High-energy nuclear physics:

ALICE at the LHC

Speaker: Andrea Rossi (INFN Padova)

ALICE team:
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Investigating the strong force at high-energy at colliders

What happens in **proton-proton collisions at high energies** like those accessible at the **Large Hadron Collider at CERN**?

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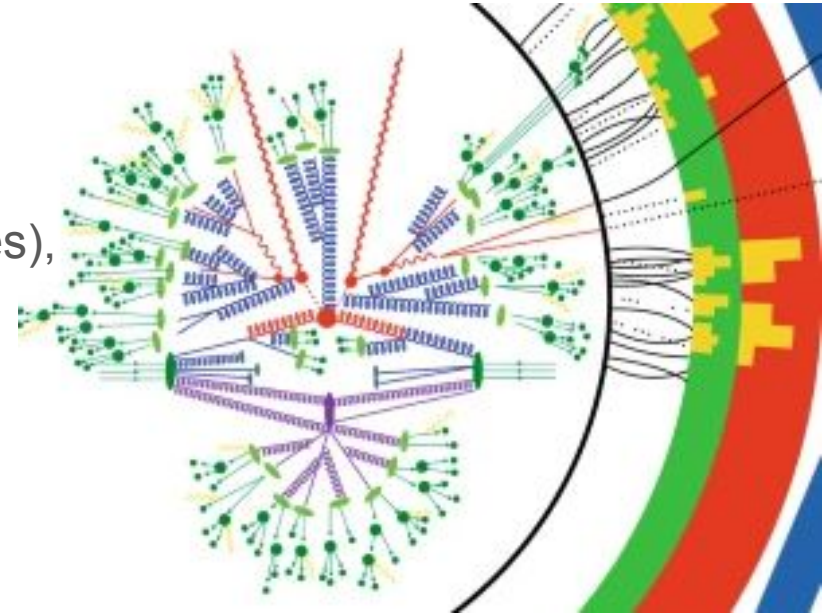
Quarks and gluons inside protons
interact and produce
several quarks and gluons (rarely other particles),
i.e. a system of interacting partons,
which **evolves until hadrons are formed**



Picture from: Georgescu, I. Simulating parton showers. *Nat Rev Phys* 3, 73 (2021)

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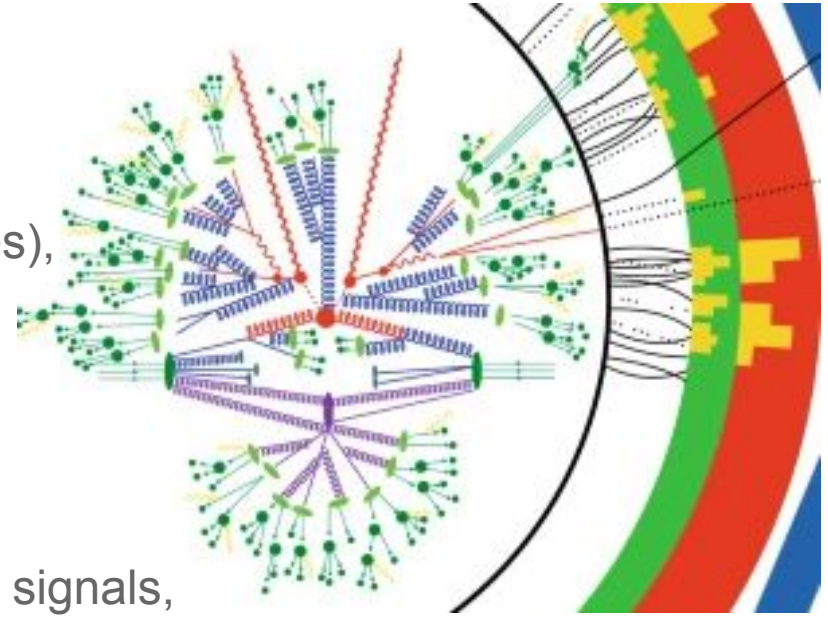

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Two types of research at high-energy colliders:

1) search for new physics → focus on very rare signals,
   the majority of the produced quarks and gluons is a background
2) understand the properties and evolution of the partonic and hadronic systems
   → learn properties of strong force and of some fundamental processes in nature

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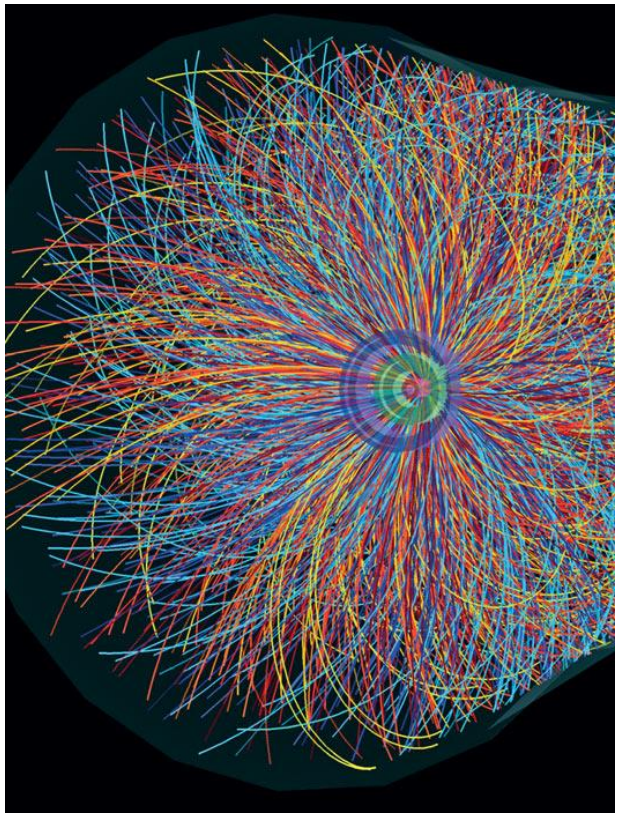
Investigating the strong force at high-energy at colliders

What happens in Pb-Pb collisions at high energies like those accessible at the Large Hadron Collider at CERN?



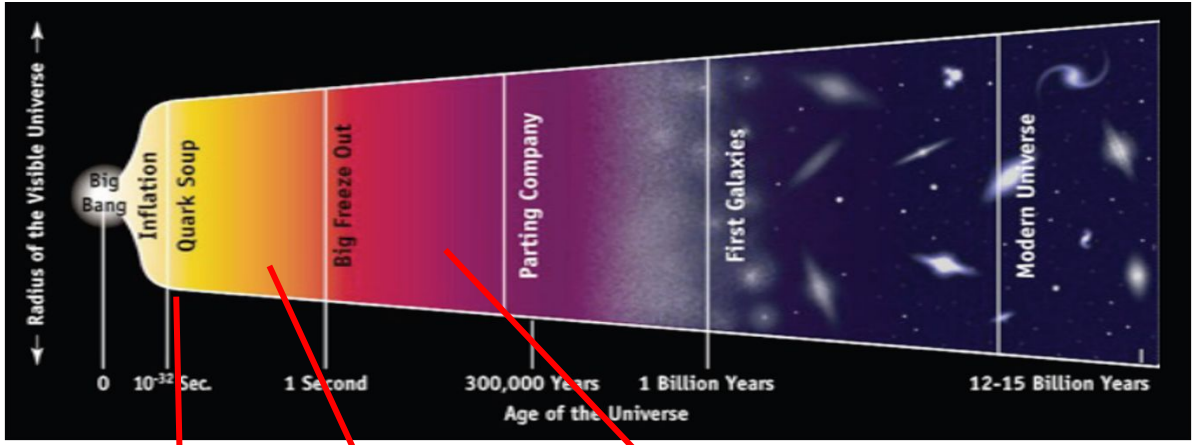
Something similar to proton-proton collisions

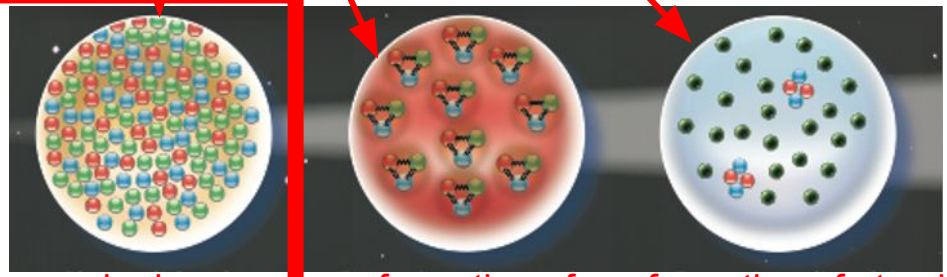
but the **number of produced quarks and gluons (and then hadrons) is much higher** (about x1000)

Partonic system with very high energy density

which behaves for a very short time (few 10^{-23} s) as a **quark-gluon plasma (QGP) state**

Quark-gluon matter in the Early Universe …





quark-gluon plasma

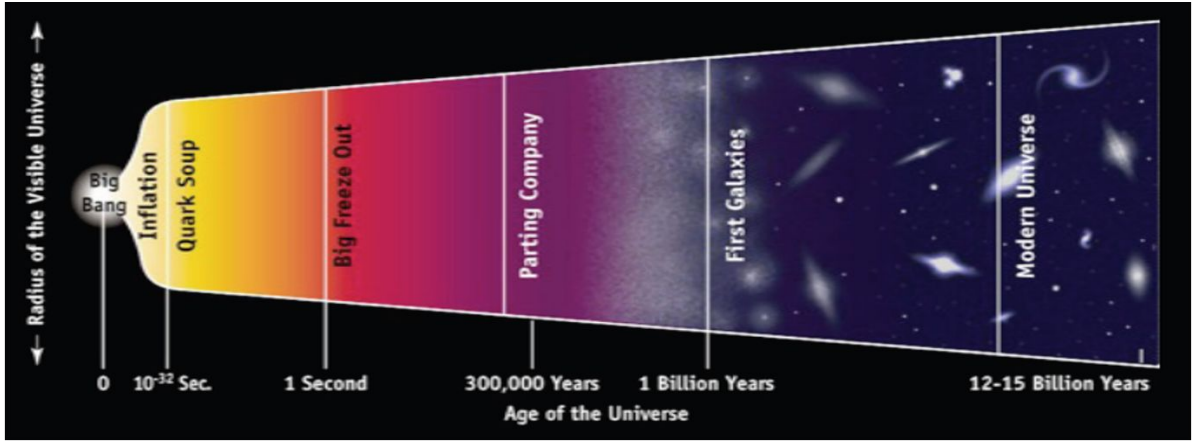
formation of protons, neutrons

formation of atomic nuclei

The transition from quarks to hadrons occurred in the expanding & cooling early Universe
~10 µs after the Big Bang

→ Before: **Quark Gluon Plasma**

Quark-gluon matter in Neutron Stars…



The transition from quarks to hadrons occurred in the expanding & cooling early Universe
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→ Before: **Quark Gluon Plasma**

QGP **may** characterise also the core of neutron stars.

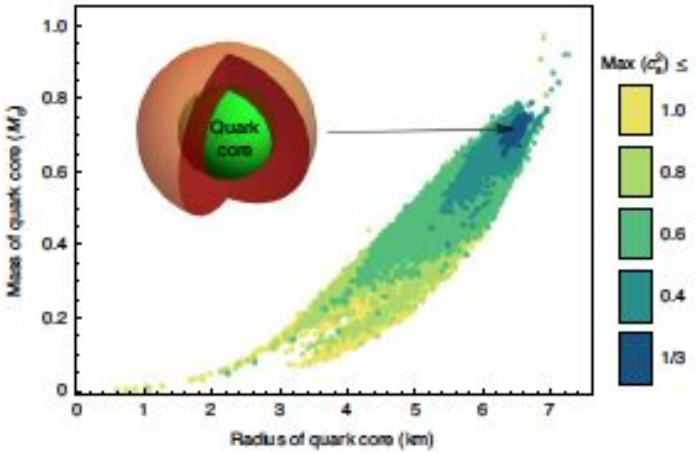
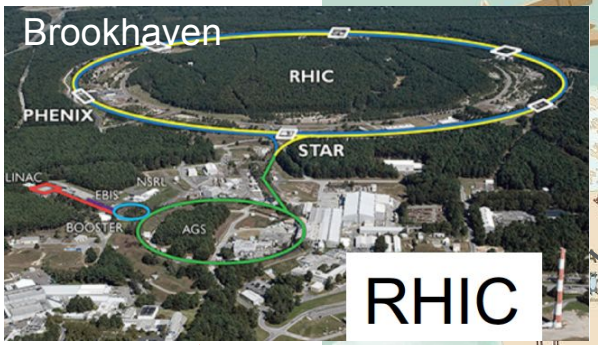
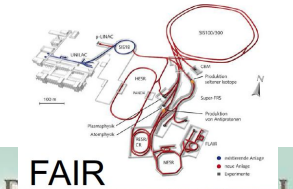


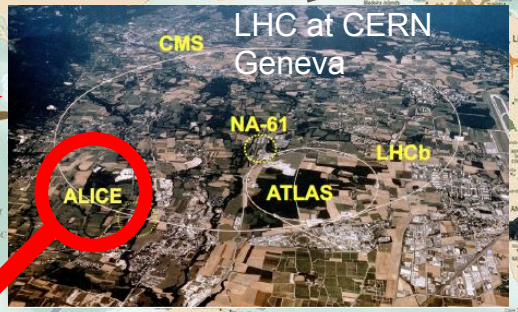
figure from Nature Physics, 16, 907-910 (2020),
https://www.nature.com/articles/s41567-020-0914-9

Quark-gluon matter on Earth



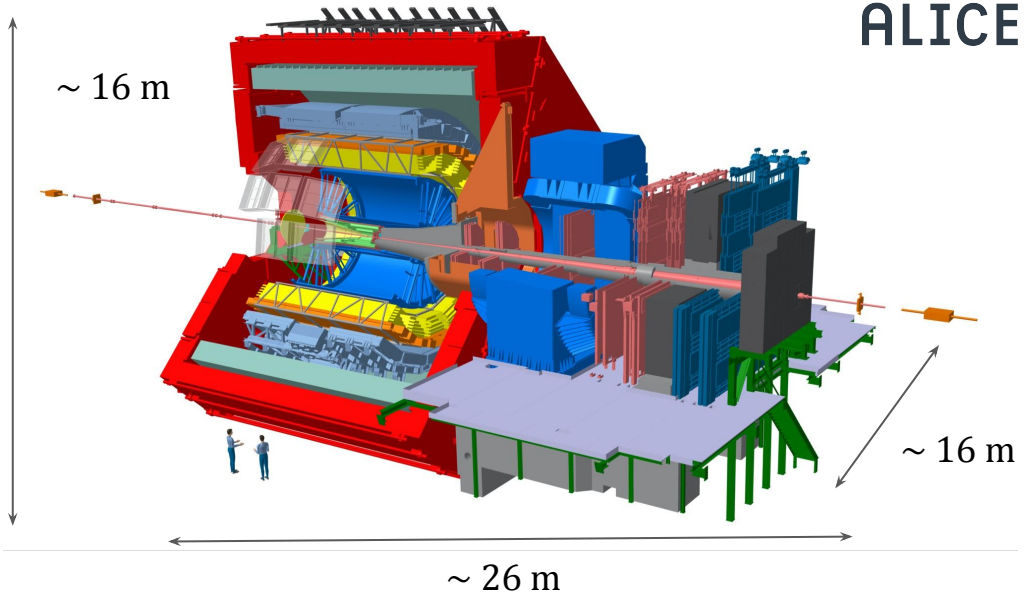


High Energy Frontier



ALICE

The ALICE experiment at the Large Hadron Collider



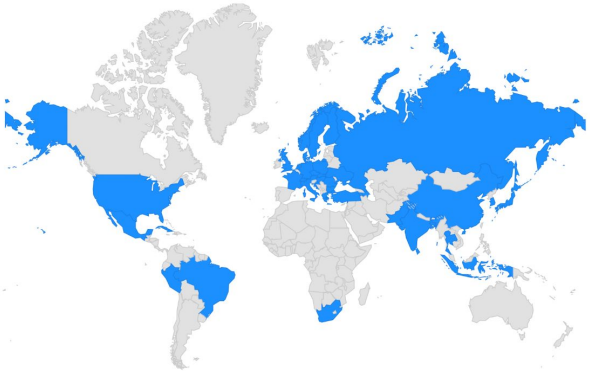
"Gigantic" particle accelerator (LHC) with gigantic apparatus
→ magnets, trackers, muon-chambers, calorimeters… and several other detectors to study the transition from hadrons to quarks (and return) in laboratories

ALICE public webpages (just look for "ALICE CERN"): https://alice-collaboration.web.cern.ch/ https://alice.cern/alice-physics

The ALICE experiment at the Large Hadron Collider

ALICE

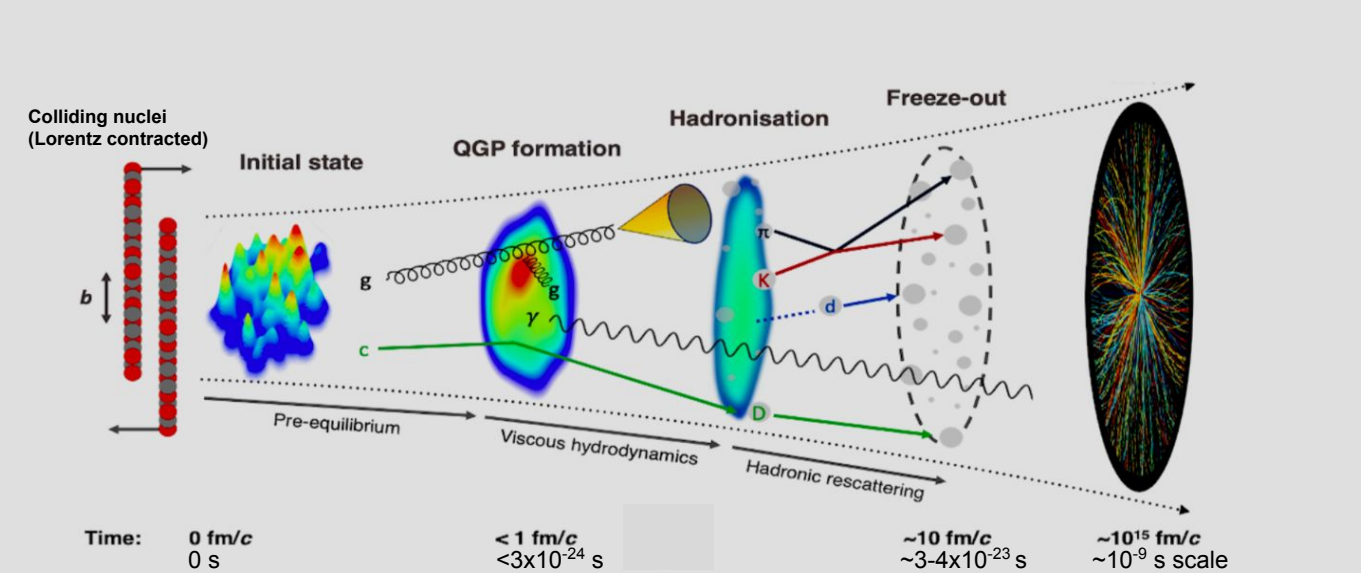
40 countries, 170 institutes, ~2000 members



International Collaboration
→ Network of contacts

- PhD, post-doc
- spend periods at CERN or in foreign institutes

Back to nuclei collisions: system evolution and phases



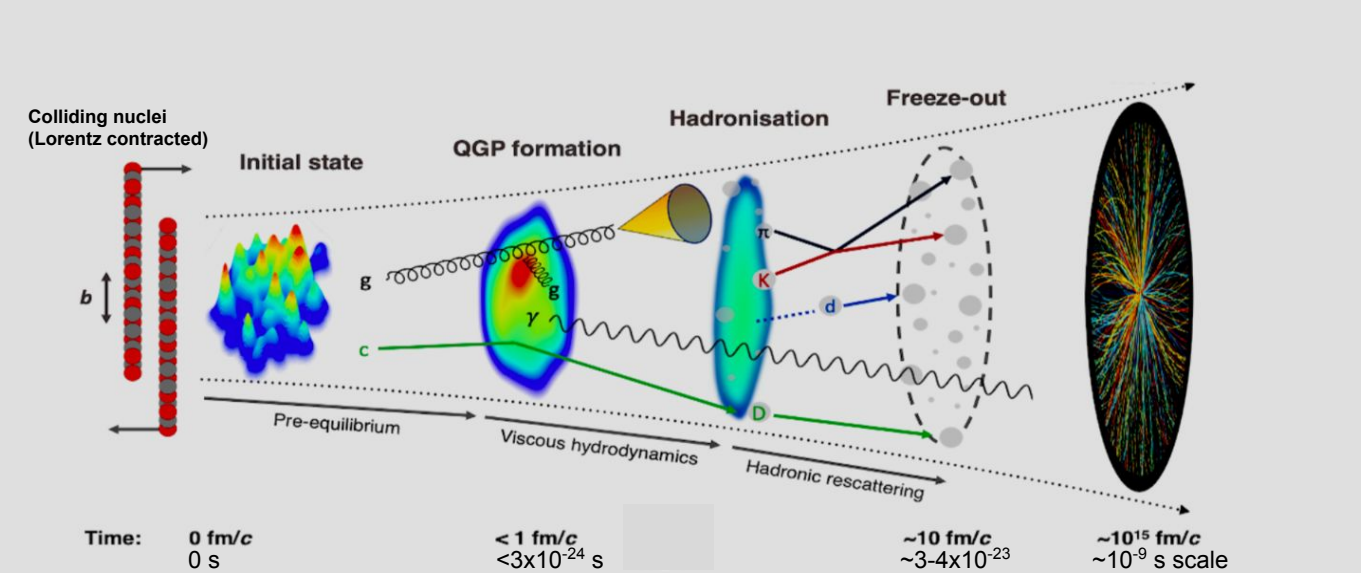
Temperature

Phase transition critical temperature: T_c=156 MeV ~ $1.8 \cdot 10^{12}$ K

Sun core: $1.5 \cdot 10^7$ K

Sun surface: 5778 K

Back to nuclei collisions: system evolution and phases



"Language" and physics concepts used to describe system properties and evolution:

admixture of particle physics, Standard Model, Quantum Chromodynamics and statistical mechanics, thermodynamics, hydrodynamics

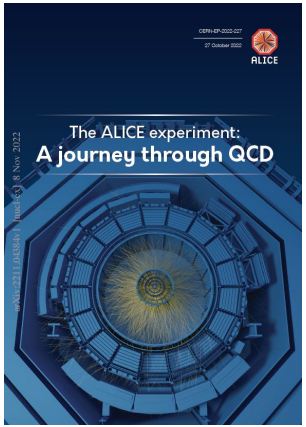
What do we want to know?

*What are the **global properties (e.g. temperature, density, volume, viscosity)** of the system?*

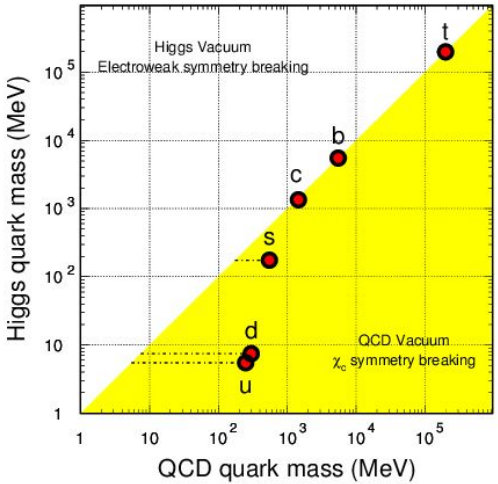
*Can we model the evolution of the quark-gluon system **from proton-proton to Pb-Pb collisions**?*

*How do **hadrons form out of a system of quarks** (hadronisation process)?*

… many more questions



https://arxiv.org/pdf/2211.04384.pdf



N.B.

- Higgs boson accounts only for a few % of the matter mass:
  M(proton) ~ 938 MeV/c^2
  M(up, down) ~ few MeV/c^2

- Most of matter mass is generated dynamically during the transition from quarks to hadrons

Activities of the ALICE group in Padova

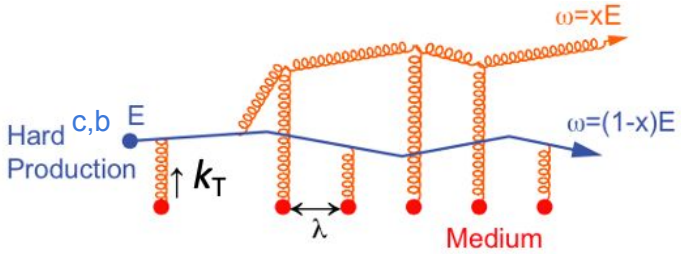
1) Data analysis
2) Silicon pixel sensors

Team composition:
12 Unipd and INFN staff members
3 post-doc
2 PhD students

Data analysis, heavy-flavour particles: physics motivation

Heavy quarks (**charm and beauty**, mass ~1.5-4.5 GeV/c^2, heavier than protons!) are ideal probes of QGP and quark-to-hadron transition

- produced in the first instants
- flavour conserved in strong interactions

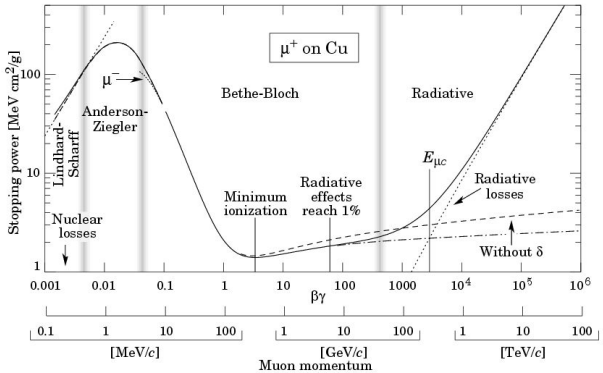


High momentum: energy loss

→ **study "Bethe-Block" curve for partons in the QGP**

Low momentum: Brownian motion markers of QGP
→ study **quark diffusion** and transport properties

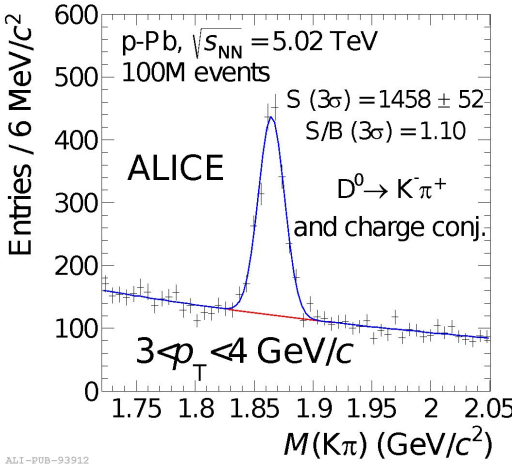
Investigate **hadronisation process**:
e.g. baryon vs. meson formation probability



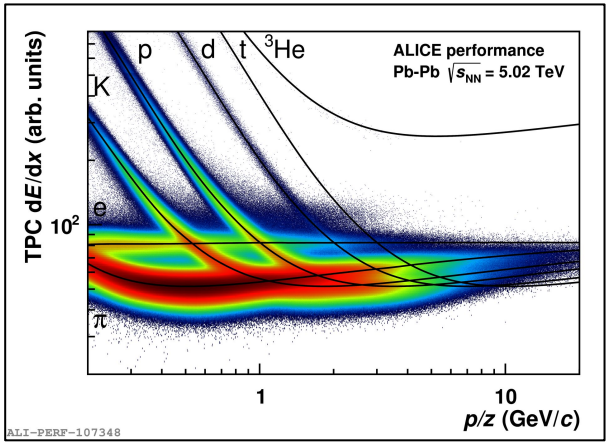
Our data-analysis toolkit

Some among the main <u>standard tools</u> used in <u>nuclear and particle physics</u>

invariant mass analysis

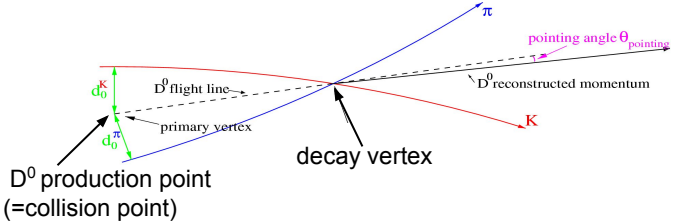


particle identification (PID)



decay vertex reconstruction

Example: sketch of $D^0 \rightarrow K^-\pi^+$ decay



charm-hadron decay length: few to hundred μm

exploit resolution (few μm) of **silicon pixel detector**

\+ **machine-learning** classification techniques. Signal hunters! Overwhelming background to reject!

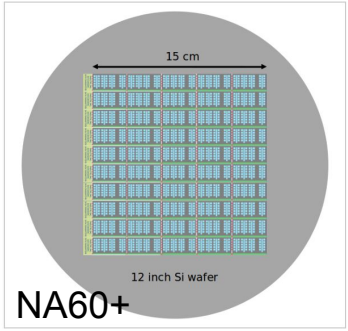
Recent detector upgrade, tons of data being collected and ready to be analysed!

<u>Software tools</u>:

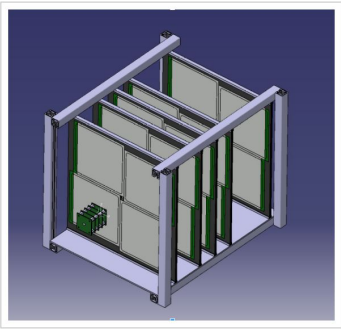
- mainly **C++**-based software (ROOT and ALICE specific software)
- **machine-learning** packages
- (python)

Activity on silicon sensors: at the frontier of detector technology

- High-precision silicon pixel detectors, as close as possible to the interaction point
  → identification of charm and beauty particles

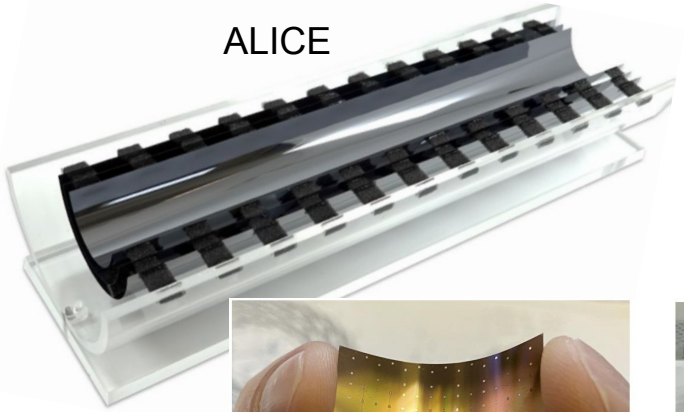


NA60+

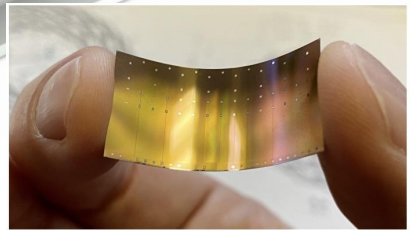


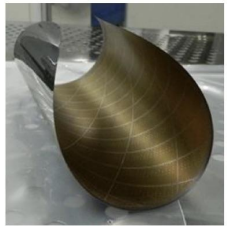
- We participate in the development of the next-generation sensors:
  - thinned to ~ 50 μm
  - long (>10 cm), wide area
  - bent in cylindrical shape around beam axis

ALICE



Imagine to hold and bend a sheet of paper … which instead is a layer of silicon pixel sensors!

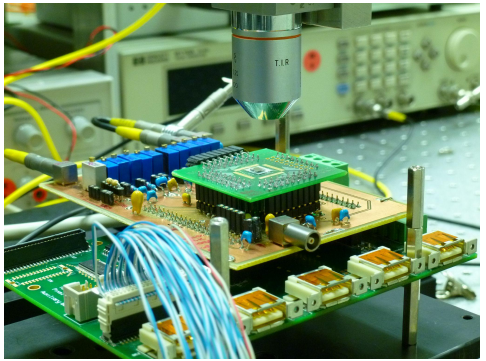




First detectors with these features!

→ presentation by P. Giubilato

Activity on silicon sensors: at the frontier of detector technology



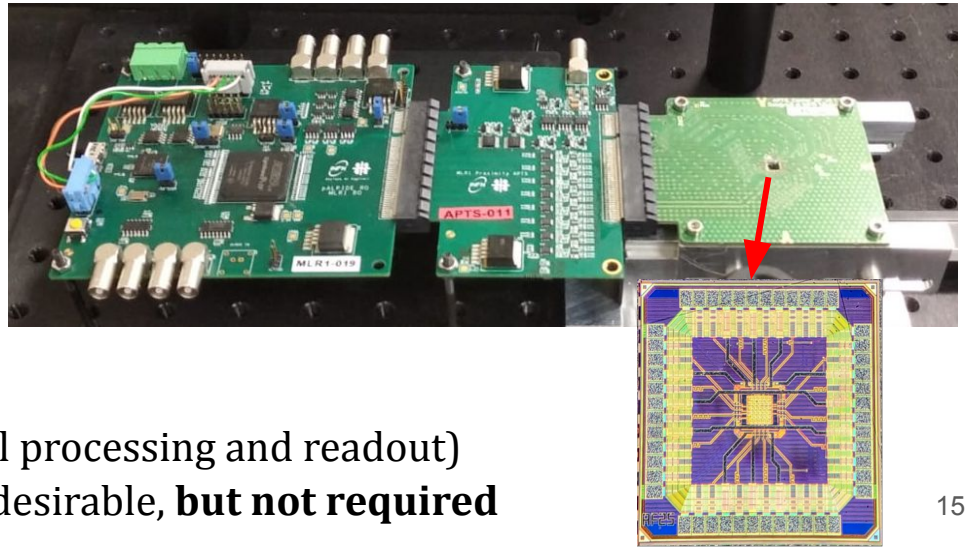
Ongoing studies in Padua clean room for:

- short-term ALICE upgrade (ITS3)
- future experiments: NA60+, ALICE 3, ePIC (→ R. Turrisi)

Collaboration with CERN and other INFN sites in Italy

Activities:

- Sensor characterization
- Sensor design (longer term)



Can learn/contribute to

- **prepare an experimental setup**
- **data taking**
- **data analysis**

Requirements:

- **Interaction of radiation with matter**
- **Basic knowledge of electronics** (for signal processing and readout)
- Some **basic knowledge** of **C++/Python** is desirable, **but not required**

Contacts

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Group:

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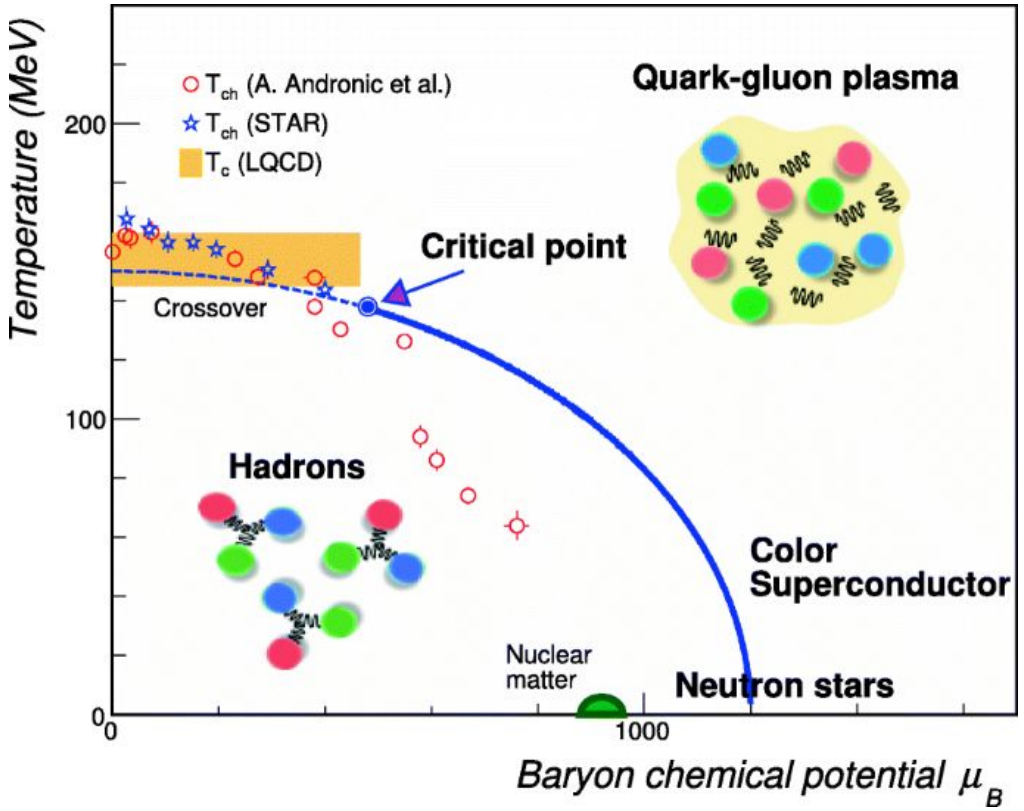
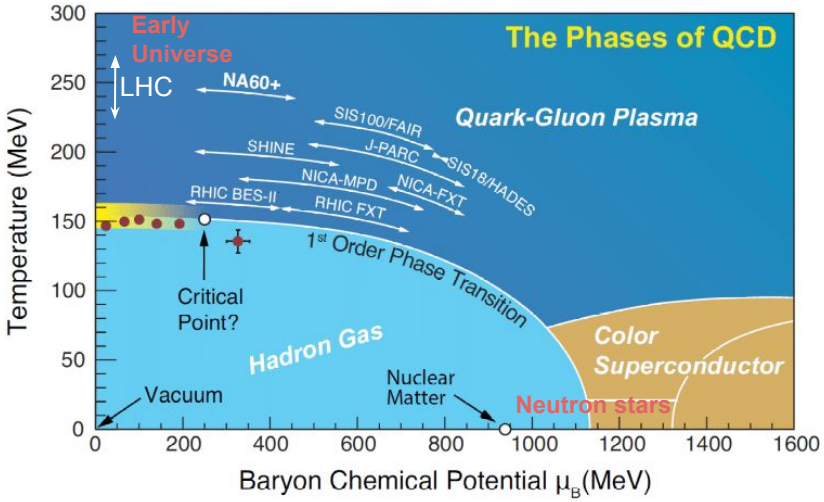
Federico Antinori (federico.antinori@pd.infn.it**)**
Marcello Lunardon (marcello.lunardon@unipd.it**)**

Work on silicon sensors:
Piero Giubilato (piero.giubilato@unipd.it)
Serena Mattiazzo (serena.mattiazzo@unipd.it)

Extra

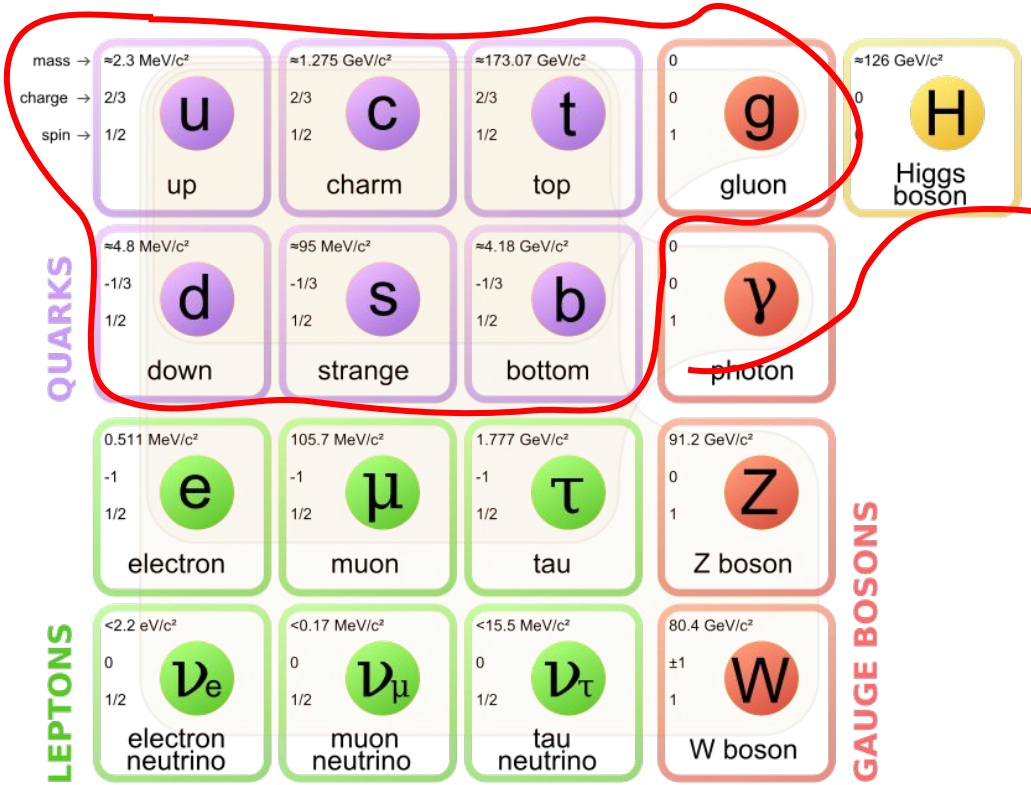
Exploring the strong-interaction phase diagram

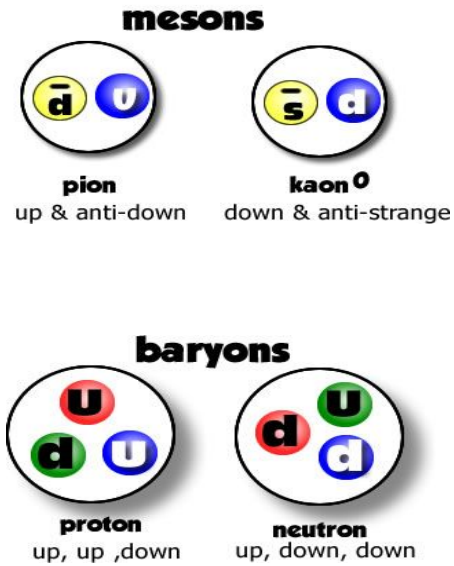




Elementary particles and hadrons

We never observe free quarks, only composite objects called hadons, in which quarks are bound and confined to stay by the strong nuclear force





Examples of experimental apparatus…