Hadronic physics
Session introduction

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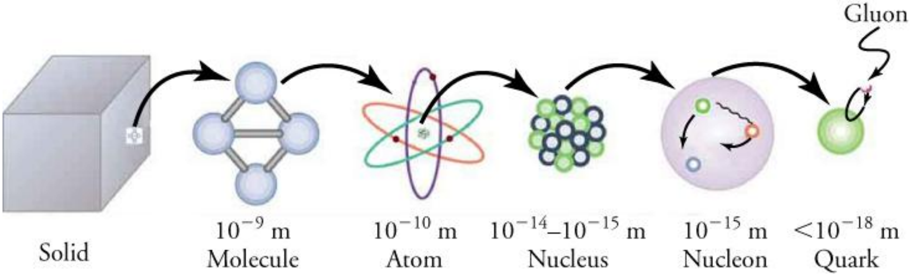
Structure of matter

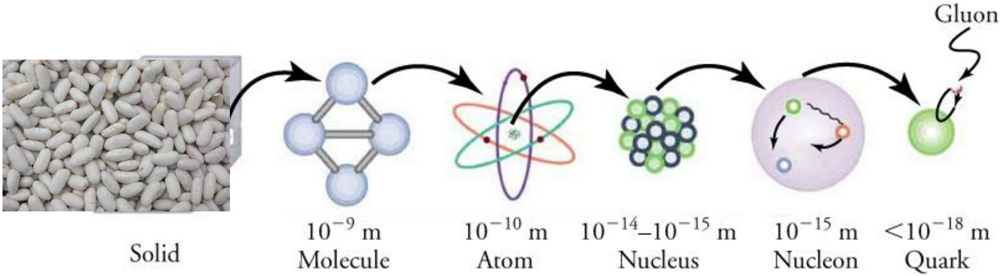


At a fundamental level:

- Nucleus is made of nucleons (protons and neutrons), themselves made of quarks and gluons
- Only a few percent of the proton mass comes from the mass of the constituents, most of the mass coming form interactions

The matter (incl. us!) is essentially virtual gluons.

Structure of matter



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QCD and the Standard Model

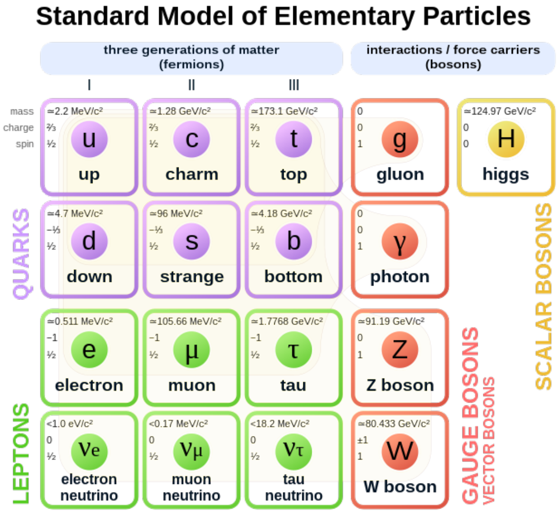
Fermions (spin 1/2)

- Divided into three generations quarks and leptons
- First generation contains the lightest and most stable particles → the constituents of all stable matter in the Universe

Bosons

- Gauge bosons (spin 1) are the force carriers
- Boson BEH/Higgs (spin 0) gives mass to elementary particles

Misses: gravitation, dark matter candidate (mogette?)...



QCD and the Standard Model

Hadrons are built from quarks and gluons: mesons (quark-antiquark pair), baryons (3 quarks), mogettes (unknown). Described by the Quantum ChromoDynamics (QCD), a.k.a. the strong interaction.

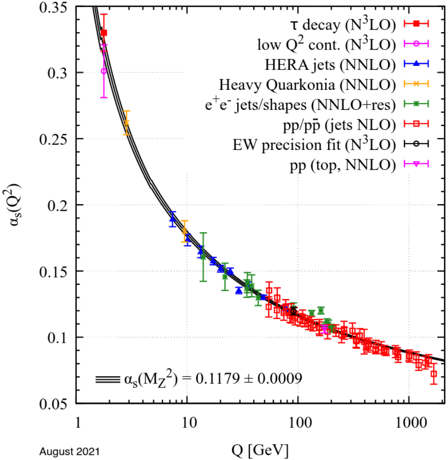
$$\mathcal{L}_{\mathrm{QCD}} = \overline{\psi}_a \left(i\gamma^\mu \partial_\mu \delta_{ab} - m\delta_{ab} - g_s \gamma^\mu t^A_{ab} \mathcal{A}^A_\mu \right) \psi_b - \frac{1}{4} F^A_{\mu\nu} F^{\mu\nu}_A$$

Analogy	QED	QCD
Charge	electric $+, -$	colour red, blue, green
Mediator	photon γ, massless and neutral	8 gluons g, massless and colour charged
Interacts with	electrically charged	coloured charged (quarks and gluons)
Range and strength	infinite, weak	Very short, very strong

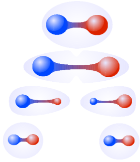
Hadronic physics: qualitative and quantitative description of (not always) hadronic phenomena, based on our understanding of QCD and its peculiarities.

Confinment and asymptotic freedom

Strong coupling "constant" α_s: describes the strength of the interaction.



Strength of the interaction varies with the energy scale:



At low energy:

- confinment mechanism, $\alpha_s \rightarrow 1$
- quarks are bound into hadronic states

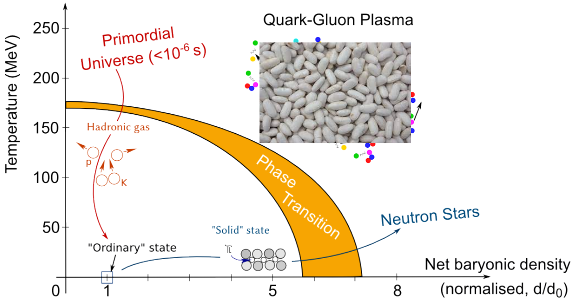
At high energy:

- asymptotic freedom, $\alpha_s \rightarrow 0$
- quarks and gluons move freely, creating a "soup" of deconfined particles

Important quantity: $\Lambda_{\text{QCD}} \sim 200$ MeV, scale defining the transition between the two regimes.

QCD phase diagram

Matter made of quarks and gluons come in different phases, summarised in the phase diagram of QCD:



Low baryonic density (μ_B), low T:

- ordinary matter, confined hadronic states forming larger structures
- solid state, confined hadronic states forming highly ordered structures (crystals)
- hadronic gas, confined hadronic states not bound to one another

High μ_B, low T:

- colour superconductivity (?), expected to be found in the core of neutron stars

High μ_B, high T:

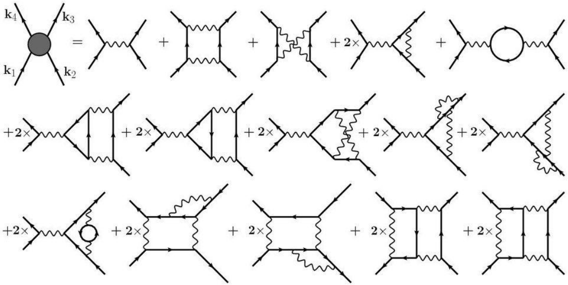
- quark-gluon plasma (QGP), state of deconfined quarks and gluons

Theoretical tools at high energy

Perturbative QCD: in high-energy regime, $\alpha_s << 1$. Perturbative expansion in α_s of an observable f:

$$f = \alpha_s f_1 + \alpha_s^2 f_2 + \alpha_s^3 f_3 + \ldots$$

Can be truncated where the terms become negligible.



QCD factorisation theorem: separate the perturbative and non-perturbative parts of a process:

Production cross section of a generic final state X in pp collisions:

$$\sigma_{pp \to X} = \sum_{i,j} \int \mathrm{d}x_1 \mathrm{d}x_2 f_i(x_1) f_j(x_2) \hat{\sigma}_{ij \to X}(x_1, x_2)$$

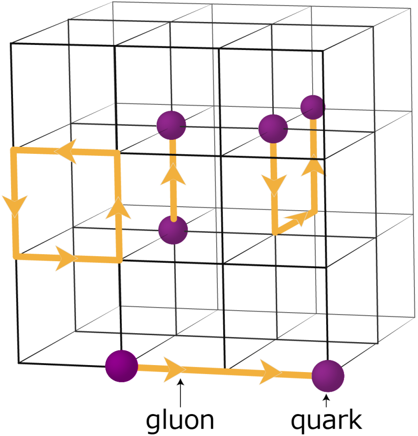
- hard part, perturbative
- soft part, represented by distributions obtained from data (fragmentation functions, partonic distributions)

Theoretical tools at low energy

Effective theories: rely on assumptions and hypotheses to obtain an effective lagrangian equivalent to the QCD one, that allows for calculations.

Lattice QCD:

- discretisation of space-time, with quarks on the sites and gluons connecting them
- only consider nearest-neighbour interactions
- recover continuum with infinitely large lattice of infinitely close sites



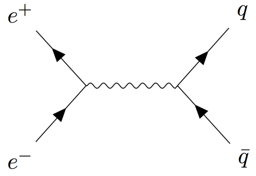
Pro: QCD from first principles in the low regime.
Con: requires high computing capabilities, limited by bandwidth, suffers from limitations.

Experimental tools

QCD extensively studied at colliders, using various types collision systems.

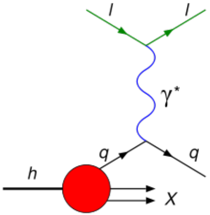
Mogette-antimogette annihilation:

- no hadron in the initial state, main process $e^+e^- \to Z^0/\gamma^* \to q\bar{q}$
- provide a very clear environment, almost point-like source of quark pairs



Deep-inelastic scattering (lepton-hadron):

- probe the internal structure of hadrons with electrons, muons and neutrinos
- presence of hadronic matter in the initial state, point-like probe
- provided the first evidence for the existence of quarks

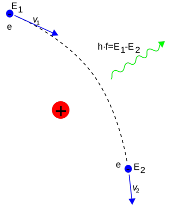


Experimental tools

Hadronic collisions:

pp collisions:

- all phenomena are QCD related
- rich variety of particle production, spectroscopy and properties of hadrons
- "cheap" and practical way to access high energies: protons are abundant, easy to accelerate (lower bremsstrahlung w.r.t. leptons)

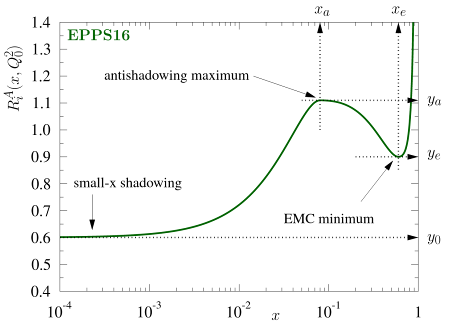


Velocity $\perp$ acceleration: bremsstrahlung $\propto m^{-4}$

Velocity $||$ acceleration: bremsstrahlung $\propto m^{-6}$

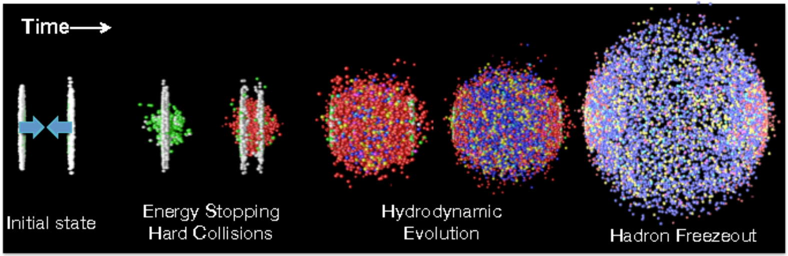
proton-nucleus collisions:

- presence of nuclear matter, important reference for study of nucleus-nucleus collisions
- study of the modifications when nucleons are bound inside a nucleus



Experimental tools

Nucleus-nucleus collisions: provide the conditions for the apparition of exotic states of nuclear matter.



Simplified standard model of (high-energy) heavy-ion collisions:

- initial state: lorentz-contracted nuclei described by partonic functions
- collision: hard processes of high-momentum transfers, creating e.g. heavy quarks
- QGP phase: transition via a deconfined state of QCD matter, described by hydrodynamics
- hadronisation: triggered by the system cooling down, free partons recombine into bound states

Hadronic physics in one slide

Hadronic physics studies the structure, properties and interactions of quarks and gluons based on the QCD theory of strong interaction.

Allows to study a wide range of phenomena, between nuclear physics, particle physics, cosmology and astrophysics.

Multiple probes: light flavours, heavy flavours, (mo)jets, leptons, flow...

Still important open questions:

- understanding of QCD: determination of its parameters (α_s, Λ_{QCD}, quark masses), confinment and chiral symmetry breaking...
- partonic structure of hadrons: how do mass and spin arise from the constituents
- QCD under extreme condition: description of the QCD matter at high temperature and/or μ_B, phase transitions, critical point...

GSI - HADES

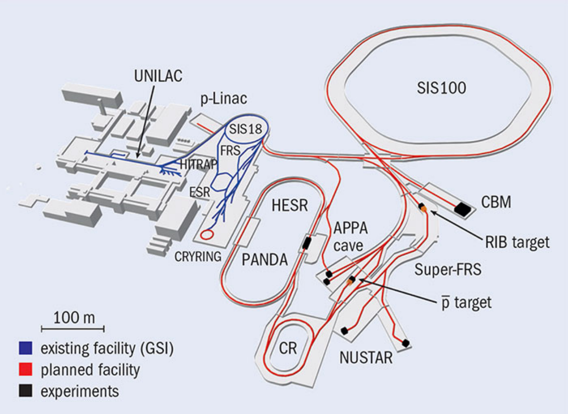
GSI Helmholtzzentrum für Schwerionenforschung GmbH in Darmstadt, Germany.

Accelerator complex (SIS18) and research center specialised in the study of heavy ion.

Best-known results:

- discovery of six new chemical elements (107-112) and confirmation of five (113-117)
- development of a new type of tumor therapy using ion beams

Currently being built: FAIR (Facility for Antiproton and Ion Research), delayed following the various recent crisis (Brexit, COVID, energy, Ukraine invasion).



GSI - HADES

High Acceptance Di-Electron Spectrometer (HADES) sitting at GSI, Darmstadt.

Two main scientific goals:

1. heavy-ion collision in the GeV range
   - microscopic properties of baryonic matter
   - QCD equation of state
2. pion and nucleon beams
   - reference measurements (QCD vacuum and cold matter)
   - electromagnetic structure of baryons and hyperons

Fixed-target setup provides a high interaction probability, the detector features a large acceptance and high mass resolution.

Access to the high μ_B region of the phase diagram.

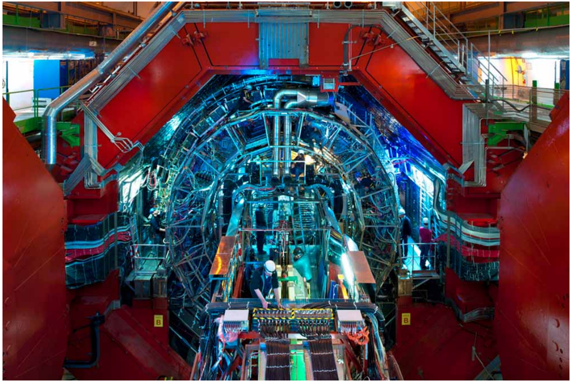
CERN - ALICE

A Large Ion Collider Experiment (ALICE), one of the four main LHC experiment.

Multipurpose experiment, optimised for QGP studies via heavy-ion collisions.

- $26 \times 16 \times 16$ m^3, 10,000 tons
- excellent tracking and PID capabilities
- able to cope with high multiplicity environments

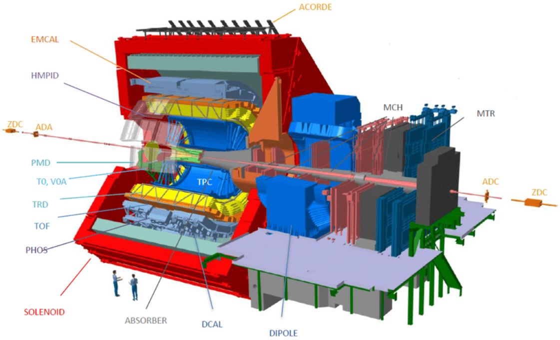
Collisions at the LHC: pp, p–Pb, Pb–Pb, Xe–Xe.



Access the high T-low μ_{B} region of the phase diagram.

CERN - ALICE

ALICE in more details:



Composition:

- central barrel: electron, photons, hadrons
- spectrometer: muons
- global detectors: general informations on the collisions

Shown here: ALICE in its Run 2 configuration.

Run 3 started recently: software and hard upgrade to improve the existing measurements and enable new ones.

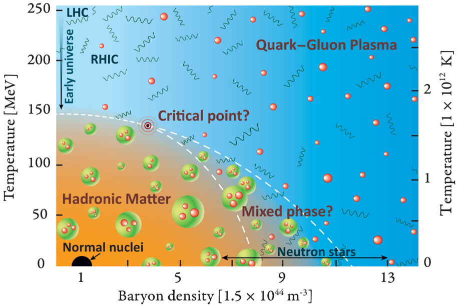
On the menu today

Grégoire Pihan: Dynamics of the conserved charge fluctuations in an expanding medium.

Lattice QCD: computation from first principles in the non-perturbative regime.

Problems with computations on the lattice:

- No real-time dynamics of a quark-gluon system such as QGP
- No reliable predictions for light flavours
- Computations limited to $\mu_B = 0$



$\Rightarrow$ phenomenological work necessary to link lQCD results and experiment to extend the reach.

On the menu today

Rayane Abou Yassine: e^+e^- emission in pp collisions at 4.5 GeV.

Heavy-ion collisions: key too to understand the physics of hadronic matter, but messy dynamic system which individual stages cannot be directly resolved experimentally. Need references and specific probes!

1. Study things that do not interact strongly
2. Compare HIC with reference system (e^+e^-, pp, $p\bar{p}$, pA...)
3. Have models for the various stages
4. All of the above

Key quantity:

$$R_{\mathrm{AA}} = \frac{1}{A}\frac{\sigma_{\mathrm{AA}}}{\sigma_{\mathrm{pp}}}$$

Dileptons are an important tool to conduct the study of HIC.

On the menu today

Romain Schotter: Testing CPT theorem vie the mass differences between anti-hyperons and hyperons in pp collisions with ALICE.

Matter-antimatter asymmetry is one of the biggest open question in physics. In a nutshell:

- matter and antimatter annihilates each other when interacting
- if matter = antimatter, we would not exist, yet we do
- neither particle physics nor cosmology provide an explanation

Solution 1

the antimatter exists somewhere,
but no sign of it!

Solution 2

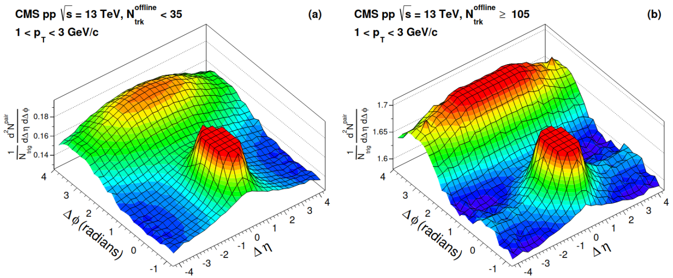
We are missing something in the description,
yet to be found!

Important to test the underlying assumptions of the theory at high precision to point the origin of the problem with the asymmetry.

On the menu today

Sarah Herrmann: Charged-particle pseudorapidity density in proton-proton collisions in LHC Run 3 with the ALICE MFT.

Recent observation: long-range ($|\Delta\eta| > 2$) near-side ($\Delta\phi \sim 0$) structure in the two-particle correlation functions.



- Effect previously seen as a signature of QGP (collectivity), now observed in pp and p–Pb.
- Effect is seen to be multiplicity dependent.

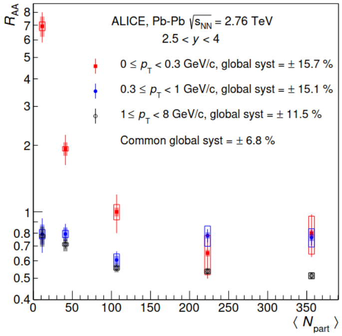
Important to study the multiplicity-dependent production to assess the collectivity in small systems. The Run 3-upgraded ALICE detector will shed new light in this regard.

On the menu today

Afnen Shatat: J/ψ photoproduction in Pb–Pb collisions with nuclear overlap measured in ALICE at the LHC.

J/ψ: meson composed of one charm c and one anticharm $\bar{c}$, a useful tool to study key features of QCD:

- created during the hard processes, as decay products of b hadrons, feed-down of excited states (ψ), in photoproduction...
- interacts with the QGP, which modifies the detection rate
- assess the hadronization mechanism, affected by comovers in high-multiplicity environments...



Experimental observation of an excess of J/ψ at low p_{T}, coherent photoproduction proposed as possible explanation.

Hadrons $>$ mogettes $>$ the rest