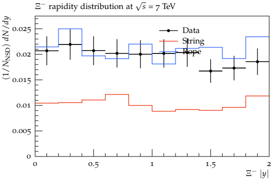
K $dn/d\eta$



Λ $dn/d\eta$



Ξ $dn/d\eta$



Work in progress (GG, LL, CB)

More work needed to unravel the dynamics of high energy nucleus collisions, and the plasma phase diagram

Conclusions

Understanding the strong force is a very complex problem

- Non-linear eq. of motion
- Coupling blows up for soft processes: models needed
- Vacuum structure unknown: gluon and quark condensates
- Similarities with superconductor and superfluidity
- Exact matrix elements difficult in higher orders
- Higher orders in the coupling associated with large logs
  Approximations in cascade evolutions needed

PYTHIA: Phenomenological input from *ep* collisions

plus pertubation theory for hard processes

give very good description of high energy *pp* scattering

DIPSY: Less phenomenological input: lower accuracy

Gives more detailed information about:

- Evolution dynamics of the large dipoles (soft partons)
- Correlations
- Fluctuations and diffraction
- Unitarity constraints
- Collisions with nuclei

Still many questions, more experimental data and more work needed, *e.g.* to understand diffractive events and the QCD phase diagram and equation of state

Not discussed here: Low energy pert. theory

Lattice calculations and more