NuPECC LRP 2016-2017 : WG 2

Properties of strongly interacting matter

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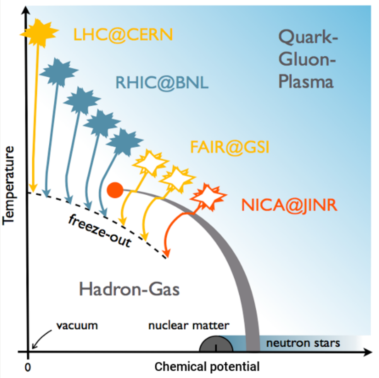
Silvia Masciocchi

Darmstadt Town Meeting

January 11th, 2017



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Outline of section 2

4.2.1 Introduction

Basics of QCD Four fundamental forces rule the interactions of matter in Nature: the gravitational force, the electromagnetic force, the weak force and the strong force. Except for gravity, for which the quest of a microscopic quantum description has remained somewhat elusive so far, these forces are described in terms of local quantum field theories. In these field theories, spin-$\frac{1}{2}$ matter fields carry charges pertaining to the local (gauge) symmetries of the theory and are coupled to spin-1 bosonic fields that mediate the interaction. For the weak and strong forces, these fields are also charged under the gauge symmetry.

The quantum field theory that describes the strong force, Quantum ChromoDynamics (QCD), has been discovered in the early 1970's, following a number of experimental clues. In particular, deep-inelastic scattering experiments led to two crucial observations: (i) the electrical charge of hadrons is not smoothly distributed but is carried by spin-$\frac{1}{2}$ constituents which, to the extent allowed by the spatial resolution of the experiments, are point-like, and (ii) these constituents are nearly free when probed at very short distances. QCD is the simplest field theory consistent with these properties and with the multiplets observed in hadron spectroscopy; it is a non-abelian gauge theory endowed with an internal local $SU(3)$ symmetry, in which the charged matter fields are referred to as *quarks* and the mediators of the force as the *gluons*.

Although there are six flavours of quarks (up, down, strange, charm, bottom and top), only the lightest two (up and down) appear in the valence composition of nucleons. The heavy quark flavours may appear as short-lived quark-antiquark quantum fluctuations in the hadronic wavefunctions and may also be produced in the final state of various reactions.

Two important properties of QCD are *asymptotic freedom* and *colour confinement*: the strength of its coupling decreases at short distance and increases at large distance (in contrast to Quantum Electrodynamics, where the coupling evolves in the opposite way). This behaviour explains both the scaling observed in deep-inelastic scattering experiments and the fact that the force becomes strong enough at larger distance to bind the quarks into hadrons. Neither quarks nor gluons exist as isolated particles in Nature, and the only stable arrangements are colour-singlet bound states, i.e., hadrons, which may either be mesons formed from quarks and antiquarks or (anti-)baryons formed from three (anti-)quarks. Also more exotic states, e.g. made purely from gluons (so-called glueballs) or from more than three quarks, have been suggested to exist. For instance, it is believed that tetraquark states have been produced in several experiments. Pentaquarks states have been much more elusive so far, but may have been seen in the products of proton-proton collisions at the LHC. However, despite the fact that confinement prevents a direct observation of quarks and gluons, they leave clear imprints in high-energy reactions in the form of *jets* – collimated streams of hadrons whose direction reflect the momentum of the quark or gluon that initiated them.

Asymptotic freedom has a very profound implication for hadronic matter under extreme conditions: at sufficiently high nuclear density or temperature, the average inter-parton distance becomes small, and therefore their interaction strength weakens. Above a critical energy density of the order of 0.3 GeV/fm^3, a gas of hadrons undergoes a deconfinement transition and becomes a system of unbounded quarks and gluons. Numerical evidence of this transition has been obtained from lattice simulations of QCD, in the form of a rapid increase of the entropy density around the critical energy density. The deconfinement of quarks and gluons is accompanied by a restoration of chiral symmetry, spontaneously broken in the QCD vacuum.

In the cooling history of the Early Universe, the primordial quark-gluon plasma (QGP) turned into hadrons around a few microseconds after the Big Bang, but this transition has, as far as we know, not left any imprint that is visible in present-day astronomical observations. However, the energy density necessary to form the QGP may be re-created in the laboratory via heavy ion collisions at sufficiently high energies, within volumes of the order of the nuclear size.

QCD phase diagram In equilibrium, the phase structure of nuclear matter is controlled by a small number of local thermodynamical parameters: the temperature T and the chemical potentials associated to conserved quantities, the most important of which is the baryon chemical potential, $\mu_{\rm B}$, related to baryon number conservation. Figure 1 summarizes our present knowledge of the phase diagram in the $T, \mu_{\rm B}$ plane. More specifically:

(a) In the chiral limit of two-flavour QCD, i.e., for vanishing up- and down-quark masses, a phase transition exists, that separates a phase of broken chiral symmetry at low temperature from a chirally symmetric phase at high temperature. This transition also persists at small, non-vanishing values of the baryon chemical potential.

(b) For QCD with its physical spectrum of small but non-zero up and down quark masses and a heavier strange quark, the transition from the low- to the high-

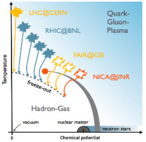


Figure 1: Illustration of the QCD phase diagram. Adapted from J. Phys. Conf. Ser. **432** (2013) 012013, courtesy of C. Schmidt.

temperature regime is rapid and accompanied by large changes in the properties of strongly interacting matter. However, it is presumably not a genuine phase transition but a "cross-over transition". At vanishing baryon chemical potential this transition occurs at about $k_{_B}T = 155$ MeV and restores chiral symmetry up to residual explicit breaking effects arising from non-zero values of the light quark masses. It also shows clear features of a deconfining transition, with the low-temperature regime being best described by ordinary hadronic degrees of freedom, while in the high-temperature phase quarks and gluons emerge as the dominant degrees of freedom.

(c) Properties of strongly interacting matter at very high temperature or baryon chemical potential can be calculated using perturbative techniques. In this asymptotic regime, nuclear matter consists of weakly interacting quarks and gluons in the QGP phase. At least for high temperatures and vanishing baryon chemical potentials such calculations can be cross-checked with lattice-QCD calculations.

(d) Close to the cross-over region, in particular on the high-temperature side of the transition, nuclear matter is strongly coupled. In this region, the transport coefficients are very small, implying a strong collective behaviour of the nuclear matter. This has profound consequences on our understanding of heavy ion collisions: despite large space-time gradients in these collisions, strongly interacting matter exhibits properties similar to that of an ideal fluid.

(e) One or more colour-superconducting phases exist at asymptotically large net baryon number density and sufficiently low temperature. It is rather likely that this phase is homogeneous, but it may display spatial variations of the colour-superconducting order parameter when the density is lowered.

(f) Under conditions of vanishing pressure and temperature nuclear matter forms a quantum Fermi liquid with a density of about 0.16 nucleons per fm^3. Upon heating, it undergoes a first-order liquid-gas transition, which ends in a critical point of second order. The associated critical temperature is rather well established to be around 15 MeV.

Apart from these few anchor points, our knowledge of the phase diagram from first-principle approaches remains scarce, in particular in the experimentally interesting region of intermediate net baryon number densities. At present, these regions are not accessible to lattice-QCD calculations. In order to shed light on their properties, phenomenological studies have been performed, using models that have some resemblance to QCD while avoiding its technical problems. To give one example, in QCD with a large number of colours, a new phase, termed the "quarkyonic phase", was proposed at low temperatures and baryon chemical potentials exceeding that of the nuclear matter ground state. However, without experimental constraints, these model approaches often lead to inconclusive results.

Equation of state, thermodynamics and transport The equation of state (EoS) and other thermodynamical properties of a system in equilibrium are encoded in its partition function, while its transport coefficients can be extracted from the low momentum behaviour of spectral functions.

In regions of high temperature and/or high baryon chemical potential, a perturbative approach is possible thanks to asymptotic freedom. In regions where the coupling constant is large, non-perturbative calculations are necessary. In the strip where $\mu_{\rm B}/T \ll 1$, one may use lattice QCD. However, lattice QCD fails at large $\mu_{\rm B}$ due to "sign problem": the integrand is not positive definite and thus cannot be sampled by a Monte-Carlo method. Various analytical methods have been developed to circumvent this problem, but they all involve truncations and are therefore approximate. More details on these techniques can be found in Box. 1.

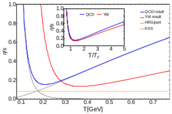
Heavy-ion collisions The idea to collide heavy ions accelerated at ultra-relativistic energies for bringing nuclear matter into the deconfined QGP phase and studying its properties in the laboratory dates back to the

Box 1 - Theoretical tools for calculating the EoS and transport coefficients

At high temperatures or high chemical potentials, asymptotic freedom allows to compute the partition function perturbatively in terms of a power series in the strong coupling constant, provided one resums the large corrections due to collective effects (e.g. Debye screening, Landau damping...).

As one decreases temperature and chemical potential towards values of the order of the QCD scale parameter, $\Lambda_{QCD} \sim 0.2$ GeV, weak coupling techniques are no longer applicable. A non-perturbative first-principle approach is lattice QCD. Calculations with physical quark masses are computationally expensive, but advances in computing hardware and algorithms have rendered them feasible. See the section 4.2.4 for a discussion of the computing resources needed in this area.

This method works very well only for vanishing baryon chemical potential. At non-zero μ_B, the fermionic determinant contained in the integrand becomes complex valued, precluding Monte-Carlo samplings. At small baryonic chemical potential ($\mu_B/T \lesssim 1$), other methods (reweighting, Taylor expansion, analytic continuation of calculations performed at imaginary μ_B) may be used to partially circumvent this problem.



When applied to the calculation of transport coefficients, lattice QCD faces an additional difficulty related to the extraction of a spectral function from an Euclidean correlator, which requires some prior information about the unknown spectral function. A common approach is the Maximal Entropy Method (MEM), a Bayesian method to obtain the most likely spectral function.

Besides lattice QCD, other non-perturbative first-principle methods are functional methods in the continuum, such as Dyson-Schwinger equations (DSEs) or the Functional Renormalization Group (FRG), that do not suffer from the fermion sign problem and can thus be applied at any value of T and μ_B. Although a priori exact, these approaches require truncations in practice, which makes them approximate. The figure shows the FRG calculation of the shear viscosity to entropy ratio as a function of temperature (from Phys. Rev. Lett. **115** (2015) no.11, 112002).

early '80s (see the Box 2 for a timeline of heavy-ion facilities). Pioneering studies at the Brookhaven Alternating Gradient Synchrotron (AGS) and the CERN Super Proton Synchrotron (SPS) promptly demonstrated that the energy deposit and the nuclear stopping in the central rapidity region were quite large. At higher center-of-mass energy, the colliding system enters a new regime characterized by nuclear transparency: the inertia of the colliding nucleons becomes so large that they cannot be completely stopped. Nevertheless, the initial energy density in the central rapidity region, inferred from the number of produced particles via Bjorken's formula, keeps increasing with energy. The net baryon density at mid rapidity approaches zero already at RHIC energy ($\sqrt{s_{NN}} = 200$ GeV), and the initial energy density in central PbPb collisions at the LHC ($\sqrt{s_{NN}} = 2.76$ TeV) is more than an order of magnitude larger than that of the deconfinement transition predicted by lattice QCD. The challenge for the coming years consists in a detailed experimental characterization of the different features of the phase diagram (e.g. the critical endpoint) as well as a determination of the parameters that characterize the hot medium (e.g. its transport coefficients). In this quest, the experimental control variables are the colliding energy, the ions used in the collisions and the centrality of the collisions.

4.2.2 High-temperature matter

In this Section, we focus on the strongly interacting QGP (sQGP) produced in nuclear collisions at the highest available energies. In these collisions, a QGP is formed with high temperature and low baryon chemical potential μ_B, i.e., with a minimal excess of quarks over anti-quarks. The QGP produced in these collisions is therefore very similar to the QGP in the early Universe and is in the low μ_B limit where lattice QCD calculations

4.2 Properties of Strongly Interacting Matter

Box 2 - Timeline of heavy-ion facilities

Bevatron (Billions of eV Synchrotron) : from 1954 to 1993 at Lawrence Berkeley National Laboratory, U.S.
AGS (Alternating Gradient Synchrotron) : since 1960 at Brookhaven National Laboratory, U.S. It is now used as injector for RHIC.
SPS (Super Proton Synchrotron) : since 1976 at CERN. It is now the injector for the LHC.
RHIC (Relativistic Heavy Ion Collider) : since 2000 at Brookhaven National Laboratory, U.S.
LHC (Large Hadron Collider) : since 2009 at CERN.

are reliable.

The goal of the high energy heavy-ion programme is to identify and characterize the properties of the QGP. This programme naturally has two steps: understanding the dynamics of heavy-ion collisions, e.g., via comparison to phenomenological models, and the extraction of fundamental QGP/QCD properties that can be compared to (lattice) QCD results.

Figure 2 illustrates the **three main stages** of a heavy-ion collision: (i) an early non-equilibrium stage, (ii) an expansion stage, and (iii) a final freeze-out stage. An advantage of this modular structure is that it allows for the use of more or less advanced theoretical tools in each stage. In this way the modeling of heavy-ion collisions can be gradually improved and used to constrain further the properties of strongly interacting matter. This picture, and the associated phenomenology, has indubitably evolved over the last 30 years as observables have been identified that are sensitive to specific processes in each phase.

The first stage, which also provides initial conditions (spatial distribution of the deposited energy and pressure, initial flow velocity) for the subsequent hydrodynamical stage, is the least known and is often described by simple geometrical models (e.g. the Glauber Monte-Carlo approach) in which the underlying strong interactions are encapsulated in the inelastic nucleon-nucleon cross-section. More ab-initio descriptions, such as the Colour Glass Condensate (CGC), in which one treats the collision in terms of partonic degrees of freedom (mostly gluons in the relevant kinematical regime for RHIC and LHC) and the QCD interactions, are being actively developed nowadays. Although some observables that have been measured by LHC experiments in PbPb collisions (e.g. J/ψ photo-production) provide evidence for nuclear gluon shadowing, further efforts are required to extract its amount. A more comprehensive study of this regime of large nuclear gluon density will be possible at the Electron-Ion Collider (EIC) currently planned in the USA, by allowing a direct measurement of nucleonic and nuclear structure functions, and in particular the longitudinal one which is most directly sensitive to the gluon content. In the CGC picture, the initial scatterings produce a dense system (made of strong colour fields, the so-called Glasma) that quickly approaches a hydrodynamical regime. It takes less than a fm/c for the system to become a nearly perfect fluid whose expansion can be described by relativistic viscous hydrodynamics.

During the second stage –the fireball expansion–, the bulk evolution is described by relativistic viscous hydrodynamics. Due to the near perfect fluid nature of the QGP, the initial geometrical anisotropy is efficiently converted into a momentum anisotropy of the final particles. Event-by-event fluctuations lead in the final state to significant higher order harmonics (triangular flow and above) of the azimuthal particle distribution, in addition to the 2nd order one (elliptic flow). Their systematic measurement has recently provided an avenue for constraining initial-state model calculations and transport properties of the QGP both at RHIC and the LHC. Moreover, this bulk evolution provides the substrate for the medium modifications of hard probes, although a better integration of these two aspects of the description is certainly needed.

Hadronisation takes place when the system reaches the pseudo-critical temperature (in the hydrodynamical description, this transition is encoded in the EoS). After hadronisation, the scattering rate decreases quickly and a kinetic description becomes more appropriate than hydrodynamics. This third stage may be described by hadron cascade models such as, e.g. UrQMD. Given the cross-sections for the scatterings between the various hadrons species, this kinetic description can in principle describe the (possibly successive) decoupling of the hadrons from the fireball. The measured relative abundances of hadrons indicate that chemical freeze-out happens at a temperature T_{ch} which is very close to the hadronisation temperature and at nearly zero μ_B. Subsequently, the hadrons continue to rescatter elastically until they reach the kinetic freeze-out temperature, T_{fo}, where they decouple and freely stream to the detectors.

Since the last NuPECC long range plan, the Large Hadron Collider (LHC) at CERN has started and completed its first heavy-ion running period, 2010-2013, and begun its second period, 2015-2018. The new LHC data extend the rich experimental programmes at the Bevatron, SPS and RHIC, increasing by factors of

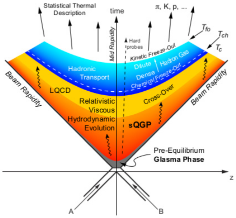


Figure 2: Space-time evolution of the system created in heavy-ion collisions. The different stages are specified on the right side and some theoretical tools used to describe them are listed on the left side.

about 7, 25 and 55 the energies accessible in proton-proton, heavy-ion and proton-ion collisions, respectively. This jump in collision energy has provided abundant access to so-called **hard probes**, whose production is calculable within perturbative QCD and any modification due to the propagation through the medium can be used to probe the QGP properties. At the LHC, the energy loss of heavy charm and bottom quarks can be directly compared for the first time, which allows to test the quark mass dependence of the energy-loss mechanisms. The much more abundant charm production greatly increases the J/ψ production rate by coalescence of c and $\bar{c}$ quarks. The J/ψ yield in PbPb collisions at the LHC is consistent with deconfinement followed by such a recombination. For Υ states, the much larger production cross-section has enabled the first measurement of the dissociation of the 1S, 2S, and 3S bottomonium states individually.

In addition to the rich new set of heavy-ion results from the LHC, unexpected novel insights related to initial state dynamics has come from pp and pPb collisions. It was expected that these collisions would mainly provide a calibration of the initial state and it was therefore surprising to observe large azimuthal anisotropies of the underlying event in these systems. These asymmetries are very similar to those seen in heavy-ion collisions, where they are attributed to the creation of the sQGP perfect fluid.

The LHC has run pPb collisions again in 2016, due to the large interest in small systems, and it is expected that in 2018 there will be a long PbPb run. In 2019-2020, LHC will be shut down to upgrade and prepare the experiments for Run-3. The goal of the heavy-ion upgrades is to be able to handle optimally the factor ~ 10 increase of the event rate to 50 kHz. In the case of the ALICE detector, which is the only dedicated heavy-ion experiment at LHC, the upgraded detector will be able to analyze the full rate of events online, thereby increasing the sensitivity for most measurements by one to two orders of magnitude.

Recent Experimental and Theoretical Developments One of the long-standing puzzles in the field is the question of how the colliding system evolves quickly towards a local isotropic state in momentum space. Two important developments were made recently towards solving this '**fast isotropisation**' puzzle. On the one hand, descriptions of the initial state based on CGC initial conditions have shown that the approach to isotropy in such dense systems is much faster than in the hard-scattering regime. On the other hand, developments within relativistic viscous hydrodynamics have shown that significant deviations from isotropy can be realized even with a small viscosity. These developments offer the perspective of describing via viscous hydrodynamics the full evolution from the initial saturated gluon state to the final freeze-out stage, in an almost seamless fashion.

Unlike hadronic observables, whose prediction is complicated by final state interactions, **photons and dileptons** interact only electromagnetically and therefore escape from the fireball without reinteracting after production. The yield of thermal photons (i.e. the black body radiation from the hot QGP) is very sensitive to the QGP temperature and can be predicted by a combination of QCD perturbative calculations and hydrodynamical simulations. Direct photons have been measured in PbPb collisions at the LHC ($\sqrt{s_{NN}} = 2.76$ TeV). At low p_T, one observes an excess over the non-thermal photons (prompt photons from collisions of the quarks and antiquarks contained in the incoming nuclei, photons from meson decays, etc...) that agrees reasonably well with model predictions of thermal photons (with an initial QGP temperature around $k_B T = 400$ MeV at a time $\tau_0 = 0.4$ fm/c for central collisions).

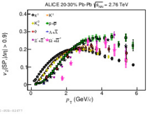


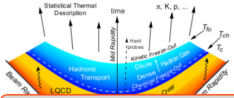
Figure 3: Elliptic flow coefficient as a function of transverse momentum, for various hadron species. From JHEP **06** (2015) 190.

One of the most important discoveries of the heavy-ion programme is that matter produced in heavy-ion collisions behaves as a nearly perfect (inviscid) fluid. This conclusion was already reached based on RHIC data, and the LHC has shown that it also holds for systems with higher initial temperature. Fig. 3 shows the relevant experimental results of the second-order harmonic anisotropy v_2 (elliptic flow) as a function of p_T, for different particles. The results are compatible with calculations of relativistic fluid dynamics (hydrodynamics) in which the fluid has a very low viscosity. Deviations from an ideal fluid may be quantified by the **shear-viscosity-to-entropy-density ratio** η/s. This ratio is estimated by comparing hydrodynamical calculations to the measurements in Fig. 3, leading to a value in the range $1 < \eta/s < 2.5$ in units of $\hbar/(4\pi k_B)$. This value is smaller than that of any other known substance, including superfluid liquid helium, and is very close to the value $\eta/s = \hbar/(4\pi k_B)$ obtained in some exactly solvable field theories in the limit of infinite coupling, suggesting that the QGP is also a strongly interacting medium. Recently, it has been demonstrated that the inclusion of bulk viscosity effects in event-by-event simulations can have an impact on both the flow harmonics and particle spectra. This offers exciting prospects for determining the bulk viscosity to entropy ratio, ζ/s, from experimental data.

The important question of the **thermalisation of heavy quarks** appears to be partly answered for charm: the positive elliptic flow of charmed hadrons indicates that charm quarks take part in the collective expansion of the QGP. Their degree of thermalization is however not well constrained. For the bottom sector, thermalisation remains an open issue.

Analyses of the ratios of hadronic yields within **statistical hadronization models** (SHM) indicate a temperature of chemical freeze-out just below the hadronisation temperature, and almost zero baryon chemical potential. Nowadays, these models also include, besides the ratios, fluctuations of conserved charges inferred from susceptibilities computed in lattice QCD simulations.

For the high temperature and low μ_B values extracted at the LHC, the yields of matter and anti-matter are almost equal (they differ only by the baryon number of the incoming nuclei, that remains localized at forward rapidities). These collisions are therefore the most abundant source of anti-nuclei in the laboratory. This makes it possible to compare the properties of nuclei and anti-nuclei in order to look for CPT violating effects. This has recently been done in a measurement by ALICE of the mass of anti-nuclei up to anti-deuterons and $^3\overline{\mathrm{He}}$. Within the achieved experimental undertainties, no difference was observed, so that this measurement provides the most stringent **constraint on CPT violation**



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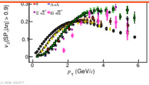

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One of the most important discoveries of the heavy-ion

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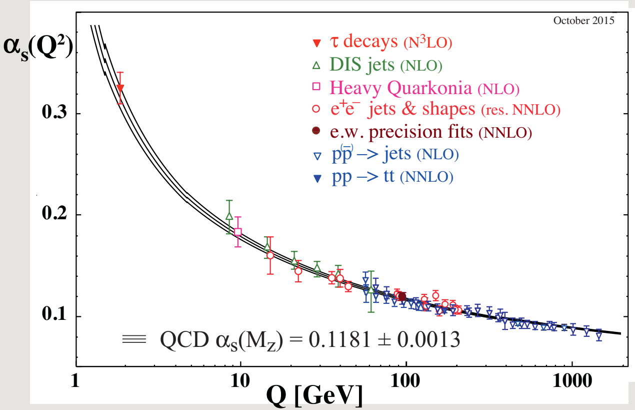
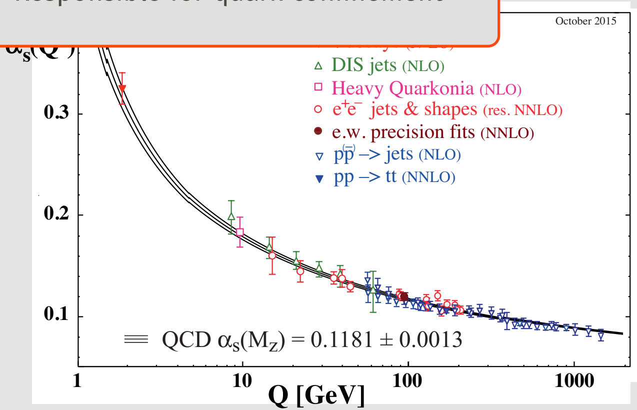
Introduction

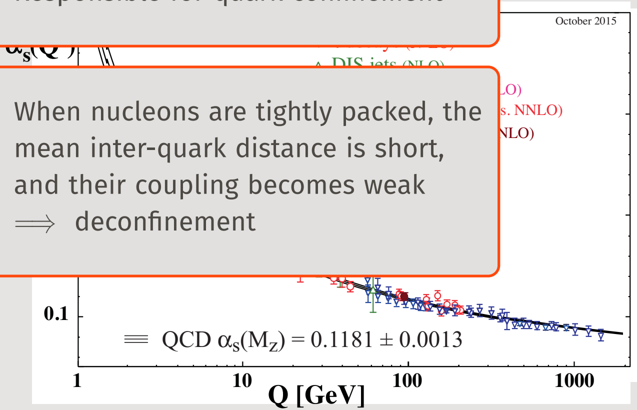

October 2015
αs(Q²)
τ decays (N³LO)
DIS jets (NLO)
Heavy Quarkonia (NLO)
e+e− jets & shapes (res. NNLO)
e.w. precision fits (NNLO)
pp(−) –> jets (NLO)
pp –> tt (NNLO)
0.3
0.2
0.1
QCD αs(Mz) = 0.1181 ± 0.0013
1
10
100
1000
Q [GeV]

- Responsible for quark confinement

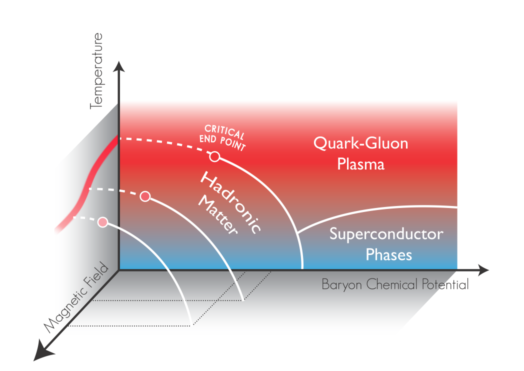


- Responsible for quark confinement

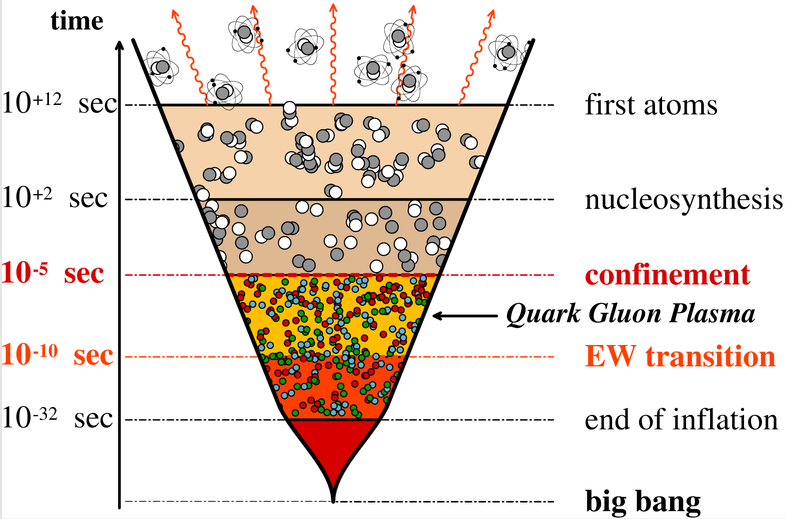
- When nucleons are tightly packed, the mean inter-quark distance is short, and their coupling becomes weak $\Longrightarrow$ deconfinement



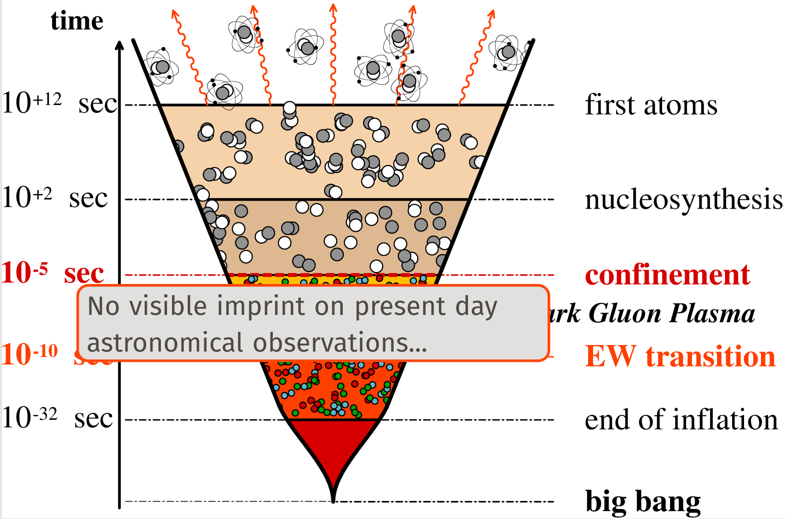
Phase diagram (sketch) of QCD matter



- **Control parameters :**
  - Temperature
  - Chemical potentials
  - External fields



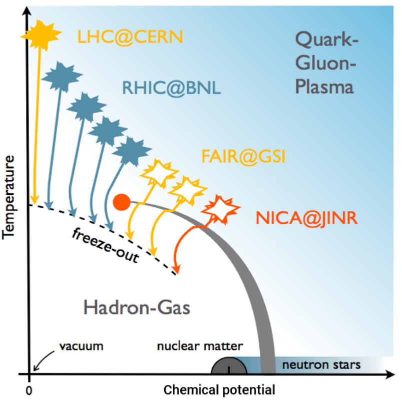
time
10^{+12} sec
10^{+2} sec
10^{-5} sec
10^{-10} sec
10^{-32} sec
first atoms
nucleosynthesis
confinement
Quark Gluon Plasma
EW transition
end of inflation
big bang



No visible imprint on present day astronomical observations...

Heavy ion collisions

- Recreate the conditions of the deconfinement transition in the laboratory by colliding large nuclei at ultra-relativistic energies



- **Experimental handles :**
  - beam energy
  - ion species

Timeline of Heavy Ion facilities

Bevatron (Billions of eV Synchrotron) :
From 1954 to 1993 at Lawrence Berkeley National Laboratory, U.S

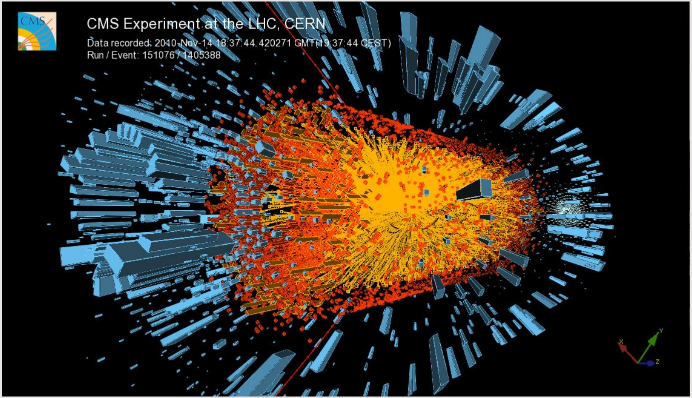
AGS (Alternating Gradient Synchrotron) :
Since 1960 at Brookhaven National Laboratory, U.S
Now used as injector for RHIC

SPS (Super Proton Synchrotron) :
Since 1976 at CERN
Now the injector for the LHC

RHIC (Relativistic Heavy Ion Collider) :
Since 2000 at Brookhaven National Laboratory, U.S

LHC (Large Hadron Collider) :
Since 2009 at CERN

Heavy Ion Collision @ LHC



Theory...

QCD

$$\mathcal{L} = -\frac{1}{4}F^2 + \overline{\psi}(i\not{D} - m)\psi$$

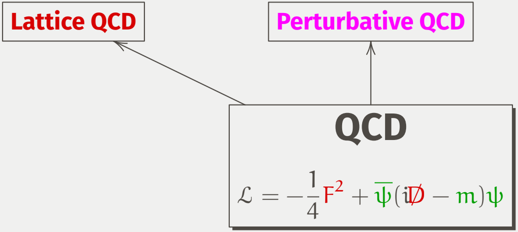
Theory...

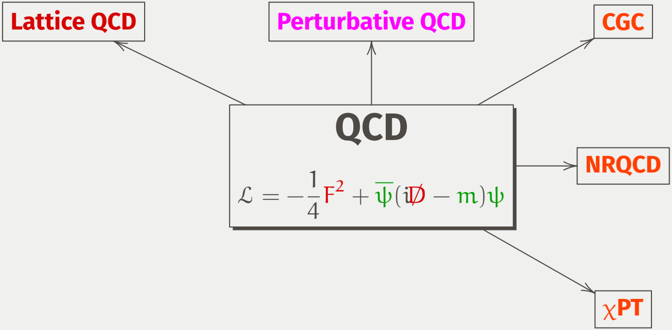
Lattice QCD

QCD

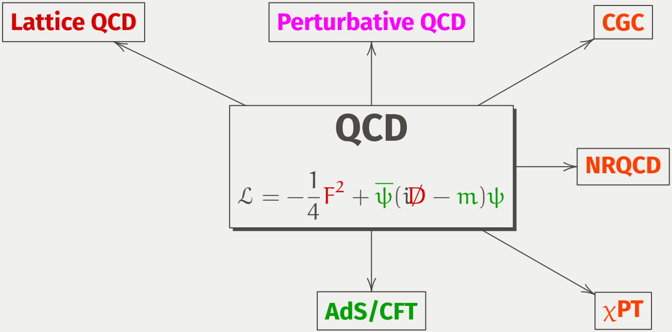
$$\mathcal{L} = -\frac{1}{4}F^2 + \overline{\psi}(i\not{D} - m)\psi$$

Theory...

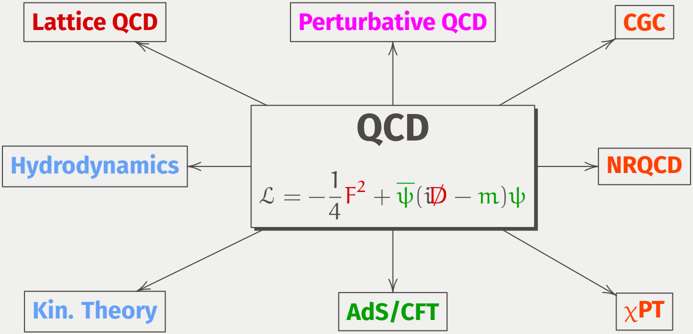

Lattice QCD
Perturbative QCD
QCD
$\mathcal{L} = -\frac{1}{4}F^2 + \overline{\psi}(i\not{D} - m)\psi$


Lattice QCD
Perturbative QCD
CGC
QCD
$\mathcal{L} = -\frac{1}{4}F^2 + \overline{\psi}(i\not{D} - m)\psi$
NRQCD
χPT

Theory...


Lattice QCD
Perturbative QCD
CGC
QCD
$\mathcal{L} = -\frac{1}{4}F^2 + \overline{\psi}(i\not{D} - m)\psi$
NRQCD
AdS/CFT
χPT

Theory...



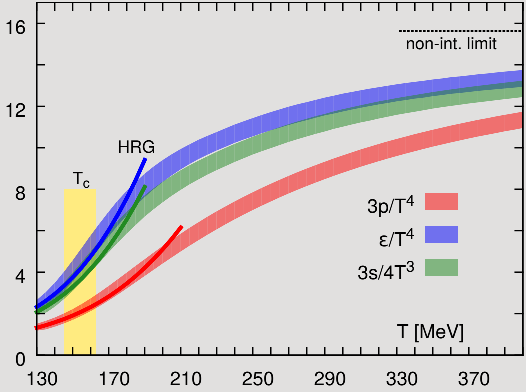
Lattice QCD
Perturbative QCD
CGC
QCD
$\mathcal{L} = -\frac{1}{4}F^2 + \bar{\psi}(i\not{D} - m)\psi$
Hydrodynamics
NRQCD
Kin. Theory
AdS/CFT
χPT

Theory...

- **Thermodynamics :**
  - Equation of state
  - Susceptibilities
  - Transport coefficients
- **Dynamical evolution :**
  - Thermalization / Isotropization
  - Expansion and cooling
  - Hadronization
- **Investigation of medium properties with perturbative probes**
  - Jets
  - Photons
  - Heavy quarkonia

- **Thermodynamics :**
  - Equation of state
- **D**
- **I**
  p

Example : Equation of State



High-Temperature matter

- **High T and low μ_B**
- **Minimal excess of quarks over antiquarks**
- **Similar to the QGP in the early universe**

Main Goals :

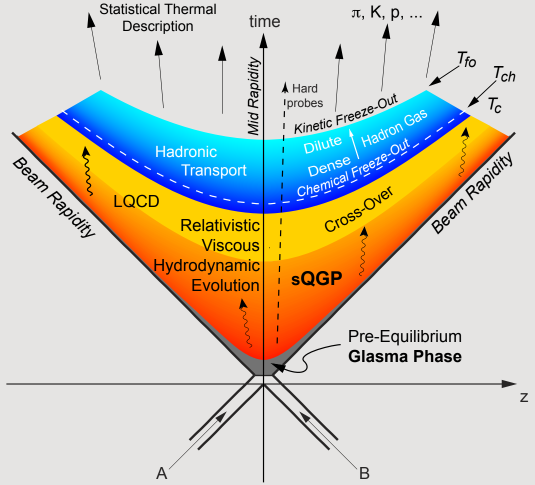
- **Identify and characterize the properties of the QGP**
- **Extract fundamental QGP parameters that may be compared to QCD**

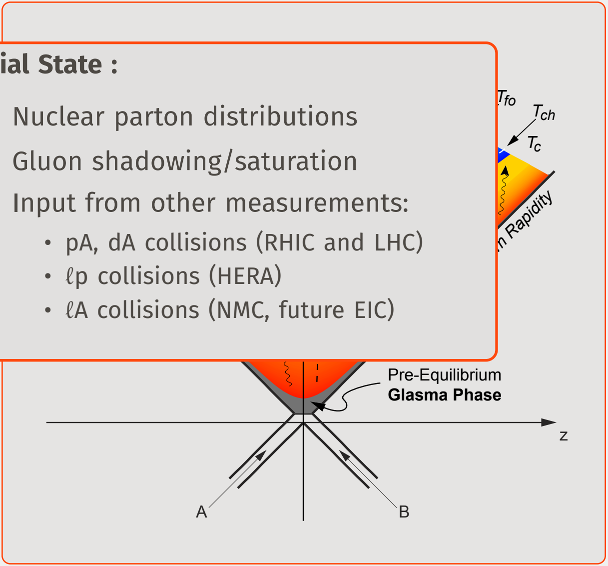
Since last NuPECC LRP (2010)

- LHC Run-1 : 2010-2013
- LHC Run-2 : 2015-*2018*
- Collision energy increase w.r.t. RHIC :
  - $\times 25$ for AA collisions
  - $\times 55$ for pA collisions

Main classes of observables

- **Bulk observables :** provide information of the space-time development of the collision
- **Hard probes :** rare processes (high p_T jets, photons, heavy quarkonia, open heavy flavors)


Statistical Thermal
Description
time
π, K, p, ...
T_{fo}
T_{ch}
T_c
Hard
probes
Kinetic Freeze-Out
Mid Rapidity
Hadronic
Transport
Dilute
Hadron Gas
Dense
Chemical Freeze-Out
Beam Rapidity
LQCD
Relativistic
Viscous
Hydrodynamic
Evolution
Cross-Over
Beam Rapidity
sQGP
Pre-Equilibrium
Glasma Phase
z
A
B



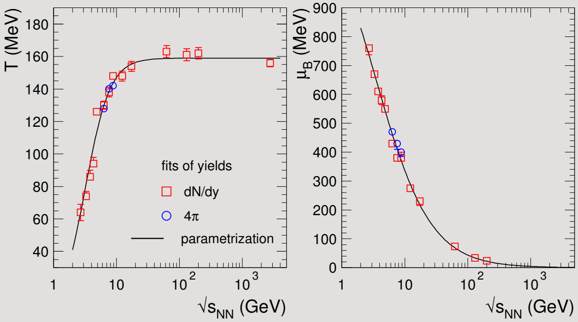
Initial State :

- Nuclear parton distributions
- Gluon shadowing/saturation
- Input from other measurements:
  - pA, dA collisions (RHIC and LHC)
  - ℓp collisions (HERA)
  - ℓA collisions (NMC, future EIC)

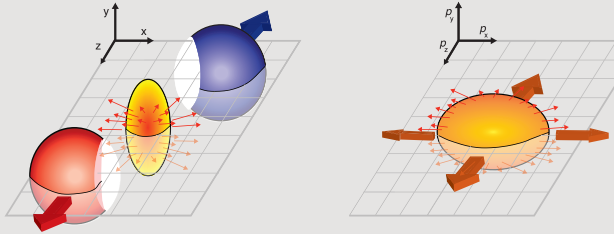
Initial State :

Freeze out :

- From yield ratios, *Statistical Hadronization Models* give the **temperature** and **chemical potential** at chemical freeze-out



Flow observables



Goals :

- Assess the transport properties of the QGP (viscosity, etc..)
- Provide constraints on its equation of state
- Validate models of bulk evolution that are used in the computation of other observables
- Constrain the initial state

Goals :

- Assess the transport properties of the QGP (viscosity, etc.)

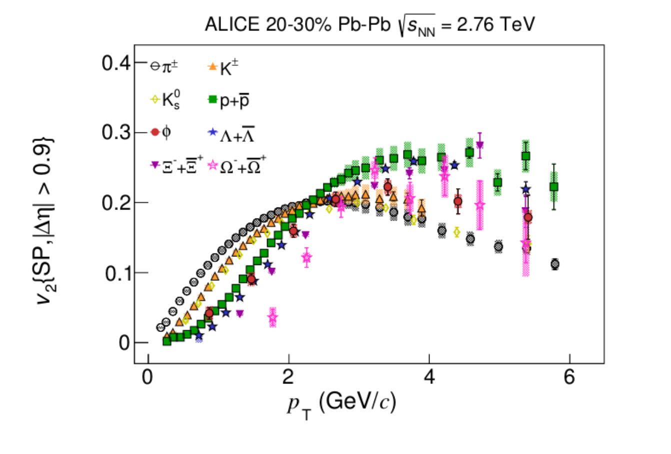
Observables :

- Azimuthal distribution of the produced particles
- Fourier coefficients v_1, v_2, v_3,...
- Orientations of the principal axes Ψ_1, Ψ_2, Ψ_3,...

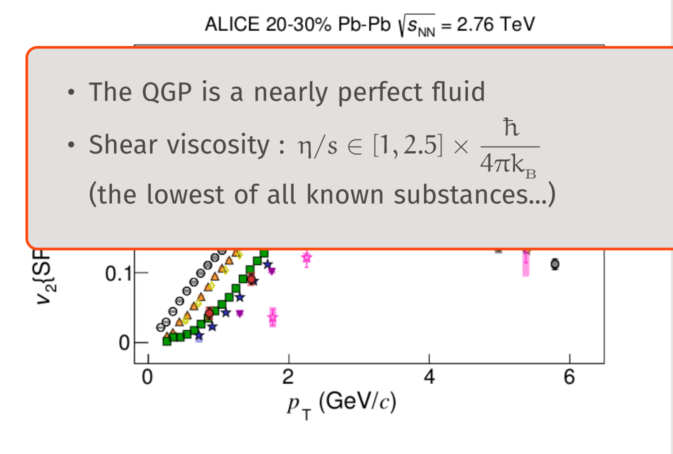
Note :

- Initial geometrical fluctuations play a crucial role in these studies

Example : p_T-dependence of v_2 of identified hadrons

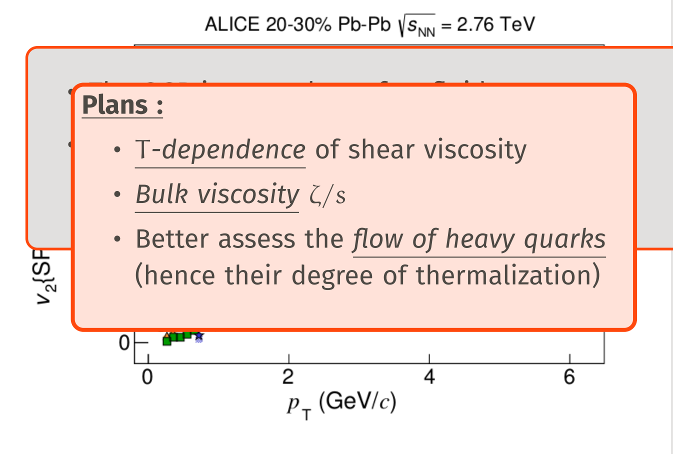


Example : p_T-dependence of v_2 of identified hadrons



- The QGP is a nearly perfect fluid
- Shear viscosity : $\eta/s \in [1, 2.5] \times \dfrac{\hbar}{4\pi k_B}$
  (the lowest of all known substances...)

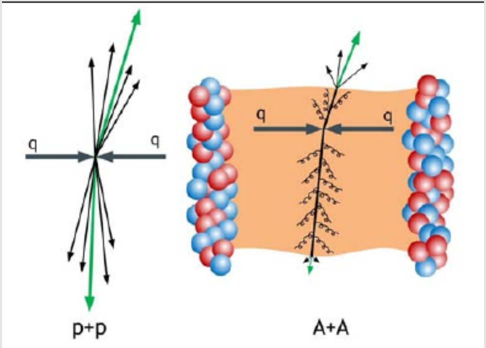
Example : p_T-dependence of v_2 of identified hadrons



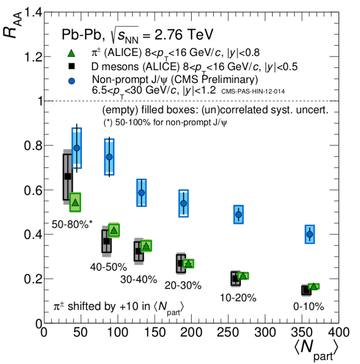
Plans :

- *T-dependence* of shear viscosity
- *Bulk viscosity* ζ/s
- Better assess the *flow of heavy quarks* (hence their degree of thermalization)

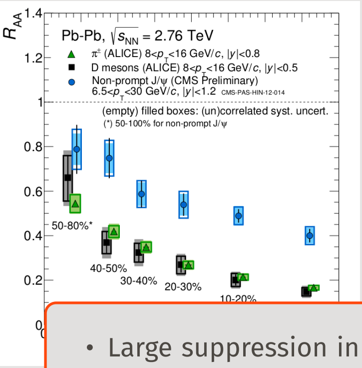
Energy loss, Jet quenching



- The QGP enhances the radiative energy losses of hard partons
  $\Longrightarrow$ use these observables as a "tomographic" tool



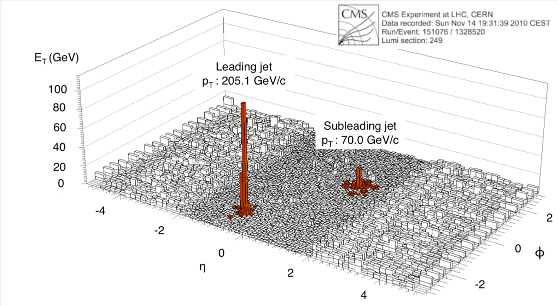
- **Nuclear modification ratios :** ratio of inclusive hadron yields in AA collisions and a reference. Measured as a function of:
    - transverse momentum
    - rapidity
    - centrality
    - hadron species



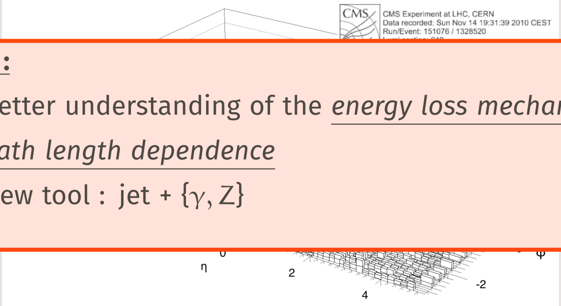
- **Nuclear modification ratios :** ratio of inclusive hadron yields in AA collisions and a reference. Measured as a function of:
  - transverse momentum
  - rapidity
  - centrality

- Large suppression in central collisions for all "light" partons (including charmed quarks)
- Smaller suppression for bottom quarks

  $\Longrightarrow$ in agreement with theoretical expectations (*dead cone effect*)



- Now feasible : direct observation of reconstructed jets
- Provides a handle on the energy of the jet before quenching
- New handles to characterize energy loss (jet opening angle)

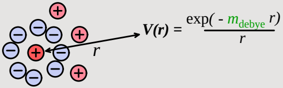


Plans :

- Better understanding of the *energy loss mechanism(s)*
- *Path length dependence*
- New tool : jet + $\{\gamma, Z\}$

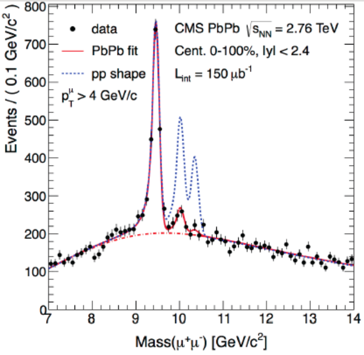
- Now feasible : direct observation of reconstructed jets
- Provides a handle on the energy of the jet before quenching
- New handles to characterize energy loss (jet opening angle)

Debye screening



- Debye screening weakens the binding of $Q\overline{Q}$ pairs
- Sequential suppression pattern depending on the binding energies

D

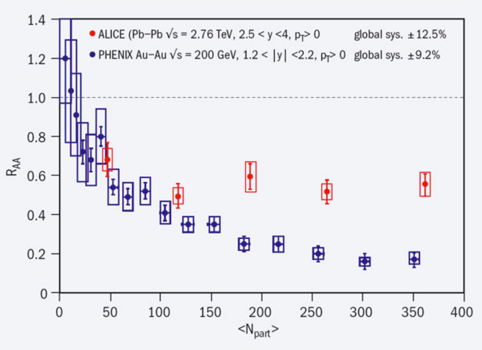


- Differential suppression of the 1S, 2S and 3S states of Υ

…ye screening weakens
…binding of $Q\overline{Q}$ pairs

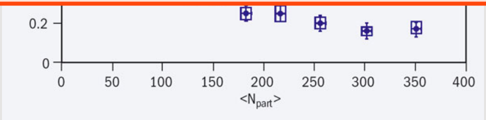
…uential suppression
…tern depending on the
…ding energies

J/ψ suppression at RHIC and LHC



- At LHC : copious production of $c, \bar{c}$ $\Rightarrow$ large density
  $\Rightarrow$ formation of J/ψ by recombination of unrelated c and $\bar{c}$

J/ψ suppression at RHIC and LHC

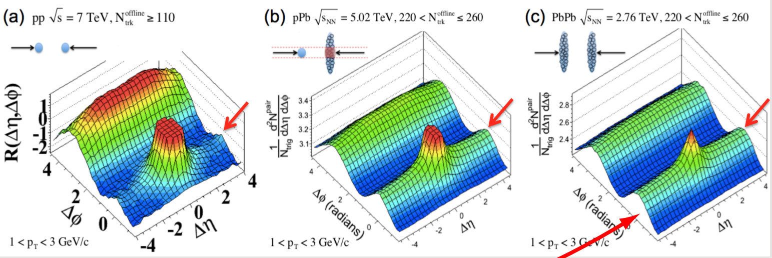


Plans :

- Characterize *when quarkonia are formed*
- Assess the *initial temperature* from quarkonia yields
  (also with electromagnetic probes : thermal photons/dileptons)

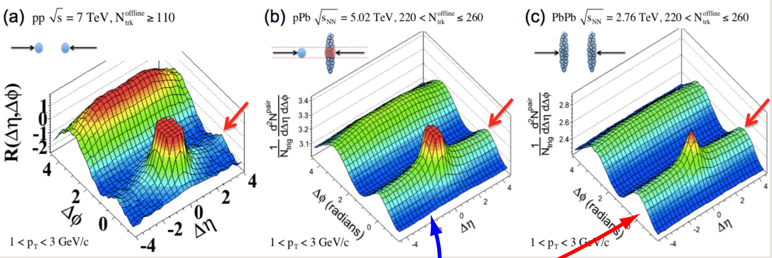
- At LHC : copious production of $c, \bar{c} \Rightarrow$ large density
  $\Rightarrow$ formation of J/ψ by recombination of unrelated c and $\bar{c}$

The mystery of small systems

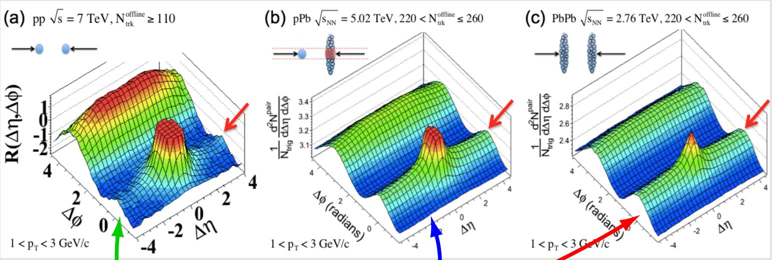


- AA collisions : this is flow !

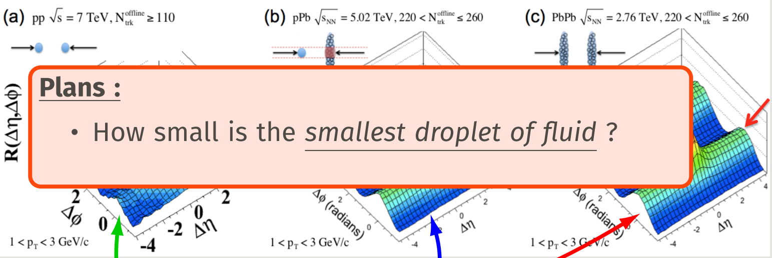
The mystery of small systems



- AA collisions : this is flow !
- pA collisions : maybe flow ?



- AA collisions : this is flow !
- pA collisions : maybe flow ?
- pp collisions : could it still be flow ?!



Plans :

- How small is the *smallest droplet of fluid* ?

- AA collisions : this is flow !
- pA collisions : maybe flow ?
- pp collisions : could it still be flow ?!

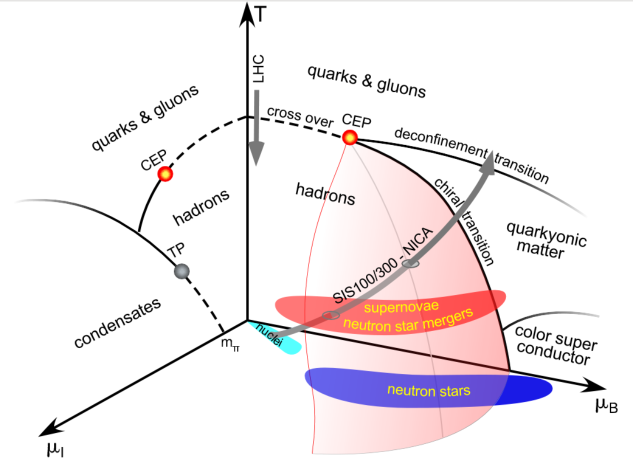
High-Density matter

- **Low T and high μ_B**
- **Large net baryon density**

Main Goals :

- **Explore the QCD phase-diagram at $\mu_B \neq 0$**
- **Search of the QCD critical endpoint**
- **Study of hyper-nuclei**

- Presently not accessible to ab initio theoretical approaches (lattice QCD)
- Main areas of interest :
    - Critical endpoint
    - Color-superconductivity (qq condensation)
    - Possible separation of deconfinement and chiral symmetry restoration (*quarkyonic phase* : still confined but chirally symmetric)
    - Hyper-matter (non-zero strangeness)
- Moderate collisions energy : max net baryon density reached for $\sqrt{s_{\mathrm{NN}}} \sim 5 - 6$ GeV (up to $10 \times \rho_0$)


T
LHC
quarks & gluons
quarks & gluons
cross over
CEP
CEP
deconfinement transition
hadrons
hadrons
chiral transition
quarkyonic matter
TP
SIS100/300 - NICA
supernovae
neutron star mergers
condensates
nuclei
m_π
color super conductor
neutron stars
μ_B
μ_I

Current activities

- HADES at SIS-18 (GSI)
- NA61/SHINE at SPS (CERN)
- Beam energy scan at RHIC (BNL)

Main observables

- **Collective flow**
- **Strangeness**
- **Dileptons**
- **Charmed hadrons**
- **Event-by-event fluctuations**

Main goals

- Role of partonic degrees of freedom
- Softening of the equation of state

Observables

- Directed flow v_1
- Elliptic flow v_2

Main goals

Plans :

- Flow of *identified hadrons*
- *Differential flow between particles and anti-particles*
- Flow of *weakly rescattering hadrons* (e.g., Ω, ϕ)

- Directed flow v_1
- Elliptic flow v_2

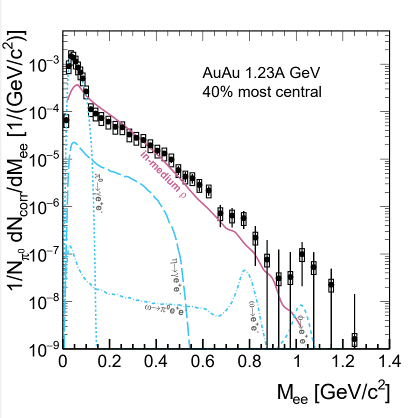
Main goals

- Onset of deconfinement
- Measure of equilibration
- Density of the fireball

Plans :

- Yields of *multi-strange hyperons*

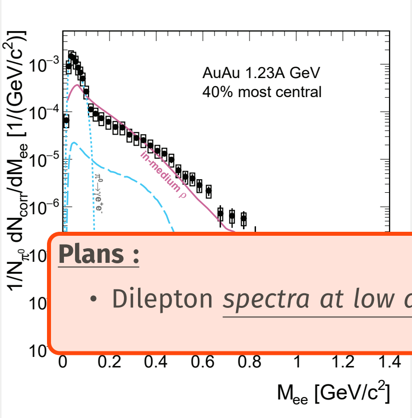
Dileptons



Goals

- Temperature estimates
- Modifications of vector meson spectral functions
- Chiral symmetry restoration
- Collective effects (flow)

Dileptons



Goals

- Temperature estimates
- Modifications of vector meson spectral functions

Plans :

- Dilepton *spectra at low and intermediate mass*

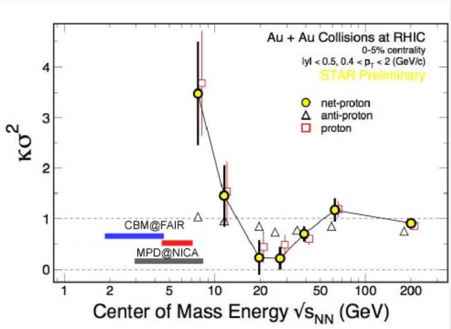
Main goals

- Probe of deconfinement through Debye screening
- Degree of thermalization (flow)
- Formation mechanism of charmed hadrons at large μ_B

Plans :

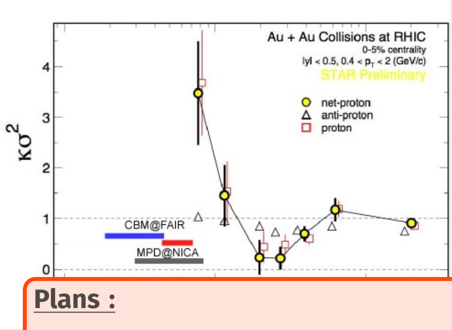
- *Yield* of charmed hadrons
- *Collective flow of* D *mesons*

EVENT-BY-EVENT FLUCTUATIONS



Goals

- Assess susceptibilities through fluctuations of conserved quantities (baryon number, strangeness, electrical charge)
- Assess vicinity of critical point



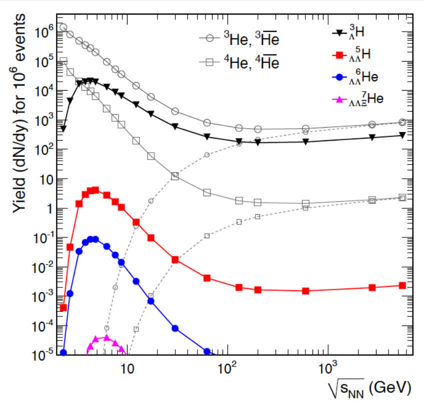
Goals

- Assess susceptibilities through fluctuations of conserved quantities (baryon number, strangeness, electrical charge)
- Assess vicinity of

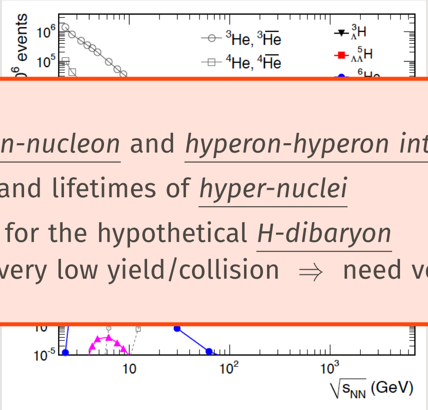
Plans :

- Measurement of *higher moments (skewness, kurtosis)*

Expected yields of light hyper-nuclei



Expected yields of light hyper-nuclei



Plans :

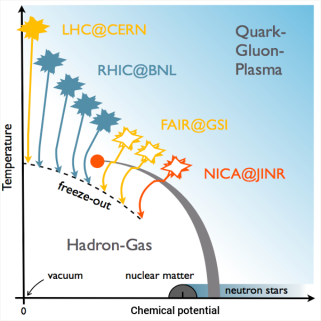
- *Hyperon-nucleon* and *hyperon-hyperon interactions*
- Yields and lifetimes of *hyper-nuclei*
- Search for the hypothetical *H-dibaryon*
  Note : very low yield/collision $\Rightarrow$ need very high rate

Future plans

- Facilities
- Computing
- Instrumentation

Facilities and experiments

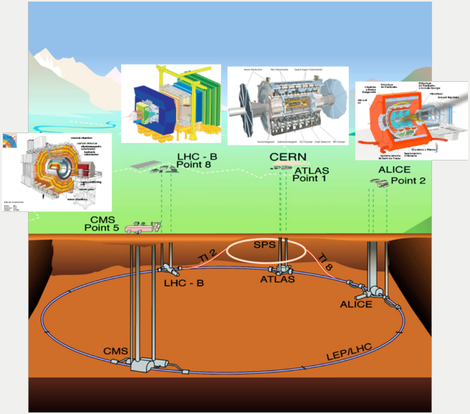
- Existing and operating :
  - LHC at CERN
- Realization approved and on-going :
  - FAIR at GSI
  - NICA at JINR
- Under exploration :
  - NA60+ at the CERN SPS
  - AFTER at the CERN LHC
  - Future Circular Collider



Heavy-Ion program at the LHC

High-Temperature matter produced in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76 - 5.02$ TeV

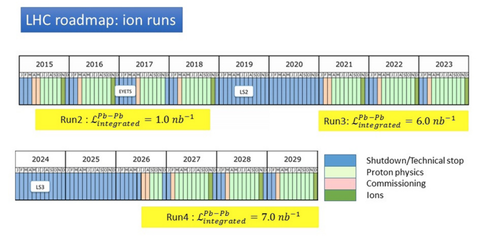
$L_{\mathrm{int}} \approx 1\ \mathrm{nb}^{-1}$ in Run-1 and Run-2 (2010-18)



- $\times 10$ integrated luminosity
- Improvements in the accelerator chain during long shutdown 2 (2019-2020)
- PbPb collisions at 50 kHz interaction rates from 2021

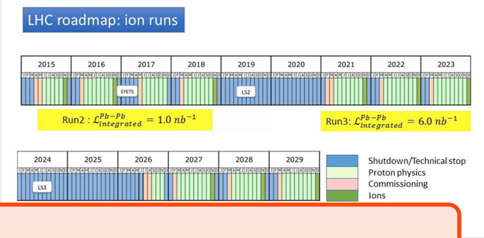
Heavy-Ion program at the LHC

- Run-3 and 4 : 2021-29
- $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV
- $\mathrm{L_{int}} > 10$ nb^{-1}
- Experiment upgrades



- Correlations and fluctuations
- Jet structure. γ-jet and Z-jet correlations
- Low-mass dileptons
- (Anti-)(hyper-)nuclei
- Charm and beauty energy loss and degree of thermalization in the medium
- Charmonium production mechanism and elliptic flow (hadronization at phase boundary or in medium?)

- Run-3 and 4 : 2021-29
- $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV
- $\mathrm{L}_{\mathrm{int}} > 10\ \mathrm{nb}^{-1}$
- Experiment upgrades



Recommendation :

- Vigorous physics exploitation of LHC Run-3 and Run-4 to provide precision information on QGP parameters

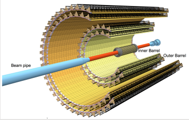
n

the medium

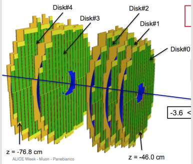
- Jet structure. γ-jet and Z-jet correlations
- Low-mass dileptons
- (Anti-)(hyper-)nuclei

- Charmonium production mechanism and elliptic flow (hadronization at phase boundary or in medium?)

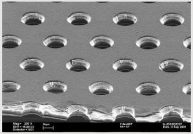
New inner tracking system with MAPS



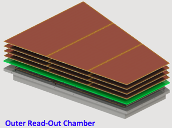
Muon forward tracker with MAPS



GEM-chambers for continuous readout of the TPC



New readout electronics. New online and offline (O^2) system

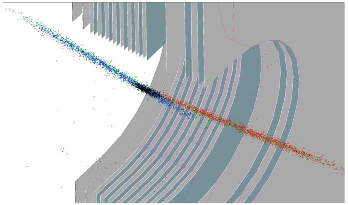


- Preserve high resolution and particle identification performance
- Fully exploit 50 kHz interaction rate
- Minimum bias data for low transverse momentum regime
  - Open heavy flavors, Heavy quarkonia
  - Light nuclei and exotic states
  - Di-lepton spectrum

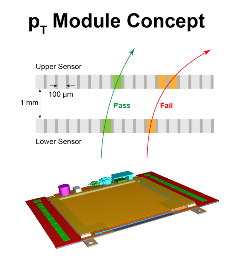
ATLAS, CMS and LHCb

LHCb :

- Upgrade in LS2 : tracking system
- Ongoing : SMOG (System for Measuring the Overlap with Gas). Gas injected in beam pipe, fixed target operation, different nuclei (He, Ne, Ar, etc...)



J. Instrum. 9 (2014) P12005.

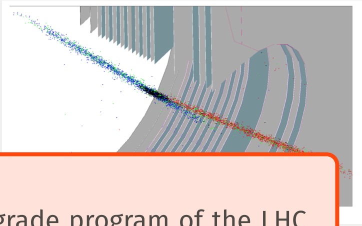


ATLAS and CMS :

- Upgrades in LS2 and 3 (pixels, trigger, DAQ, etc...)
- Focus on jet physics, quarkonia, electroweak bosons and extend to top quark!

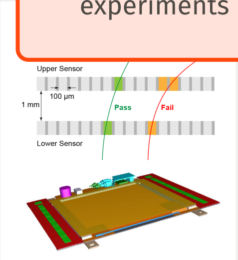
LHCb :

- Upgrade in LS2 : tracking system
- Ongoing : SMOG (System for Measuring the Overlap with Gas).



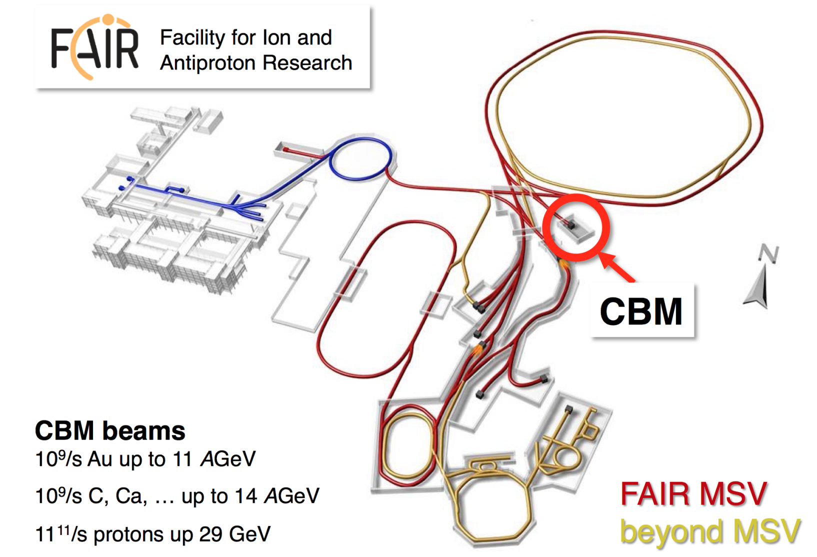
Recommendation :

- Completion of the ongoing upgrade program of the LHC experiments

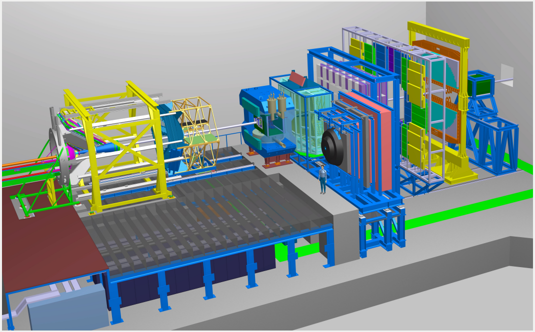


- Upgrades in LS2 and 3 (pixels, trigger, DAQ, etc...)
- Focus on jet physics, quarkonia, electroweak bosons and extend to top quark!

HEAVY-ION PROGRAM AT FAIR

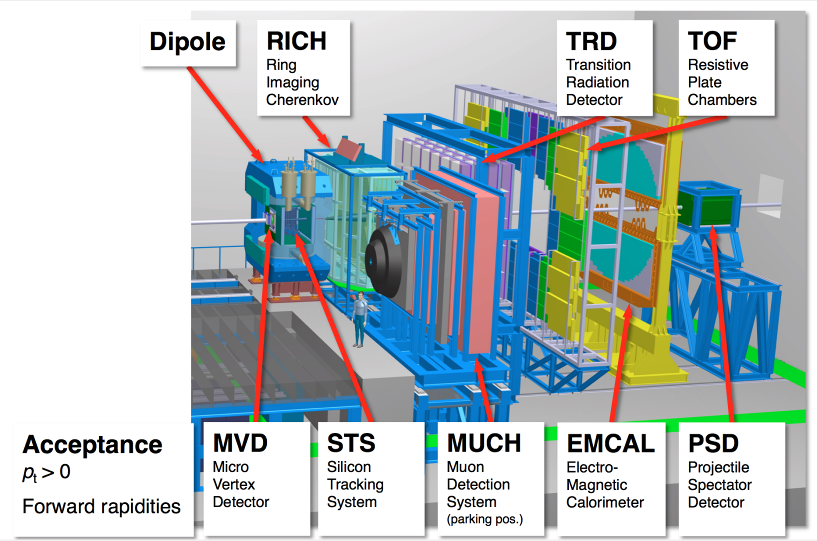


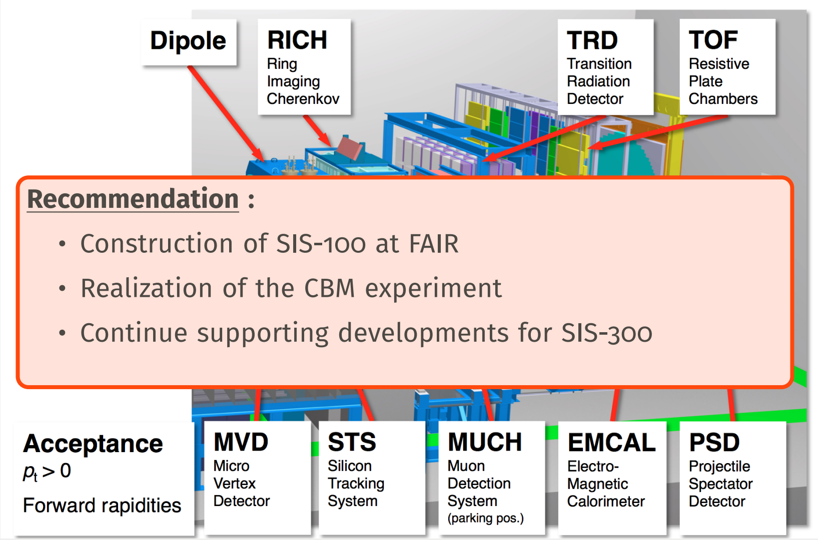
CBM AND HADES AT SIS-100



- Probe the QCD phase diagram at high net-baryon densities
  - Chiral symmetry, critical endpoint, new phases, etc...
- Strangeness, di-leptons, flow and correlations, fluctuation and higher moments, (double-)hypernuclei

Compressed Baryonic Matter

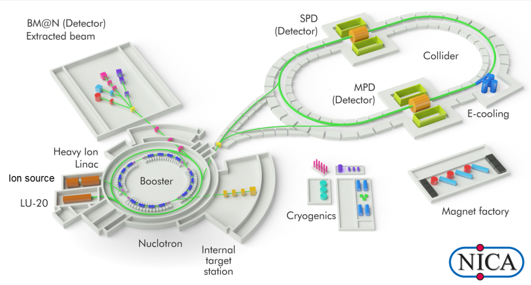




Recommendation :

- Construction of SIS-100 at FAIR
- Realization of the CBM experiment
- Continue supporting developments for SIS-300

NICA at JINR Dubna

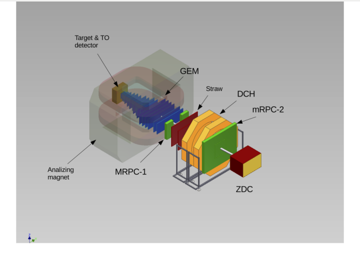


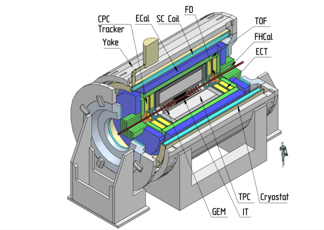
- *First stage :* BM@N fixed target detector at the nuclotron
  Au beams of 1-4.5 AGeV, protons up to 12.6 GeV
- *Second stage :* transfer line and collider
  MPD collider experiment
  Design luminosity : 10^{27} cm^{-2}s^{-1}, $\sqrt{s_{\mathrm{NN}}}$ = 4-11 GeV

BM@N AND MPD AT NICA

BM@N :

- Fixed-target exp, beams from nuclotron
- High precision tracking and particle identification
- Expected start in 2017



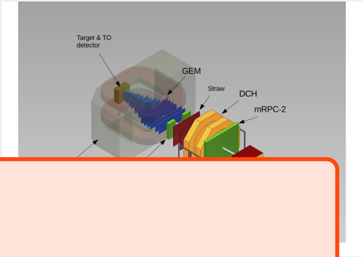


MPD :

- Collider experiment, intermediate reaction rates
- TPC, TOF, ECAL, FHCAL
- Completion of commissioning $\sim$ 2023

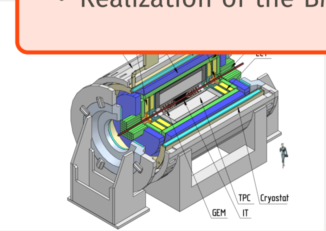
BM@N :

- Fixed-target exp, beams from nuclotron
- High precision tracking and particle



Recommendation :

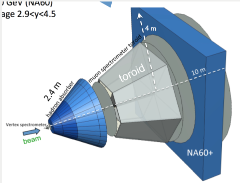
- Construction of NICA at JINR
- Realization of the BM@N and MPD experiments



- Collider experiment, intermediate reaction rates
- TPC, TOF, ECAL, FHCAL
- Completion of commissioning ~ 2023

NA60+ at the SPS, at CERN :

- Vertex + absorber + muon spectrometer
- Thermal radiation, light vector mesons and charmonia, chiral symmetry restoration, onset of deconfinement, critical endpoint
- Moderate to high baryonic density, 20-160 AGeV

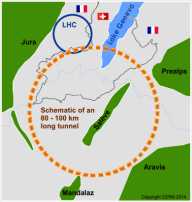


AFTER @ LHC: fixed-target at TeV :

- High luminosities, access to $y < 0$, target versatility and polarization
- Bottomonium, charm to low p_T, Drell-Yan. Nuclear PDF, factorization

Future Circular Collider (FCC) :

- 80-100 km long hadron collider, PbPb at $\sqrt{s_{NN}} \approx 63$ TeV, $L_{int} \approx 33\ nb^{-1}$/month
- Qualitatively different medium
- Collective effects, thermal charm, top quark, color coherence, new phenomena!



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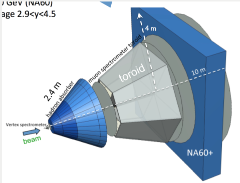

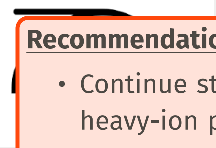

AFTER @ LHC: fixed-target at TeV :

Recommendation :

- Continue studies for AFTER@LHC, NA60+, and a heavy-ion program at the Future Circular Collider

Future Circular Collider (FCC) :

- 80-100 km long hadron collider, PbPb at $\sqrt{s_{NN}} \approx 63$ TeV, $L_{int} \approx 33$ nb^{-1}/month
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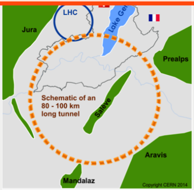

Large computer resources required for :

- **Theory :**
  - Lattice QCD : power ~ petaflop/sec
  - Hardware accelerators such as GPUs
  - Needed resources double every 1.5 years

- **Experiments :**
  - Storage of 10s of peta-bytes of experimental and simulation data. World wide access
  - Future experiments will produce a few TB/sec (to be reduced and compressed)

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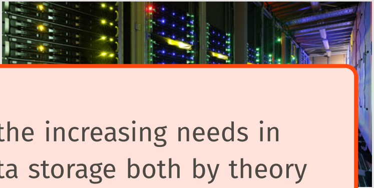

Recommendation :

- Secure resources to face the increasing needs in computing power and data storage both by theory and by experiments

  - Storage of 10s of peta-bytes of experimental and simulation data. World wide access
  - Future experiments will produce a few TB/sec (to be reduced and compressed)

COMPUTING : NEW SOLUTIONS NEEDED

- **Theory :**
  - New multi-GPU and many-core CPU architectures
  - Complex memory hierarchies
  - Corresponding software developments

- **Experiments :**
  - Distributed cloud systems, high-bandwidth wide area networks
  - Intense online processing, filtering, data reduction
  - Less GRID and more optimized data centers (e.g., Green Cube @ GSI)
  - New computing models

- **Theory :**
  - New multi-GPU and many-core CPU architectures
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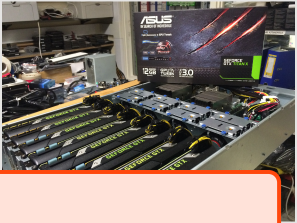


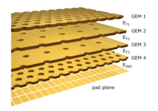
Recommendation :

- Invest in developments of new technology and algorithms

  - Intense online processing, filtering, data reduction
  - Less GRID and more optimized data centers (e.g., Green Cube @ GSI)
  - New computing models

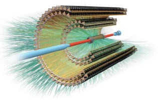
Next generation heavy-ion experiments : high particle density

GEM Time Projection Chamber



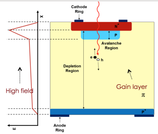
High rates, PID (ALICE)

High resolution tracking and vertexing



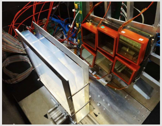
Monolithic Active Pixel Sensors (ALICE, CBM)

Ultra-fast silicon detectors



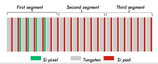
4D event reconstruction, Low-gain avalanche detectors

Compact RICH detectors



PID, Silica aerogel, Pressurized gas

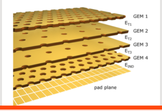
Silicon calorimeters



High segmentation, speed (ALICE, SPHENIX)

Next generation heavy-ion experiments : high particle density

GEM Time Projection Chamber



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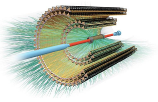

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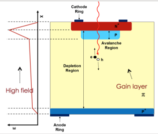

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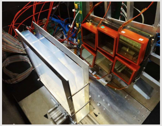
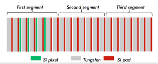


Silicon calorimeters



High

Recommendation :

- Continue at all times R&D of detectors employing new techniques for :
  - **SPEED :** faster signal production and collection
  - **RATES :** higher interaction and data rates
  - **RAD HARDNESS :** tolerate higher radiation levels

Recommendation :

- Guarantee continuous support to theory (theoretical support needed to interpret the results and to provide feedback to the experimental programme)
- Foster close collaboration between theory and experiments

Thanks !

Experiments

- Vigorous physics exploitation of LHC Run-3 and Run-4 to provide precision information on QGP parameters
- Completion of the ongoing upgrade program of the LHC experiments
- Continuation of the on-going programs at intermediate energies: HADES at SIS18, NA61 at the SPS
- Construction of SIS-100 at FAIR and realization of the CBM experiment. Continue supporting developments for SIS-300
- Construction of NICA at JINR and realization of the BM@N and MPD experiments
- Continue studies for AFTER@LHC, NA60+, and a heavy-ion program at the Future Circular Collider

Recommendations

Theory

- Guarantee continuous support to theory (theoretical support needed to interpret the results and to provide feedback to the experimental programme)
- Foster close collaboration between theory and experiments

Recommendations

Miscellaneous

- Computing: secure resources to face the increasing needs in computing power and data storage, both by theory and by experiments. Invest in developments of new technology and algorithms
- Continue at all times R&D of detectors employing new techniques to reach faster signal production and collection, to handle higher data rates, and higher radiation levels