

(an) INTRODUCTION to HADRONIC PHYSICS



Outline

- > QCD: Framework and Related Questions
 - The strong interaction and its properties
 - Key Issues in Hadronic Physics
 - The QCD phase diagram

- > QCD under Extreme Conditions: the Quark-Gluon Plasma
 - Facilities
 - Probes of QGP



Elementary Particles: Matter Bricks & Force Carriers

Relatively few truly elementary particles in the Standard Model...

... compared to the wealth of subnuclear particles discovered until now!

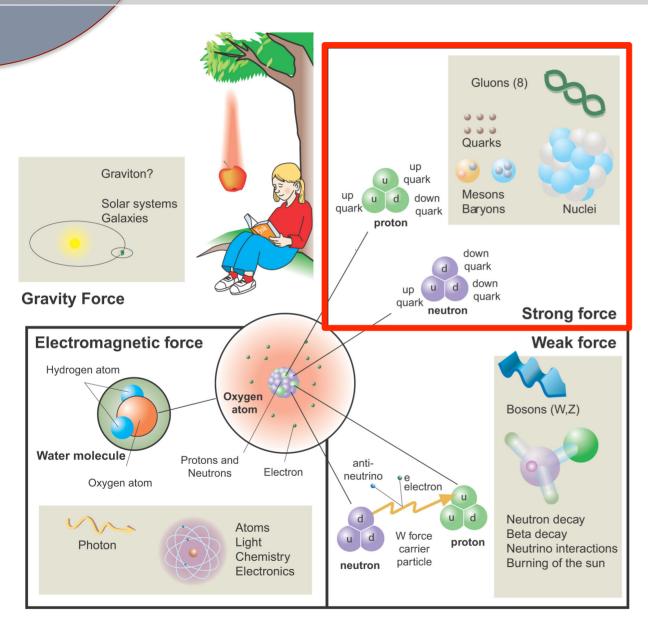
- ❖ A fact: all the subnuclear particles we list in our PDG booklet is made out of quarks, either in the "meson" or "baryon" format (even if pentaquarks seem now to be a real option in Nature)
- A question: what is responsible for the existence and the properties of the 99.9...% of the particles we know?

FERMIONS matter constituents spin = 1/2, 3/2, 5/2,								
Leptons spin = 1/2				Quarks spin = 1/2				
Flavor	Mass GeV/c ²	Electric charge	F	lavor	Approx. Mass GeV/c ²	Electric charge		
ve electron neutrino	<1×10 ⁻⁸	0	u	l up	0.003	2/3		
e electron	0.000511	-1	d	down	0.006	-1/3		
$ u_{\!\mu}^{\!$	<0.0002	0	C	charm	1.3	2/3		
$oldsymbol{\mu}$ muon	0.106	-1	s	strange	0.1	-1/3		
ν _τ tau neutrino	<0.02	0	t	top	175	2/3		
au tau	1.7771	-1	b	bottom	4.3	-1/3		

BOSONS force carriers spin = 0, 1, 2,							
Unified Electroweak spin = 1			Strong (color) spin = 1				
Name	Mass GeV/c ²	Electric charge	Name	Mass GeV/c ²	Electric charge		
γ photon	0	0	g gluon	0	0		
W ⁻	80.4	-1					
W ⁺	80.4	+1	+ th	+ the Higgs!			
Z ⁰	91.187	0					



The Fundamental Interactions



Nuclei are held together by exchanging mesons (but deuterons are easy to break apart)

Nucleons (and hadrons in general) are held together by exchanging gluons

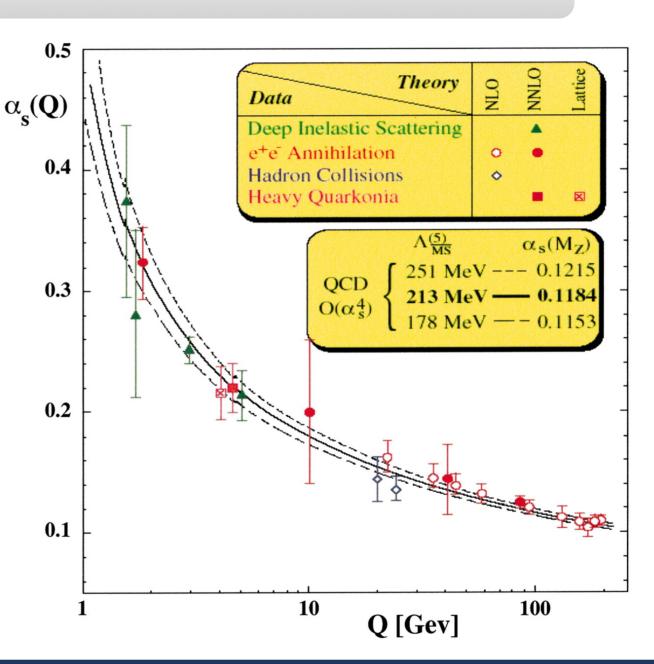
- To which extent do we understand QCD properties?
- Do we understand QCD multiparticle properties in an extended medium dominated by the strong interaction?



Strong Interaction: Asymptotic Freedom...

The QCD "running" coupling "constant"

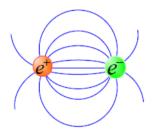
- Gross, Politzer, Wilczek 1973: Strong interactions are weak at short distances (high momentum transfers)...
- ... but at large distance the strong interaction is really strong!

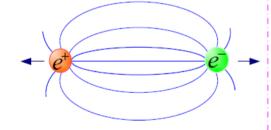




... and Color Confinement

QED





 $V_{\it QED}(r) \sim -rac{K}{r}$

QCD



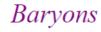
Color Flux Tube

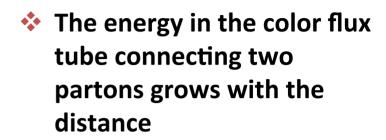


$$V_{QCD}(r) \sim Kr$$









At large distances (of the order of fm) quark-antiquark pairs pop out from the "vacuum" (it is energetically favorable to do so)



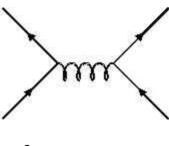
Pulling apart partons only leads to more hadrons!



Two Regimes of QCD

Perturbative QCD (pQCD) means that rigorous (converging) calculations can be done with Feynman integrals

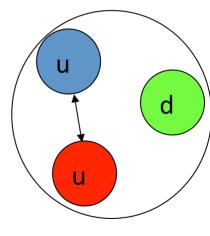
Well defined for interactions between quarks and gluons with large momentum exchange (Q² > 1 GeV)



 $Q^2 > 1 \text{ GeV}$

However, at large distances ($r \approx 1$ fm) one can no longer write down Feynman diagrams and compute amplitudes, because of the too large values of the α_S

- The particles we observe in nature are in the regime of non-perturbative QCD
- ➤ Small momentum exchange (Q² << 1 GeV) is implied in this regime. Typical example: interaction between the partons composing baryons & mesons



 $Q^2 \ll 1 \text{ GeV}$



The QCD Lagrangian

Conceptually, QCD is simple: it is a relativistic quantum field theory of quarks and gluons interacting according to the laws of non-Abelian forces between color charges

The starting point of all considerations is the QCD Lagrangian density describing the interaction between the quark-field spinors and the gluon fields, as well as the auto-coupling of gluon fields to themselves

$$\mathcal{L} = \sum_{q} \bar{\psi}_{q,a} (i\gamma^{\mu}\partial_{\mu}\delta_{ab} - g_s\gamma^{\mu}t_{ab}^{C}\mathcal{A}_{\mu}^{C} - m_{q}\delta_{ab})\psi_{q,b} - \frac{1}{4}F_{\mu\nu}^{A}F^{A\mu\nu}$$

- ➤ [There is freedom for an additional CP-violating term to be present in the QCD Lagrangian, responsible among other of the neutron electric dipole moment]
- Non-zero light quark masses explicitly break the chiral symmetry of the Lagrangian with the result that the pion, eta, and kaon have finite masses



The QCD Lagrangian

The QCD Lagrangian density is at the basis of the rich and complex phenomena of nuclear and hadronic physics

How this complexity arises in a theory with quarks and gluons as fundamental degrees of freedom is only qualitatively understood

* The QCD field equations are non-linear: this makes every strongly-interacting system intrinsically a many-body problem, wherein apart from the valence quarks many quark-antiquark pairs and many gluons are always involved

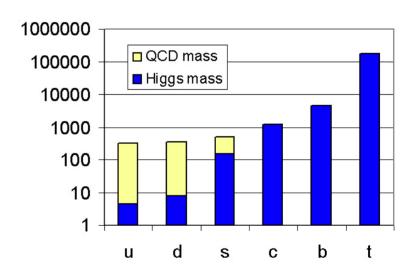


Colored particles cannot be observed as isolated degrees of freedom. The vacuum around a colored-charged particle pulsates with gluons and quark-antiquark pairs appearing and fading away: this implies an anti-screening effect of the central quark, making its color charge to diverge



Primary Goals of Hadronic Physics

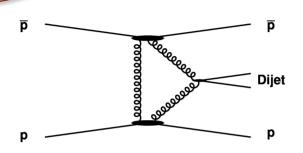
- ❖ Determining the relevant degrees of freedom that govern hadronic phenomena at all scales
- Establishing the connections of the degrees of freedom to the parameters and fundamental fields of the QCD Lagrangian
- Using our understanding of QCD to quantitatively describe a wide array of hadronic phenomena, ranging from terrestrial nuclear physics to the behavior of matter in the early universe



The theoretical foundations and the extensive experimental tests of the standard model in general and the QCD in particular are so compelling that the current focus is on understanding QCD aspects more than looking for alternative theories

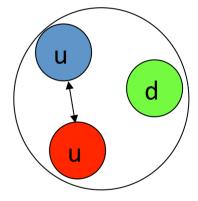


Determining the Parameters of QCD



In the perturbative regime, QCD predictions (for instance, jet rates, heavy quarkonium production in elementary collisions) can be made on the basis of the magnitude of the coupling constant. At the mass of Z: $\alpha(M_7) \approx 0.12$

In the non-perturbative regime the coupling constant diverges and the fundamental scale of QCD $\Lambda_{\rm QCD}$ emerges from QCD through the phenomenon of dimensional transmutation



- ho $\Lambda_{\rm QCD} \approx 220$ MeV corresponds to the scale where the perturbatively-defined coupling would diverge (sort of infra-red cutoff). All hadron masses are in principle calculable within QCD in terms of $\Lambda_{\rm QCD}$
- The non-perturbative regime of QCD is quantitatively less well understood: important questions still have to be addressed



Hadron Structure: Two Complementary Views

The intimate structure of hadrons can be probed and discovered with deep inelastic scattering (DIS) experiments

The conceptual advantage of the DIS approach is that the quarks and the gluons which are measured are directly related to the quarks and the gluons degrees of freedom appearing in the QCD Lagrangian (however, the information is only available in probability distributions, e.g. of finding a quark with a given momentum fraction x)

The other perspective is the one in which the d.o.f. are the valence or dressed quarks, not anymore those of the QCD Lagrangian

How should these valence d.o.f. be chosen? How are they related through their clouds of gluons and quark-antiquark pairs to the fundamental d.o.f. of the QCD Lagrangian?



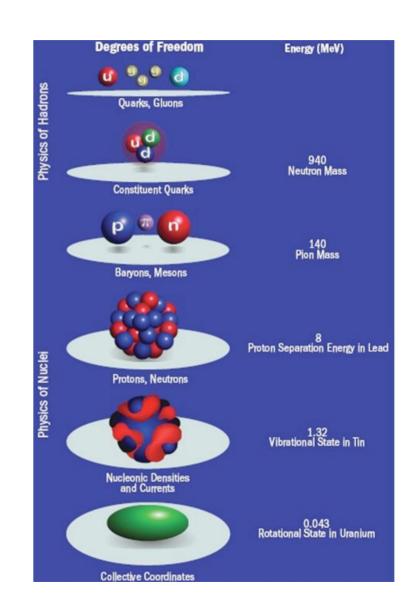
The theoretical analysis of the hadron structure in the dressed quark picture can drive experiments through a well-chosen spectroscopy program, in order to provide a solid frame to the measurements of hadron properties like charge radius, magnetic moment, form factors...



Beyond Hadrons: QCD and Nuclear Physics

The next intellectual challenge is to go beyond the physics of a single hadron and understand essential aspects of nuclear physics from first principles

- In thinking about many-nucleon systems, one immediately faces the question of the **origin of the nuclear energy scale:** why when the natural energy scale of QCD is of the order of hundreds of MeV, is the nuclear binding energy per nucleon so small, of the order of 10 MeV?
 - Does it arise from complicated details of near cancellations of strongly attractive and repulsive terms in the nuclear interaction?
 - Is there some deeper reason for this scale to arise?

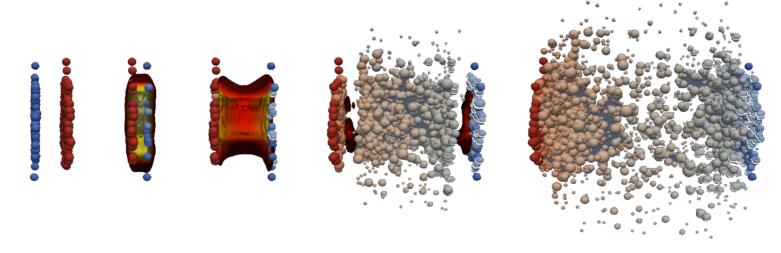




Extreme Conditions in the Laboratory...

QCD is essential to answer questions related to the physics of the early universe and high-energy astrophysics

For instance, the measurement of the temperature and the characterization of the nature of the phase transition between the QCD regimes dominated by the partonic and the hadronic degrees of freedom are goals of primary importance for cosmology



In ultra-relativistic heavy-ion collisions a plasma of quarks and gluons is created, an environment where QCD fundamental degrees of freedom can exist in a deconfined state, free from any confinement in hadronic structures

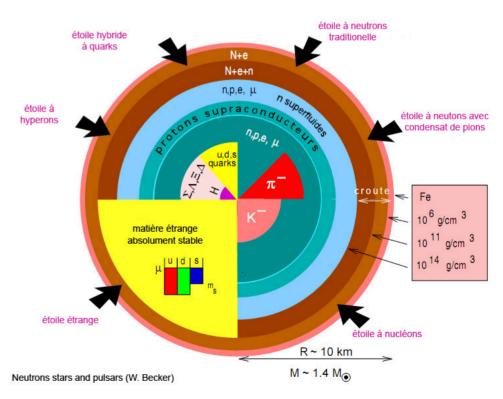


... and in the Cosmos

The physics of QCD at high densities plays a crucial role in determining the physics of neutron stars and supernovae

The equation of state at finite density is essential for quantitative calculations of the astrophysics of neutron stars

- The excitation spectrum of hadronic matter must be understood to predict neutrino emission spectra
- Can color-superconducting QCD matter exist in the core of the most massive astrophysical objects?





Theoretical Tools

In the high-energy (high-momentum-transfer) regime, the perturbative approach is applicable to QCD: precise estimations of yields, cross-sections and kinematic distributions for hard processes in elementary collisions

In the low-energy (low-momentum-transfer) regime, various approaches to non-perturbative QCD are possible. Among them:

- Lattice QCD, which attempts a direct attack to solve QCD non-perturbatively by numerical simulation in a grid or lattice of points in space and time. When the size of the lattice is taken infinitely large and its sites infinitesimally close to each other, the continuum QCD is recovered
- **Effective field theories**, which exploit the symmetries of QCD and the existence of hierarchies of scales to provide predictions from effective Lagrangians that are equivalent to QCD. Degrees of freedom can be either partonic or hadronic

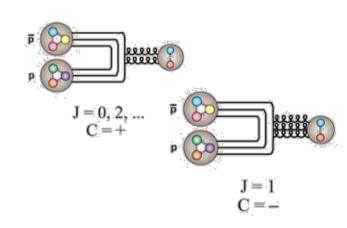


Experimental Tools

Electron-positron colliders: multi-jet yield, gluon self-coupling. Initial state well under control, but the quantum numbers are fixed: only specific hadronic states can be produced (e.g. vector resonances)

Deep inelastic scattering: partonic structure of nucleons and nuclei. Study of quark and gluon composition of the nucleons

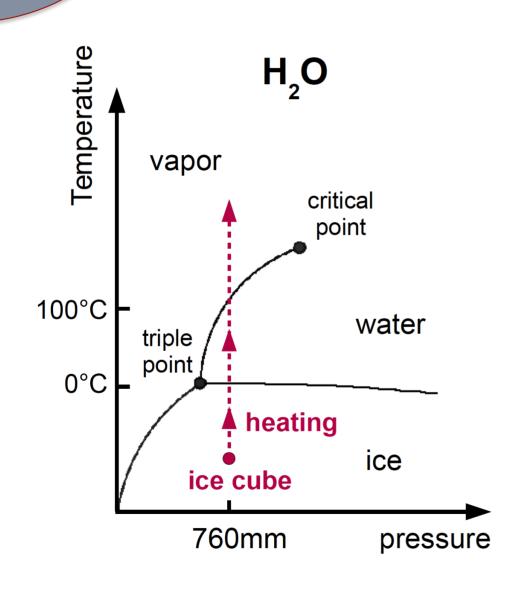
Intermediate-energy hadron collisions (especially involving antiprotons): rich variety of quantum states available for particle production. Spectroscopy of hadron states, gluonic excitations (if existing), measurement of hadron properties like charge radius, magnetic moment, form factors

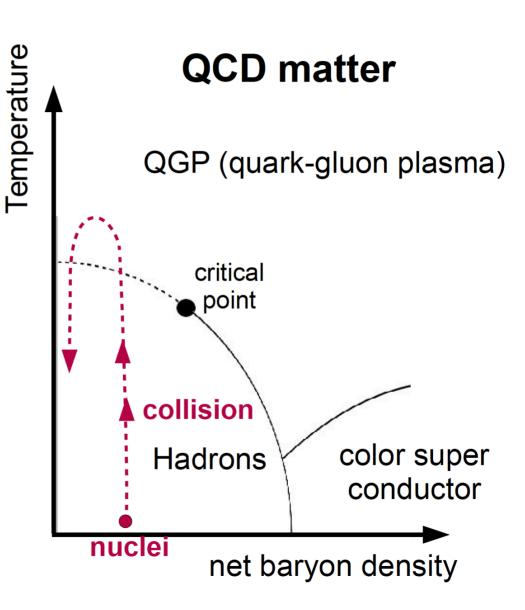


High-energy hadron collisions: test of factorization hypothesis of production cross sections in the perturbative regime (elementary collisions), study of QGP, onset of the deconfined phase and the chiral symmetry restoration in the deconfined phase



Phase Diagram of the QCD Matter...

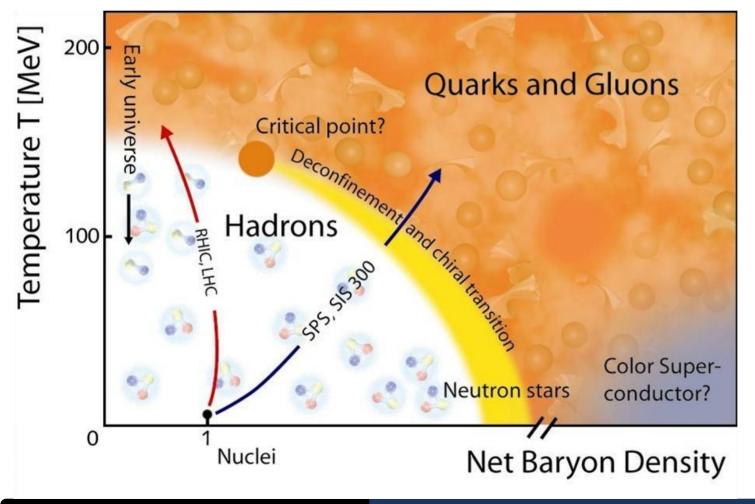






Phase Diagram of the QCD Matter...

What is the state of QCD matter under specific conditions of temperature and baryon density?



- Challenging task for the lattice QCD, experimental observations are needed!
- Which is the nature of the phase transition at large net baryon density?
- Is there a critical point?

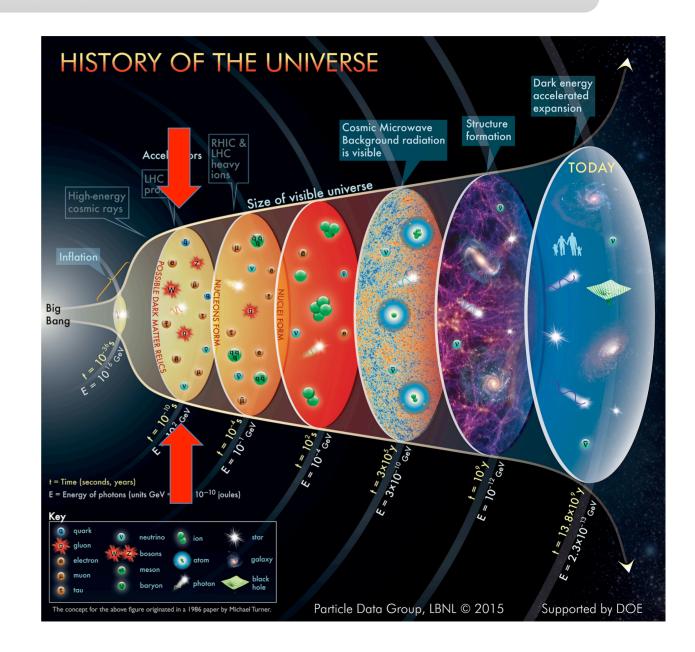


... and its Cosmological Context

In the early stages of the Universe, quarks and gluons were reaming freely due to the large temperature and energy density

As the universe cooled down, they got confined and have remained imprisoned

ever since...





Hadronic Matter under Extreme Conditions

Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry

Department of Applied Mathematics and Theoretical Physics, University of Cambridge,

Cambridge CB3 9EW, England

(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

A neutron has a radius¹⁰ of about 0.5-1 fm, and so has a density of about 8×10^{14} g cm⁻³, whereas the central density of a neutron star^{1,2} can be as much as $10^{16}-10^{17}$ g cm⁻³. In this case, one must expect the hadrons to overlap, and their individuality to be confused. Therefore, we suggest that matter at such high densities is a quark soup.

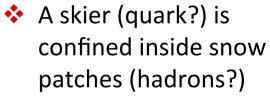
How does QCD matter behave under extreme conditions of temperature and energy density?

A question rooted in the QCD, with cosmological and astrophysical implications



Hadronic Matter under Extreme Conditions





Temperature and energy density ...



The skier can move further... a new phase develops

... go up this way



The skier (quark?) can move freely over long distance

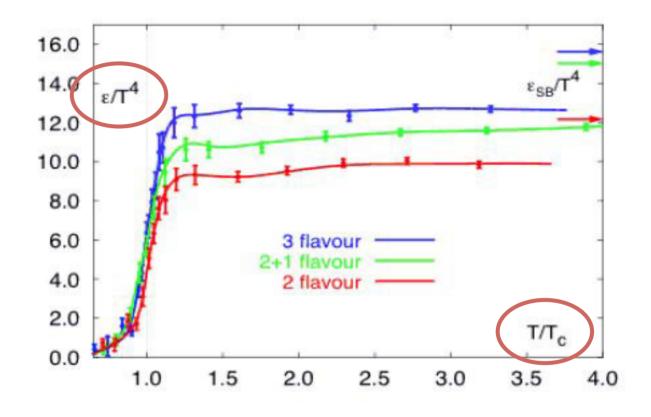




Lattice QCD Predictions

Understanding the strong force and the phenomenon of **confinement**:

- We must create and study a system of **deconfined** quarks and gluons
- But... how about the theory?



Lattice QCD is the only 1st principle calculation of non-perturbative QCD (large α_s) \Rightarrow hadron properties (e.g. masses), phase transition and QGP properties. **QGP onset:**

- \star T_C \approx 170 MeV (approx. 2·10¹² K, 100.000 times the temperature at the center of the Sun)
- $\epsilon_{\rm C} \approx 1 \, {\rm GeV/fm^3}$ (approximately 5 times the density of ordinary nuclear matter)



From QCD to QGP

Can we explore the phase diagram of hadronic matter? We think so!

- By colliding nuclei in the laboratory
- By varying the nuclei size (A) and colliding energy (net baryon density)
- By studying spectra and correlations of the produced particles
- > But... the system must be at equilibrium, so dense and large (even for a very short time) to study the multi-particle aspects of the QCD

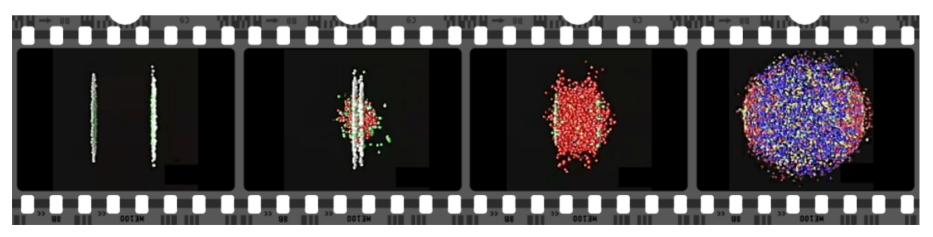
Can we create and characterize the Quark-Gluon Plasma? We hope so!

- By colliding large nuclei at large energies
- Which conditions at the phase transition? Lattice QCD predicts:
 - \triangleright Critical temperature $T_c \approx 170 \text{ MeV}$
 - Critical energy density ≈ 5 × ordinary nuclear matter



QGP in Lab: Heavy-Ion Collisions or the "Little Bang"

- Initial conditions. Large Lorentz contraction. Nucleus wave function is mostly given by gluon contributions
- **Particle (entropy) production.** Involves mostly "small-x" partons. One characteristic scale: saturation momentum Q_s . Large initial fluctuations
- * Thermalization of produced partons. QGP phase. Hydrodynamical expansion
- Hadronization (boundary between QGP and hadronic matter) and chemical freeze-out. Elastic interactions until thermal freeze-out. Measurements



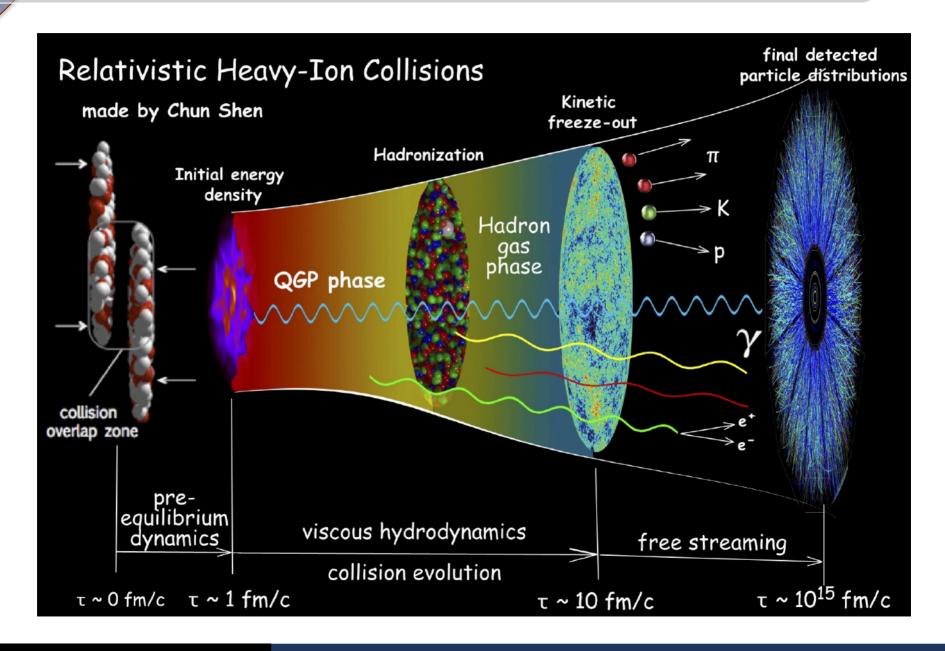
t = 0

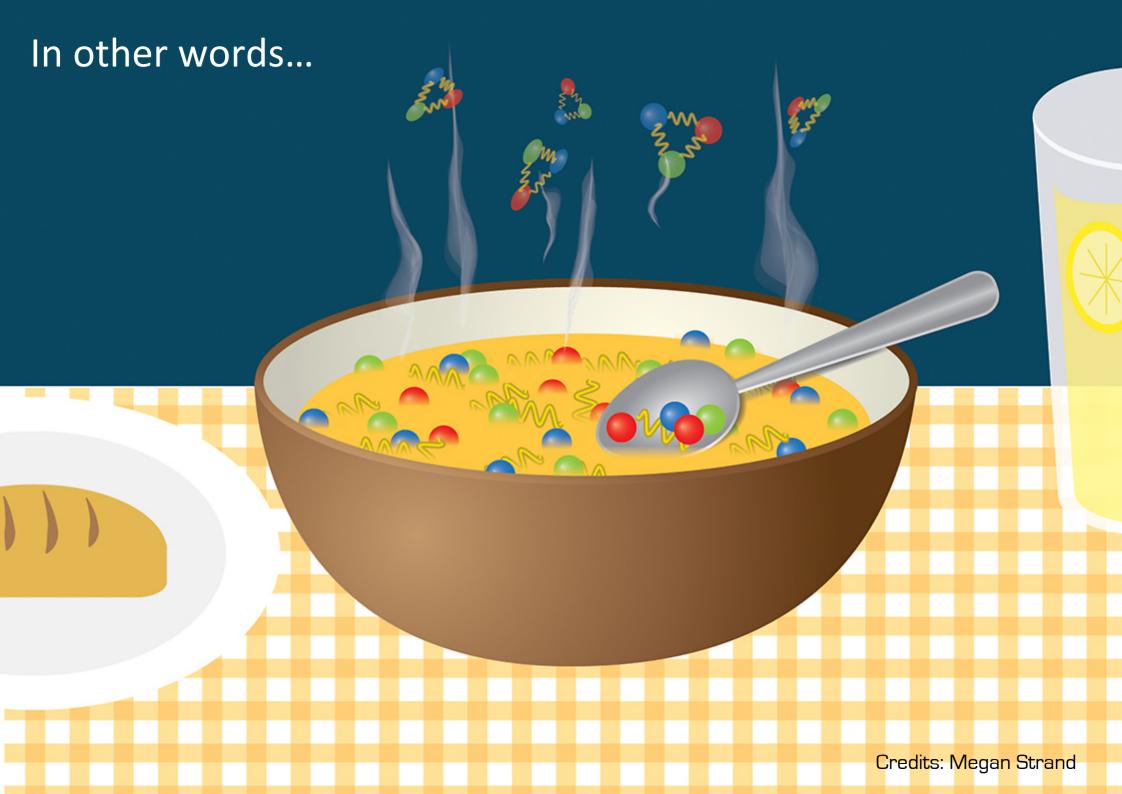
 $t \approx 0.3 \text{ fm/c}$

 $t \approx 3 \text{ fm/c}$



"Standard Model" of Heavy-Ion Collisions





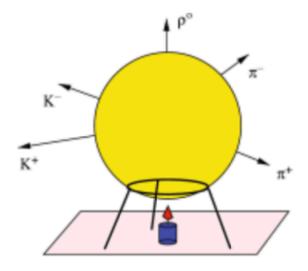


Challenge: Creating and Calibrating the Probes

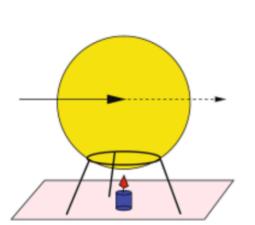
- The "probes" must be produced together with the system they probe!
- In particular: we look for probes which are created **very early in the collision evolution**, so that they are there before the matter to be probed (the QGP) is formed: hard probes (jets, quarkonia, high-p_⊤ particles, ...)
- We must have "trivial" probes, not affected by the dense QCD matter, to serve as baseline reference for the interesting probes: photons, Z and W bosons, Drell-Yan dileptons
- **❖ We must have "trivial" collision systems**, to understand how the probes are affected in the *absence* of "new physics": pp, p-A, d-A, light ions



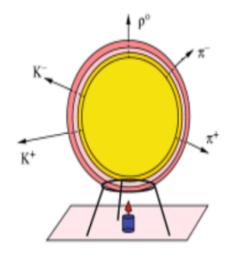
Challenge: Creating and Calibrating the Probes



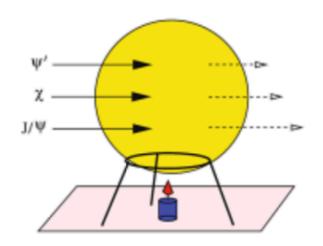
Radiation of hadrons



Energy loss by quarks, gluons and other particles



Azimuthal asymmetry and radial expansion



Suppression of quarkonia



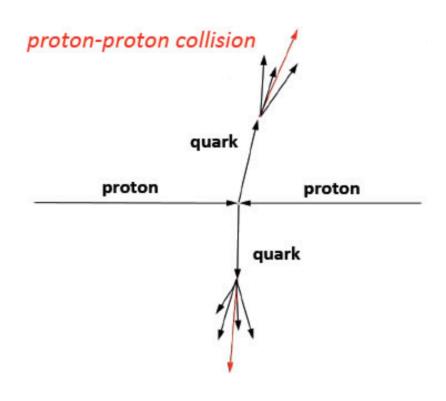
Conclusions

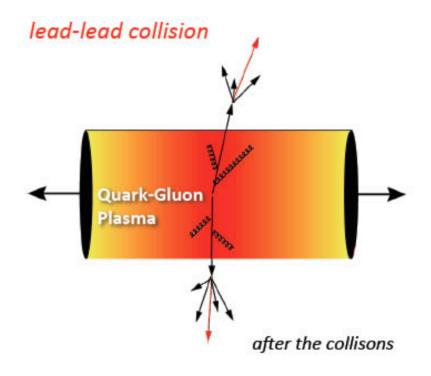
- ❖ Strong interaction physics poses a wealth of fundamental questions with profound significance for our understanding of nature and the structure of the matter of which our universe is composed
- **QCD** is the theory of hadronic interactions, whose running coupling constant defines two main regimes: perturbative at large momentum trasfer, and non-perturbative at low momentum transfer
- Huge variety of phenomena driven by hadronic interactions: a lot of work still to be done both on the theoretical and experimental side!
 - Ab-initio theoretical approaches from QCD Lagrangian not always possible or useful
 - > Several experimental programs currently active or in preparation, exploiting various collision systems and energy scales

Backup Slides



Challenge: Creating and Calibrating the Probes





The "reference"

The "QGP physics"



From the Heavy-Ion Physics Vocabulary: R

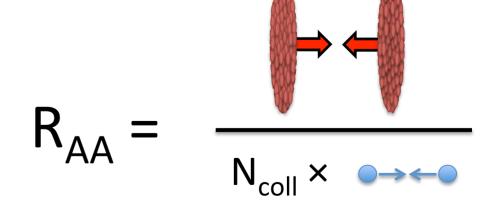
 R_{AA} = nuclear modification factor (in A-A collisions w.r.t. pp collisions)

How is it built?

- ❖ Take the outcome of a measurement in pp (e.g. J/ψ yield)
- Evaluate the expected outcome of the same measurement in A-A in the hypothesis that A-A is a simple superposition of N_{coll} nucleon-nucleon collisions
- ❖ Take the ratio between the real and the expected outcomes of the measurement in A-A, and you have the R_{AA}

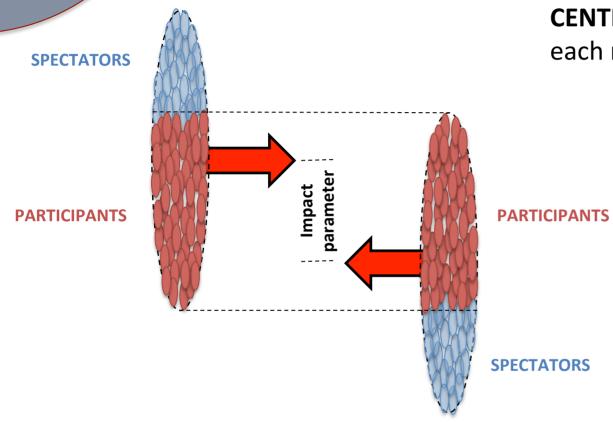
What does it mean?

The R_{AA} quantifies the influence of the hot medium on the "vacuum" physics





From the Heavy-Ion Physics Vocabulary: Centrality



CENTRALITY: parameter characterizing each nucleus-nucleus collision

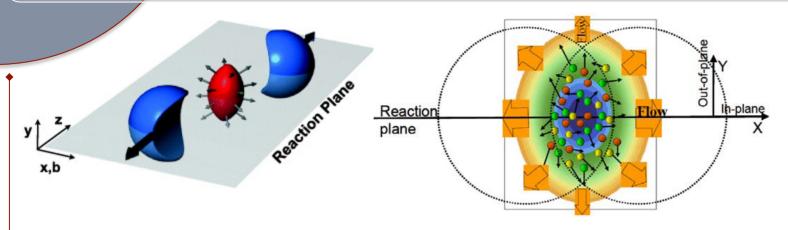
Linked to the collision geometry via the impact parameter (transverse distance between the nuclei centers)

Collision geometry implies
collision dynamics: the smaller
the impact parameter, the larger
the number of nucleons
participating to the collision

- Small impact parameter, large number of participating nucleons: "central" collision, largest hot-medium effects
- Large impact parameter, small number of participating nucleons: "peripheral" collision, smallest hot-medium effects (possibly no hot-medium effect at all)



From the Heavy-Ion Physics Vocabulary: V2



Initial spatial anisotropy of the overlap region of colliding nuclei



Anisotropy in momentum space through interactions of produced particles

Elliptic flow: measured by the v_2 parameter extracted from the Fourier decomposition of particle azimuthal distributions relative to the reaction plane Ψ_{RP}

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + 2v_2 \cos(2(\phi - \Psi_{\mathrm{RP}})) + \text{higher harmonics } (v_3, v_4, \ldots)$$

v₂ provides a measurement of collectivity: constraints the properties of hot medium

Large mean free path ⇒ particles stream out isotropically, no memory of initial asymmetry (ideal gas)

Small mean free path ⇒ large density and pressure gradients, larger mom. anisotropy (ideal liquid)

Part II: Observables

- Non-exhaustive list of possible measurements in a heavyion experiment
- Focus on the available probes/methods more than on the specific results (which varies according to the energies, and whose interpretation often still waits for a common theoretical framework)



Two Laboratories to Study the QGP

- **❖ AGS**: 1986 − 2000
 - Si and Au beams, up to 14.6 AGeV
 - Only hadronic variables
- **❖ SPS**: 1986 − 2003; 2009 →
 - Various beams up to Pb, 200 AGeV
 - Beam energy scan
 - Hadrons, photons and dileptons
- **❖ RHIC**: 2000 →
 - Various beams up to U, up to sqrt(s) = 200 GeV
 - Beam energy scan
 - > STAR, PHENIX, BRAHMS, PHOBOS experiments
- **♦ LHC**: 2009 →
 - Pb beams up to sqrt(s) = 5.5 TeV
 - > ALICE, CMS, ATLAS (maybe LHCb?) experiments

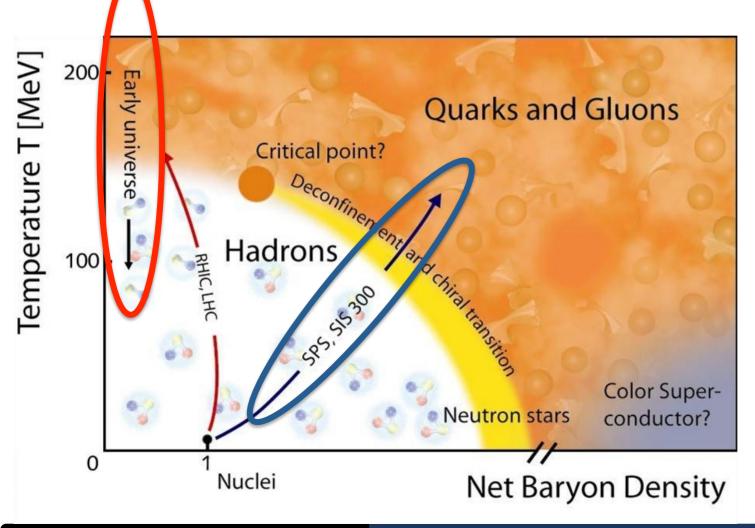






High- and Low-Energy Frontiers

The high-energy frontier: large and long-living QGP, large cross-sections for heavy-flavors. Vanishing net baryon density: Early Universe conditions

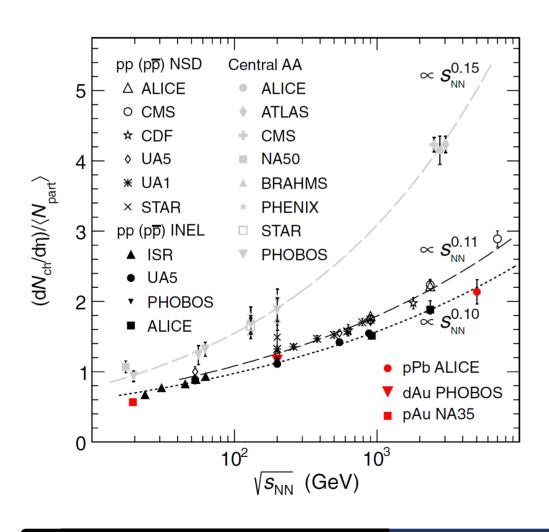


The low-energy frontier: focus on light-flavor observables.
Energy scan: search of the critical point and characterization of the phase transition



Counting Particles

First challenge to models: how many particles are produced in central A-A collisions?



- Particle multiplicity in pp, p-A and AA: well described by power-laws of the center-of-mass energy
- Dependence on sqrt(s) is stronger for AA collisions then for non-singlediffractive (NSD) pp
- sqrt(s) dependence is compatible for inelastic pp and p-A



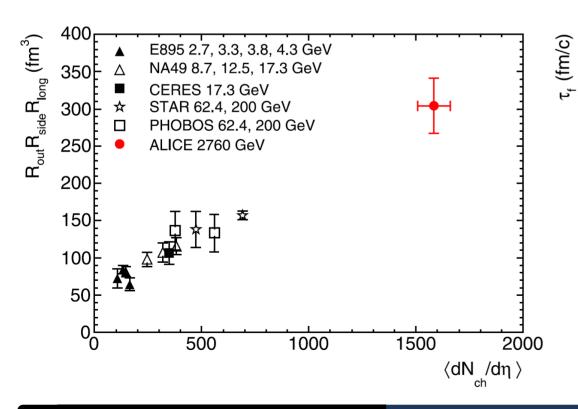
QGP Size and Temperature

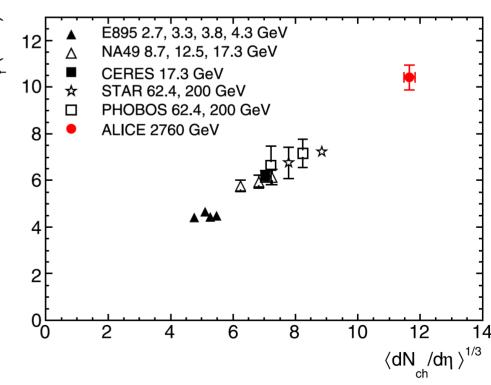
From identical boson interferometry:

- Freeze-out volume: LHC = RHIC × 2
- Lifetime (decoupling time): LHC = 40 % larger than RHIC

From direct photon measurements (not shown here):

ightharpoonup T = 304 ± 51 MeV: LHC = RHIC × 1.4



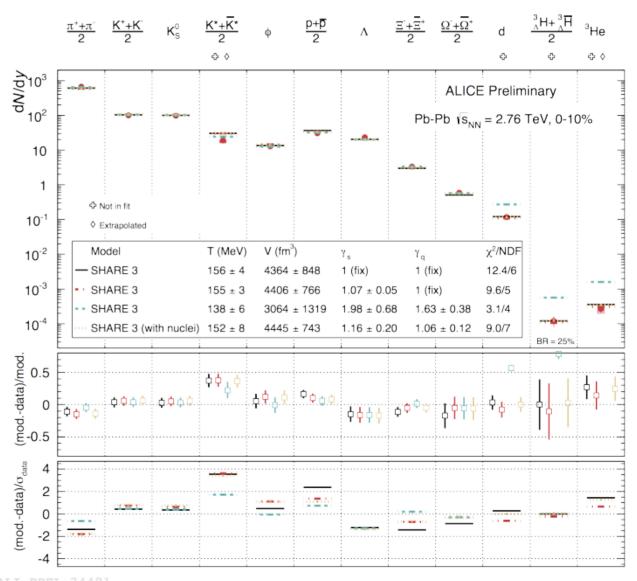




Hadron Yields: a Thermalized QGP?

Central heavy ion collisions are commonly regarded as the ideal system for the applicability of the thermal model

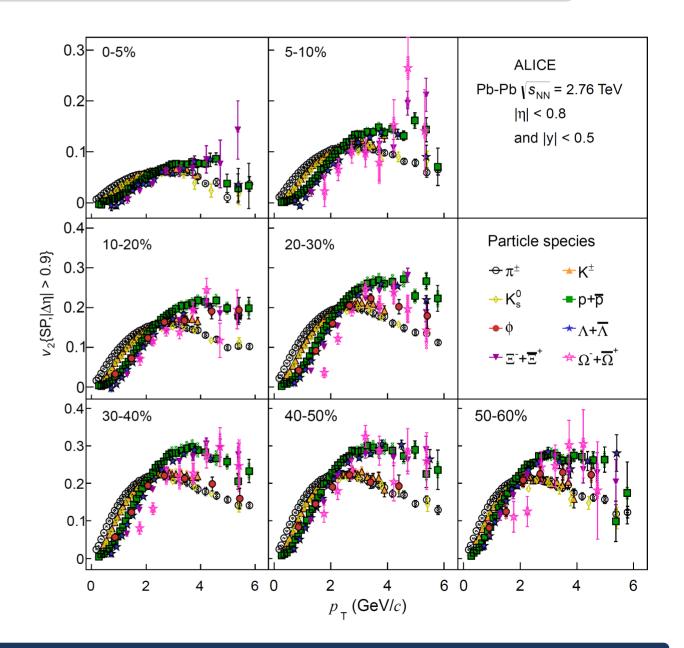
Fit of the ALICE data with an equilibrium model (SHARE)
 ⇒ χ²/ndf ≈ 2. Better than any other colliding system at the LHC, but still some tension with the data





Collective Phenomena: a Strongly-Coupled QGP?

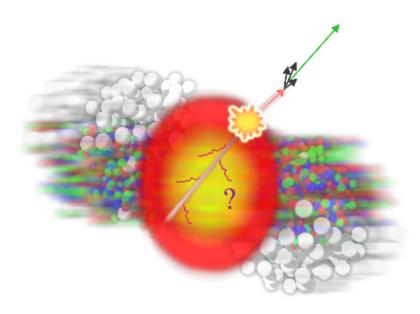
- ❖ The value of v₂ progressively increases from central to peripheral collisions up to the 40-50% centrality interval for all particle species
- This is consistent with the picture of the final state anisotropy driven by the geometry of the collision, as represented by the initial state eccentricity which increases for peripheral collisions

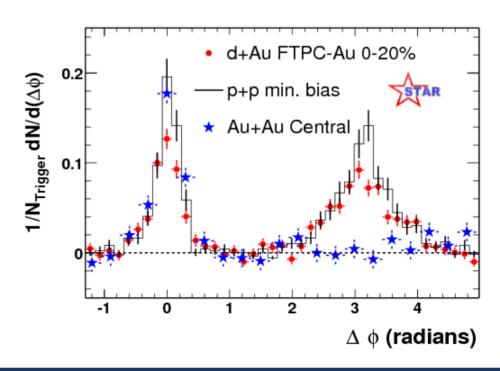




Jet Quenching: an Opaque QGP?

- When back-to-back jets of particles are produced inside the hot, dense medium produced by colliding heavy nuclei, one jet may be unable to escape the fireball
- How the jets propagate through the fireball, and how much quenching occurs, tells us a lot about the **properties of the hot matter generated in the collision**. Theory is challenged to understand this phenomenon quantitatively, using the tools of QCD

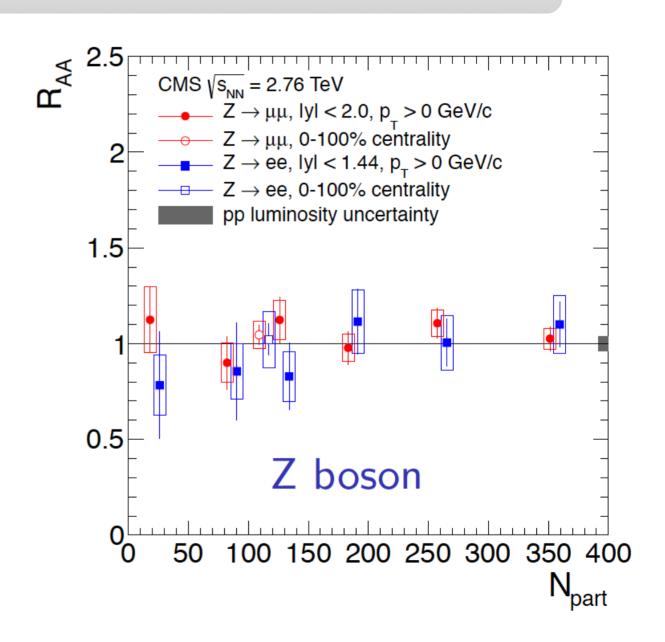






Electroweak Probes

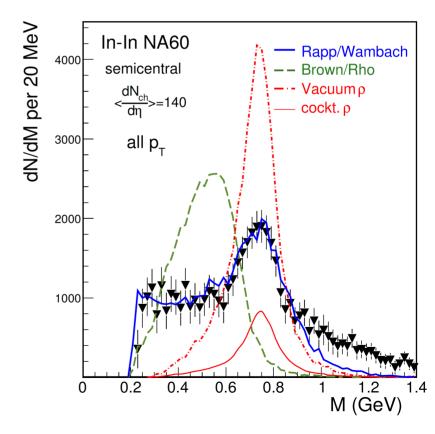
- Reference (control) probe:
 electroweak bosons are not
 affected by the strong color
 field dominating the
 deconfined medium
- Z bosons from CMS: no modification in the yield in Pb-Pb compared to pp, as expected
- No dependence on collision centrality





Electromagnetic Probes

- ❖ Golden probes to study the QCD phase transition (low-energy frontier) and its relations with the chiral symmetry restoration in the deconfined medium
- ❖ Dileptons (virtual photons) ⇒ no interactions with the hot medium, coupling with the light vector mesons
- Two more imminent (and relatively easier) objectives:
 - Describing medium modifications of the vector mesons spectral functions
 - Measure the dilepton radiation from the partonic phase (QGP) exploiting the double degree of freedom given by the mass and the p_T

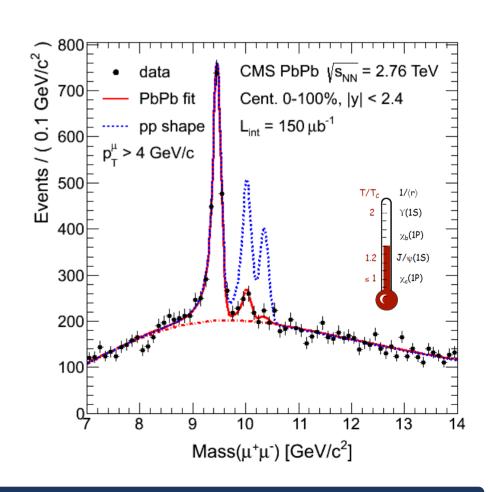




Quarkonium Suppression...

Heavy quark-antiquark bound states are called quarkonium

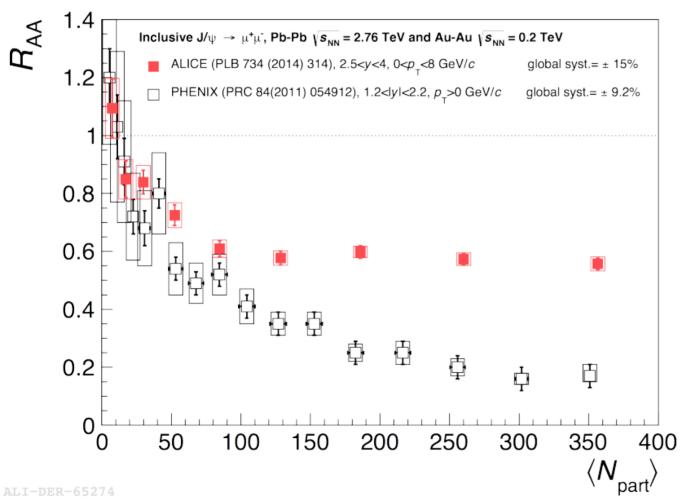
- The (meta-) stability of a quarkonium state in the vacuum is given by the specific quark-antiquark potential, shaped by the strong interaction
- But... the QGP is filled with free color charges (quarks and gluons)
 - In the QGP, the quarkonium potential is screened (equivalent to Debye screening for e.m. plasmas)
- If the screening radius drops below the quarkonium binding radius, the quarkonium should melt
- Screening radius decreases with temperature, therefore suppression of quarkonia in A-A w.r.t. p-p acts as a thermometer of QGP





.. and Recombination?

The higher the energy, the larger the charm production cross-section. Can we have recombination of dissociated cc pairs, at sufficiently large energies?



❖ PHENIX (RHIC top energy): vs ALICE (LHC Run1) ⇒ weaker centrality dependence and smaller suppression for central events

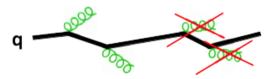


Is this the expected signature for (re)combination?
LHC Run 2 needed!



Heavy Flavors

- ♣ Large mass ($m_c \approx 1.5$ GeV, $m_b \approx 5$ GeV) \Rightarrow produced in large virtuality Q² processes at the initial stage of the collision with **short formation time** $\Delta t > 1/2m \approx 0.1$ fm << τ (QGP) $\approx 5-10$ fm/c. Insight on the short time scale of the collision
- **Charmed and beauty hadrons have a long life time** (cτ \approx 150-300 μm and cτ \approx 500 μm): information on the evolution of the deconfined medium
- Sensitivity to the density of the medium is provided by in-medium energy loss of heavy quarks ("Dead-cone" effect)



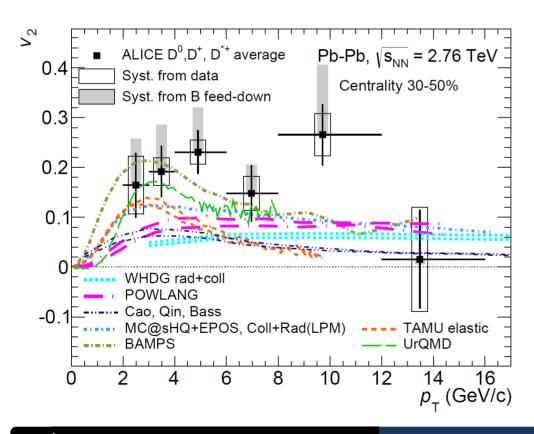
- Possible charm thermal production? \Rightarrow May increase the yield of charm hadrons at low p_T by up to 50-100%. Need to measure charm production down to $p_T = 0$
- **Measuring total charm and beauty cross section:** natural normalization for quarkonia production (main uncertainty for J/ψ regeneration models)

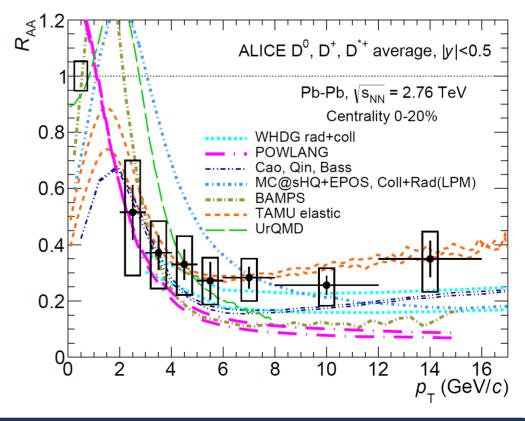
Antonio Uras



Heavy Flavors

- \diamond Simultaneous description of open charm R_{AA} and v_2 is a challenge for the models
- In general, the models that are best in describing R_{AA} tend to underestimate v_2 and the models that describe v_2 tend to underestimate the measured R_{AA} at high p_T
- Anisotropy description: charm quark energy loss in a geometrically anisotropic medium (+) mechanisms that transfer to charm quarks the elliptic flow induced during the system expansion







The SPS Heavy-Ion Program

