Quarkonia physics
in Heavy Ion Collisions

Hugo Pereira Da Costa
CEA/IRFU

Rencontres LHC France – Friday, April 5 2013

Contents

Introduction

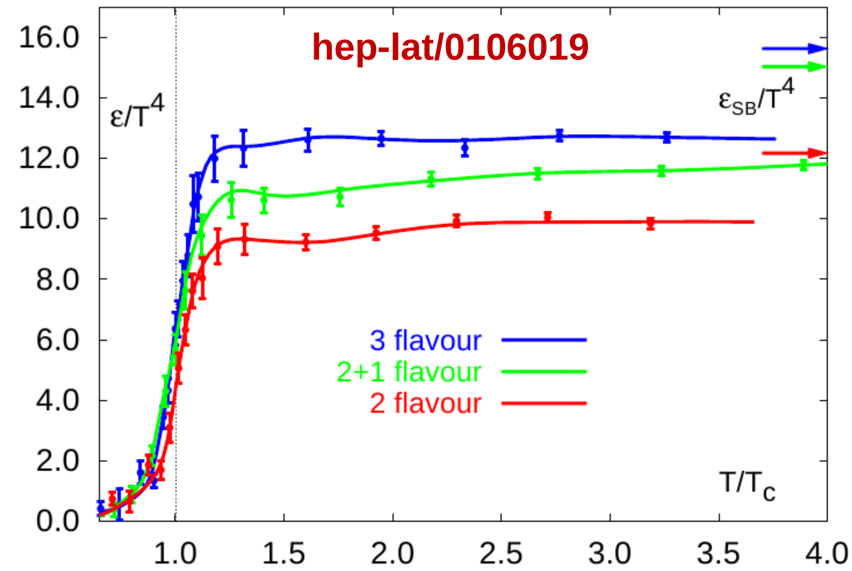
Quark Gluon Plasma

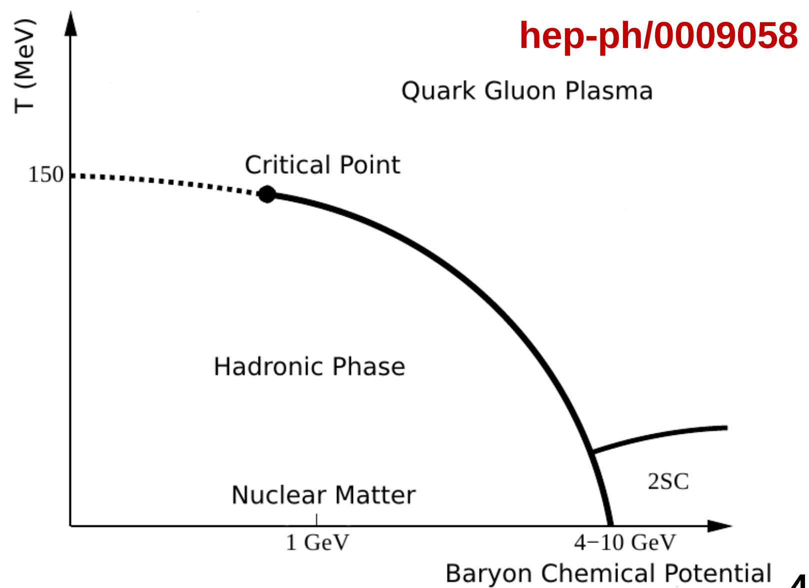
Deconfined state of quarks and gluons formed from ordinary nuclear matter provided that the temperature and energy density is high enough

This state is

- predicted by Latice QCD calculations
- should correspond to the first moments of the universe ~1μs after the Big Bang
- can be studied in the laboratory, by colliding relastivistic heavy ions

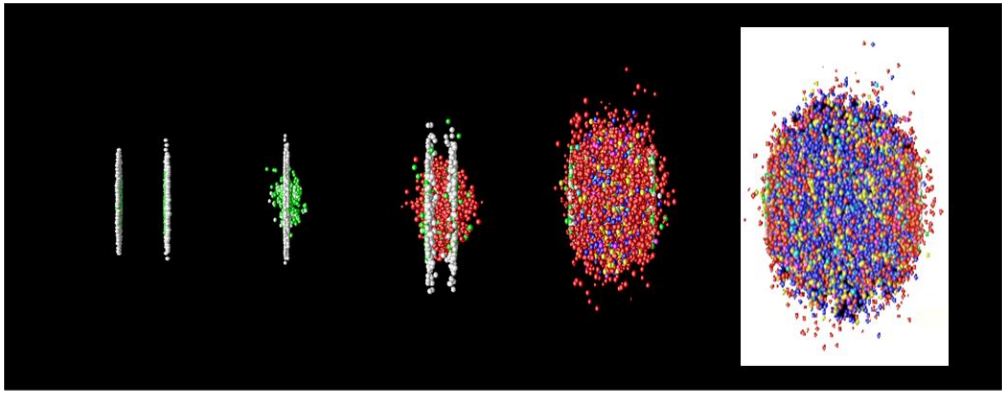
Critical temperature: $T_c \approx 150$ MeV
Energy density: $\varepsilon_c \approx 1$ GeV/fm^3





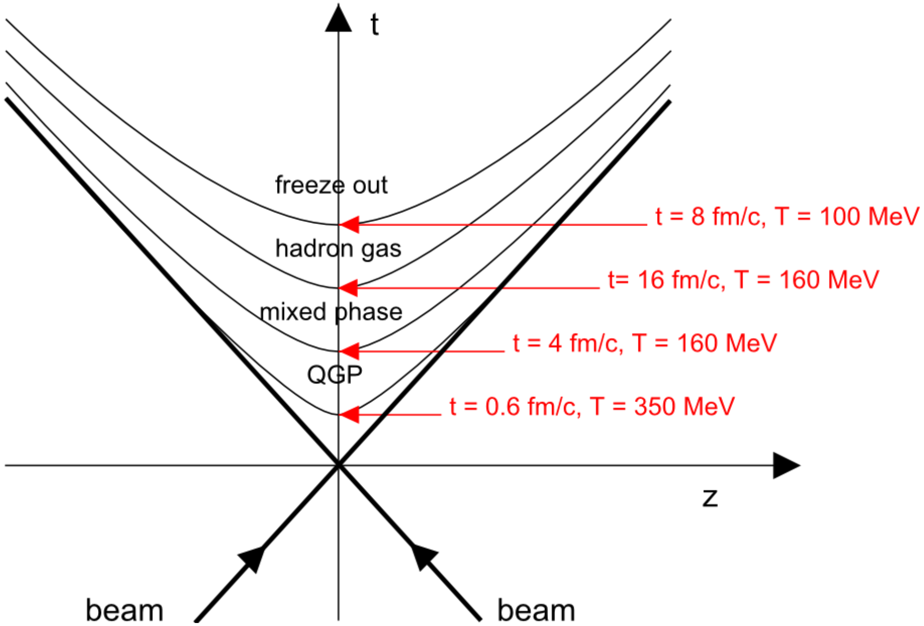
Heavy Ion Collisions

- Pre-equilibrium
- Quark Gluon Plasma
- Hadron gaz
- Free hadrons



Hard probes

- are produced at the early stage of the collision, before the formation of a QGP, via the hard scattering of partons.
- travel through the formed medium and some are affected by it.

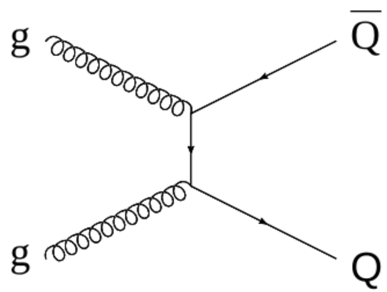


Heavy Quarkonia

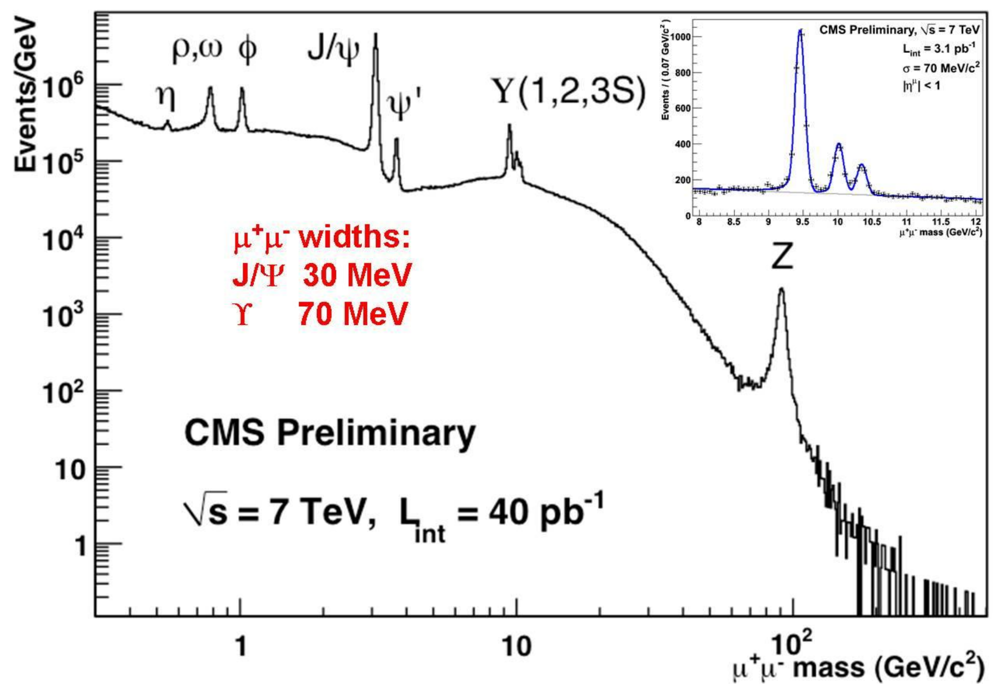
Bound states of charm quarks (J/ψ, ψ' and χ_c) and beauty quarks (ϒ 1S, 2S and 3S) that are stable for the strong interaction.

	Mass (GeV)	Radius (fm)
J/ψ	3.1	0.50
χ_c	3.53	0.72
ψ'	3.68	0.90
ϒ 1S	9.5	0.28

Due to their high mass, they are (predominantly) produced at the early stage of the collision via the hard scattering of gluons:



They can be *easily* measured, via their decay into two leptons.



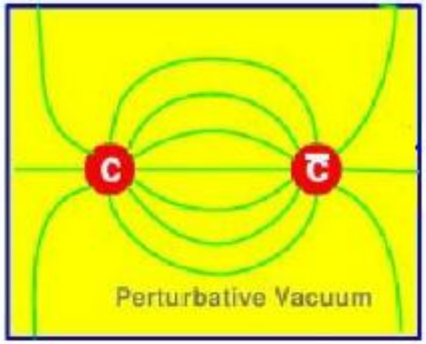
Color Screening and Sequential Suppression

In presence of a QGP, the binding potential of the QQbar pair is screened by the surrounding color charges, at distances $r > r_D$.

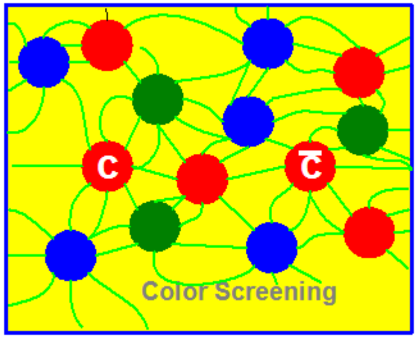
If r_D is smaller than the bound state radius, the latter cannot be formed.

One defines a dissociation temperature T_D, above which the bound state is suppressed.

In vacuum



In QGP



Dissociation temperature for heavy quarkonia bound states:

Bound State	J/ψ	χ_c	Ψ'	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
T_D/T_c	1.10	0.74	0.2	2.31	1.10	0.75

hep-ph/0106017

Complication:

The above is valid for bound states formed directly. A fraction of them comes from the decay of heavier excited states or from heavier mesons (Bs).
For instance:
~ 10% of measured J/ψ should come from ψ'
~ 30% of measured J/ψ should come from χ_c

Recombination from Uncorrelated QQbar Pairs

There are 10 to 20 ccbar pairs in central Au+Au collisions @ $\sqrt{s_{NN}}$ = 200 GeV
And ~10x more at LHC energy

<u>Statistical Coalescence Model</u>:

All ccbar pairs produced early via hard scattering
There is no J/ψ in the QGP (due to screening). It is formed at phase boundary via statistical recombination of uncorrelated c and cbar.
Similar approach to what is applied to light quarks and light/strange hadrons, to reproduce, for instance, particle ratios in the final state

nucl-th/0303036

<u>Transport Model</u>:

Assumes screening of primary J/ψ
Detailed balance between J/ψ and ccbar pairs during the QGP evolution

hep-ph/0306077, hep-ph/0504226, nucl-th/0608010

$$J/\Psi + g \leftrightarrow c\,\bar{c}$$

In all cases, the number of *recombined* J/ψ is proportional to N_c^2
It is therefore crucial to measure the ccbar production cross-section

Cold Nuclear Matter Effects

Everything that can alter the production of quarkonia in heavy ion collisions with respect to p+p collisions, in absence of a QGP.
One must measure and subtract such effects in order to evidence the effects of the QGP.

- Gluon shadowing, or saturation, at small x

- Initial state parton energy loss and p_T broadening:
  In medium gluon radiation of the incoming gluons and ccbar quarks before forming the bound state

- Nuclear *absorption*: breakup of the quarkonia (or precursors) by interaction with surrounding nucleons

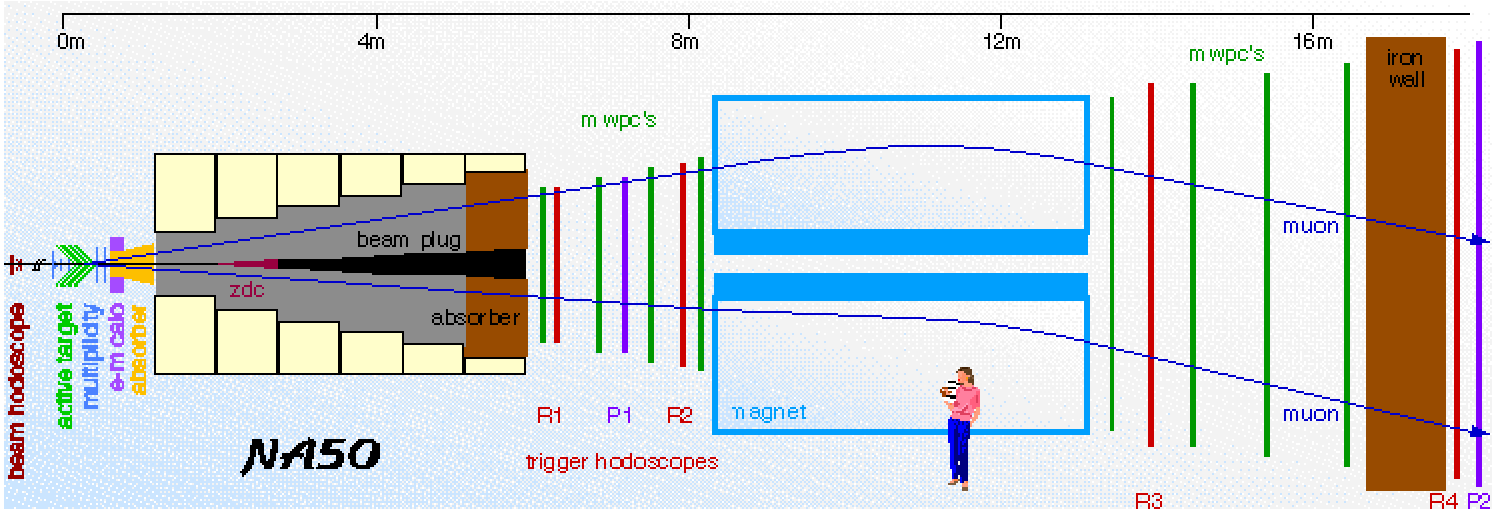
Quarkonia at the SPS

Context

Several experiments using proton and heavy ion beams from the SPS, at CERN on fixed target: NA38, NA50, NA51 and NA60

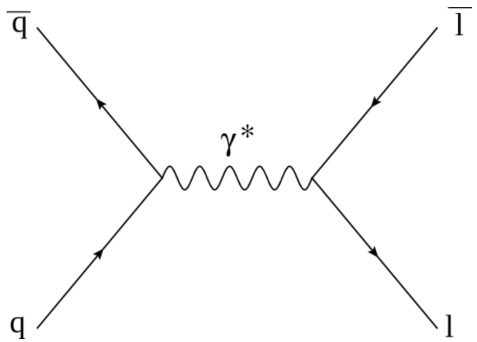
Colliding species: p+p, p+A, S+U, Pb+Pb, In+In

Colliding Energy: $\sqrt{s_{NN}} \approx 20$ GeV



J/ψ / Drell-Yan Ratio

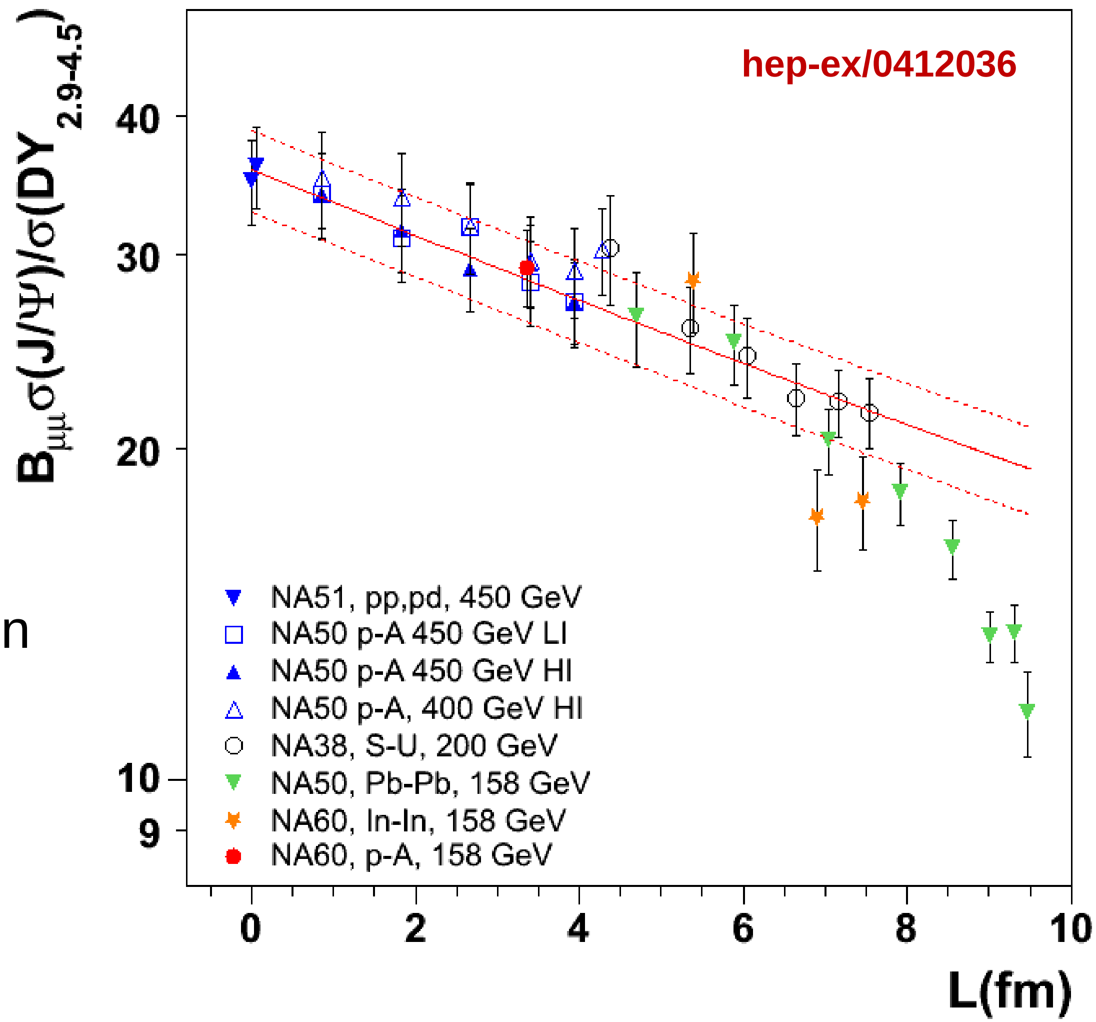
Drell-Yan:



L: path length in medium

Straight lines: nuclear absorption

$$S_{pA}^{J/\Psi} = e^{-\rho L \sigma_{breakup}}$$



At large L: *anomalous* suppression is observed, attributed to the formation of a QGP

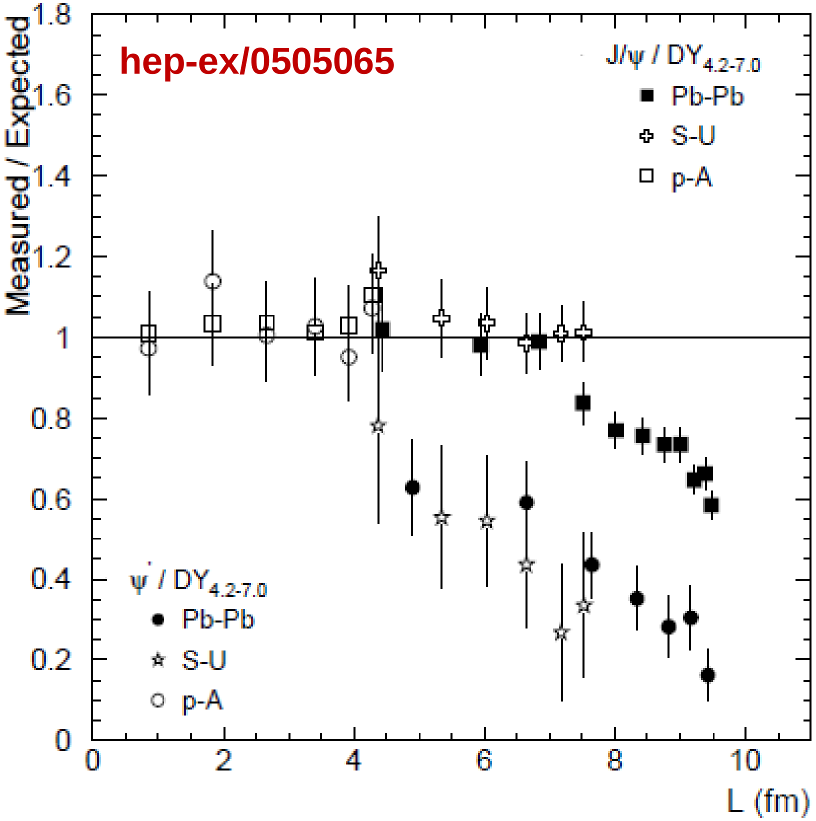
Survival probability for J/ψ and ψ’

Ratio of J/ψ and ψ’ over Drell-Yan, normalized to cold nuclear matter effect.

A similar suppression pattern is observed for ψ’ and J/ψ, but starting at smaller L for the ψ’

This is consistent with sequential suppression.

Recalling that about 40% of the measured J/ψ are from χ_c and ψ’ decay, this observation is consistent with no suppression of *direct* J/ψ



Quarkonia at RHIC

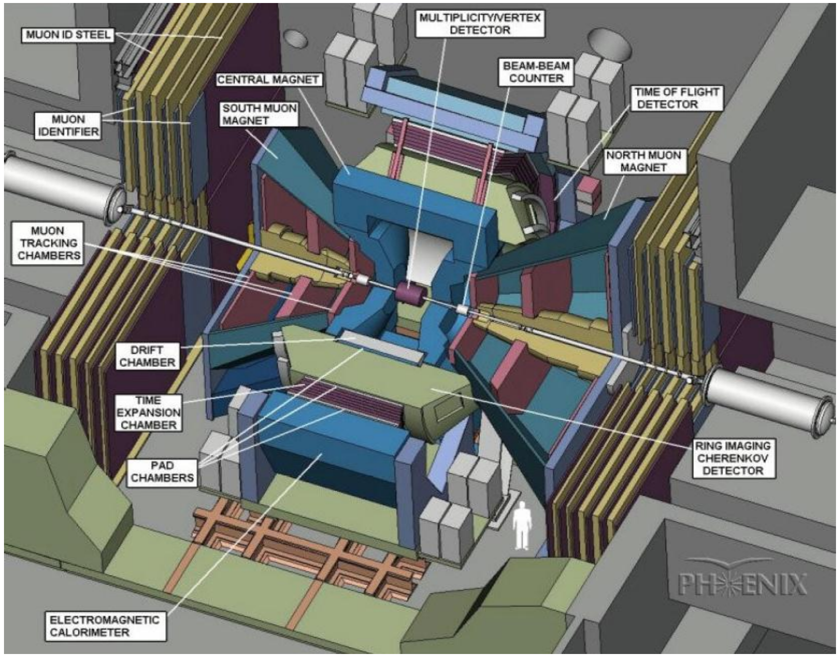
Context

Two collider experiments at RHIC (Brookhaven National Laboratory): PHENIX and STAR

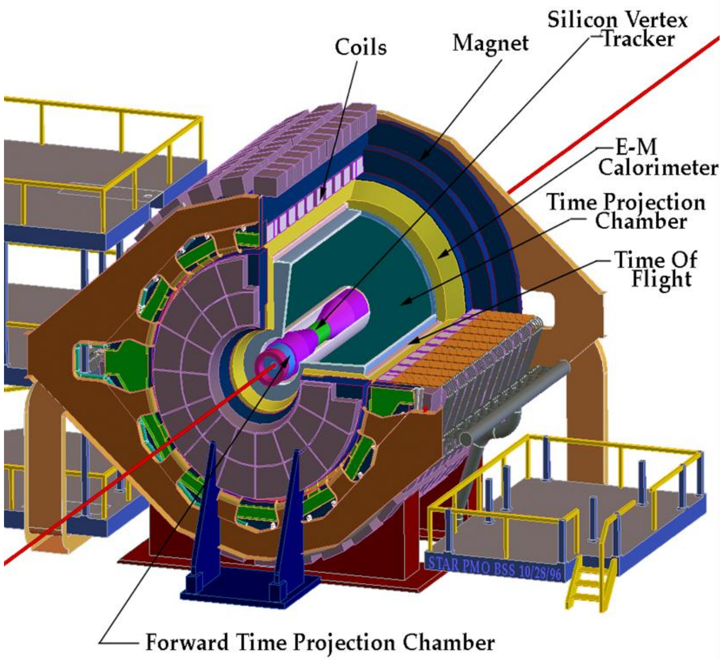
Colliding species: p+p, d+Au, Au+Au

Collision Energy: $\sqrt{s_{NN}}$ = 200 GeV (10 x SPS)

PHENIX



STAR



J/ψ Nuclear Modification Factor in Au+Au (1)

Nuclear Modification Factor:

$$R_{AA}^{J/\Psi} = \frac{\sigma_{A+A}^{J/\Psi}}{N_{coll} . \sigma_{p+p}^{J/\Psi}}$$

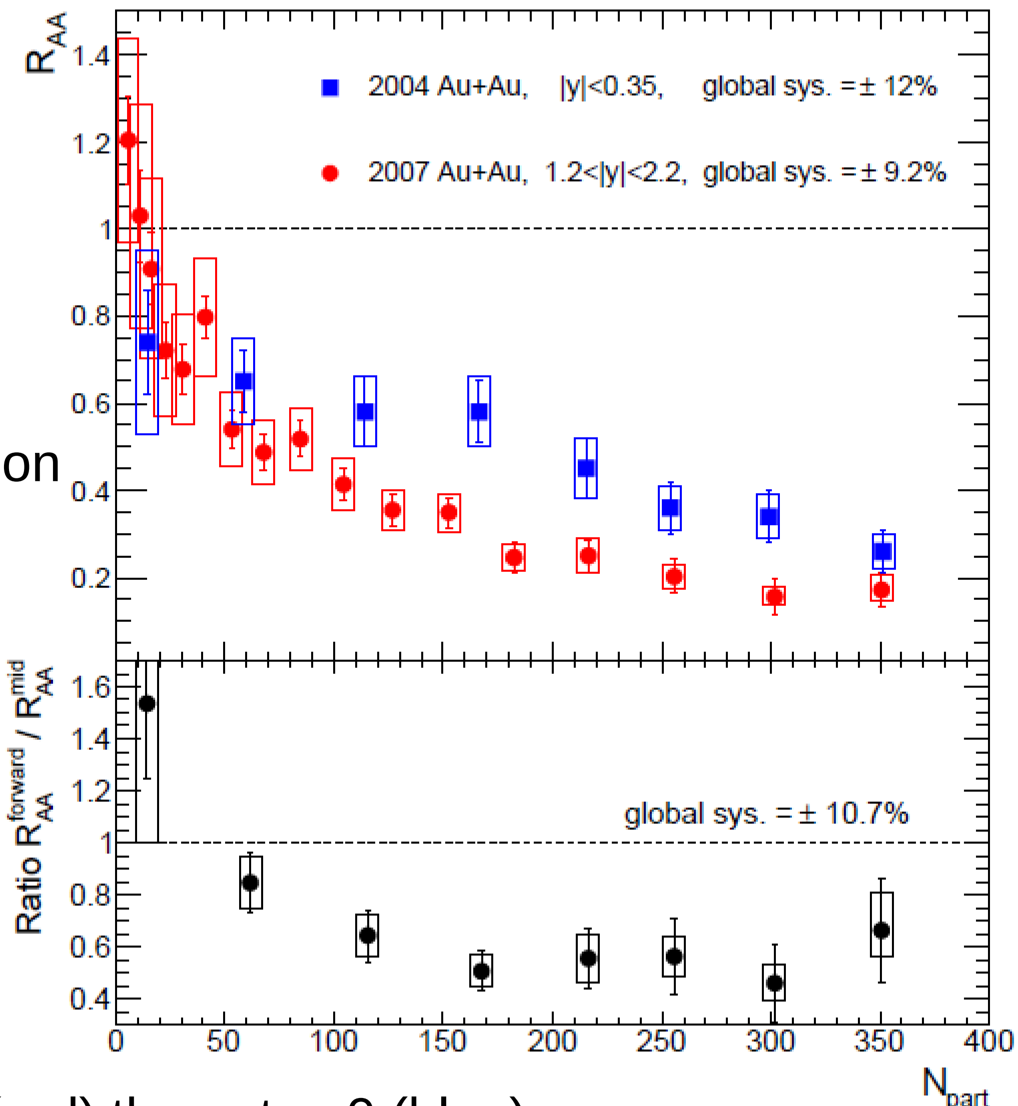
N_{coll}: number of nucleon-nucleon collisions equivalent to one HI collision

N_{part}: number of nucleons that participate to the HI collision

Little to no suppression observed for *peripheral* collisions (small N_{part})

Large suppression is observed for *central* collisions (large N_{part})

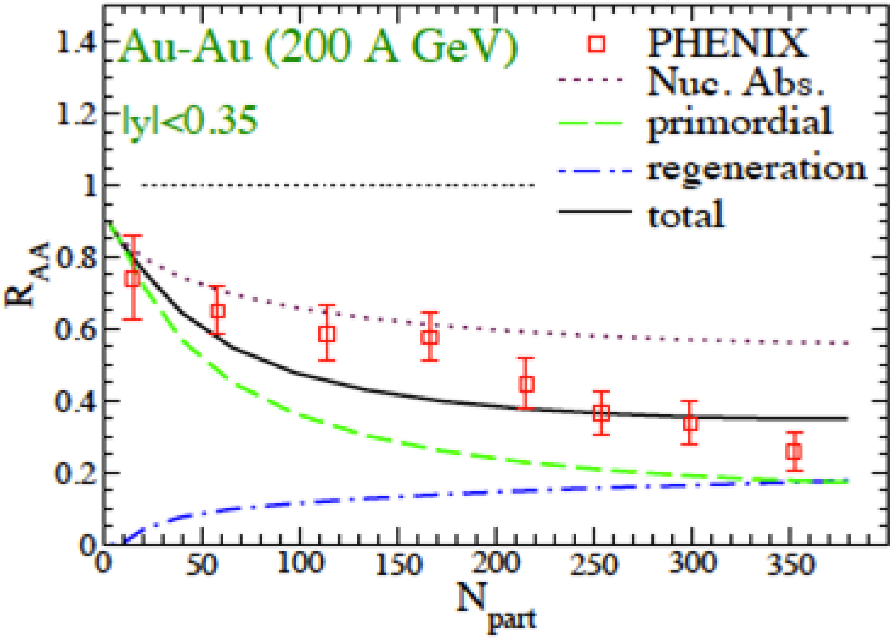
nucl-ex:1103.6269

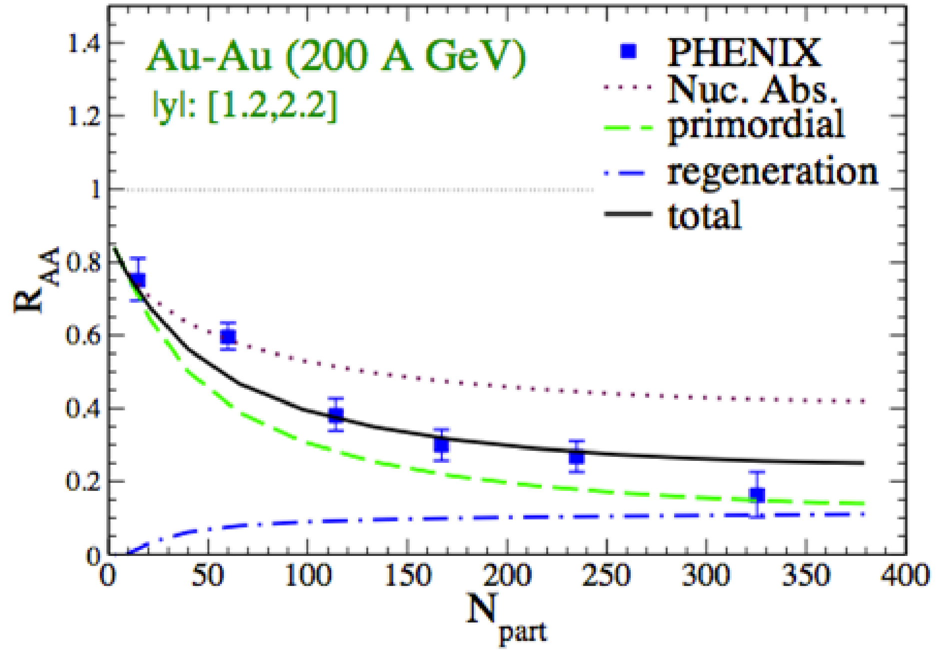


More suppression observed at y>0 (red) than at y=0 (blue)

J/ψ Nuclear Modification Factor in Au+Au (2)

nucl-ex/1103.6269



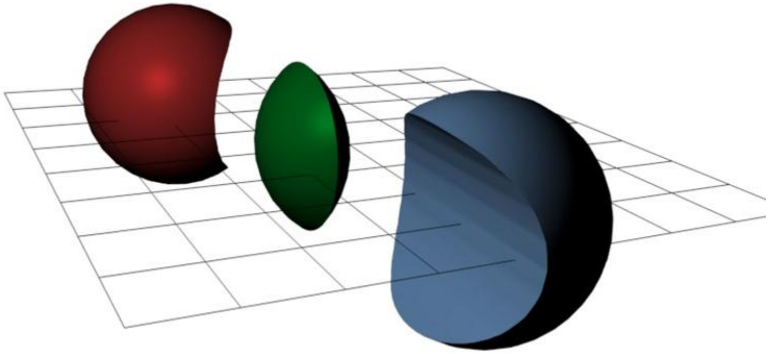


Model includes:

- Cold nuclear matter effects (shadowing and absorption cross-section). Accounts for most of the difference between y>0 and y=0, and at least half the suppression observed in central collisions
- Suppression by color screening
- Regeneration from uncorrelated charm quarks, in medium (mostly at low p_T)

J/ψ Elliptic Flow in Au+Au Collisions (1)

The elliptic flow parameter v_2 characterizes the azimuthal anisotropy of particle emission with respect to the collision's reaction plane.



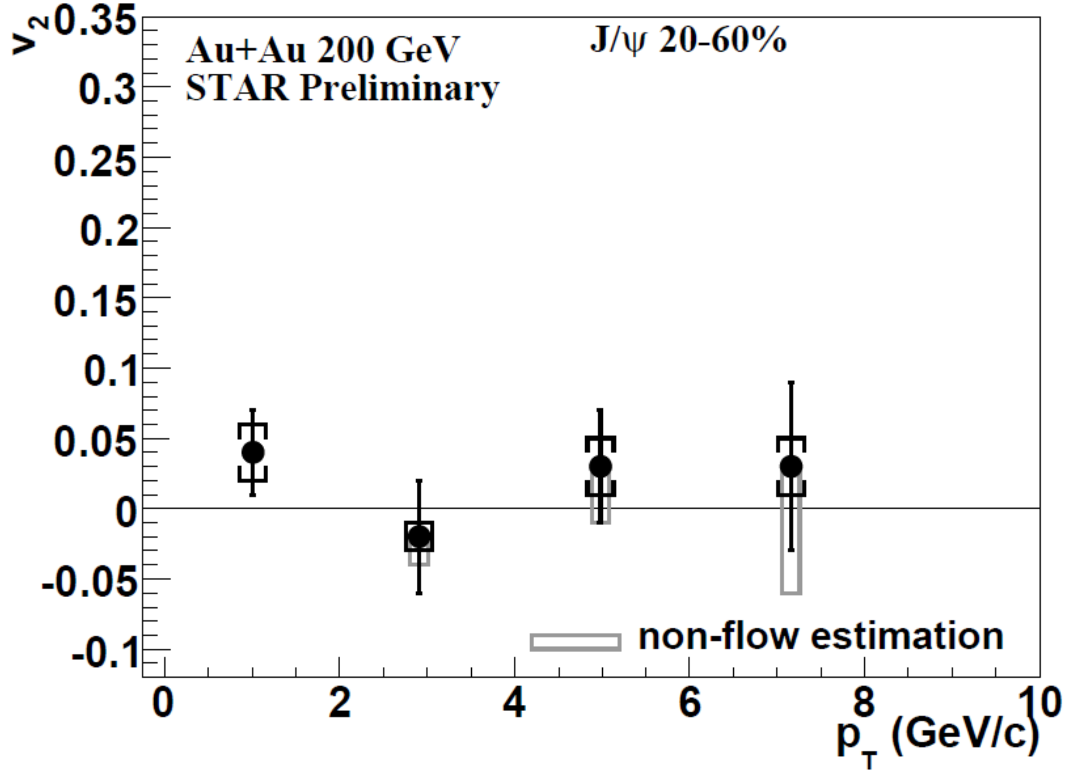
Non zero v_2 has been measured for light and heavy mesons, attributed to an early thermalization (in QGP) of their constituting quarks, and to the presence of pressure gradients in the overlapping region between the two nuclei.

Measuring the J/ψ elliptic flow has been proposed to single out J/ψ coming from the recombination of uncorrelated + thermalized charm quarks, as opposed to primary J/ψ, for which one expects $v_2 \sim 0$

J/ψ Elliptic Flow in Au+Au Collisions (2)

Elliptic flow is consistent with zero in the full pT range.

This is attributed to the fact that J/ψ produced at RHIC by recombination have too small a p_T and correspond to charm quarks for which v_2=0



(J/ψ v_2 also measured at PHENIX, but with larger uncertainties)

Outlook: Quarkonia at the LHC

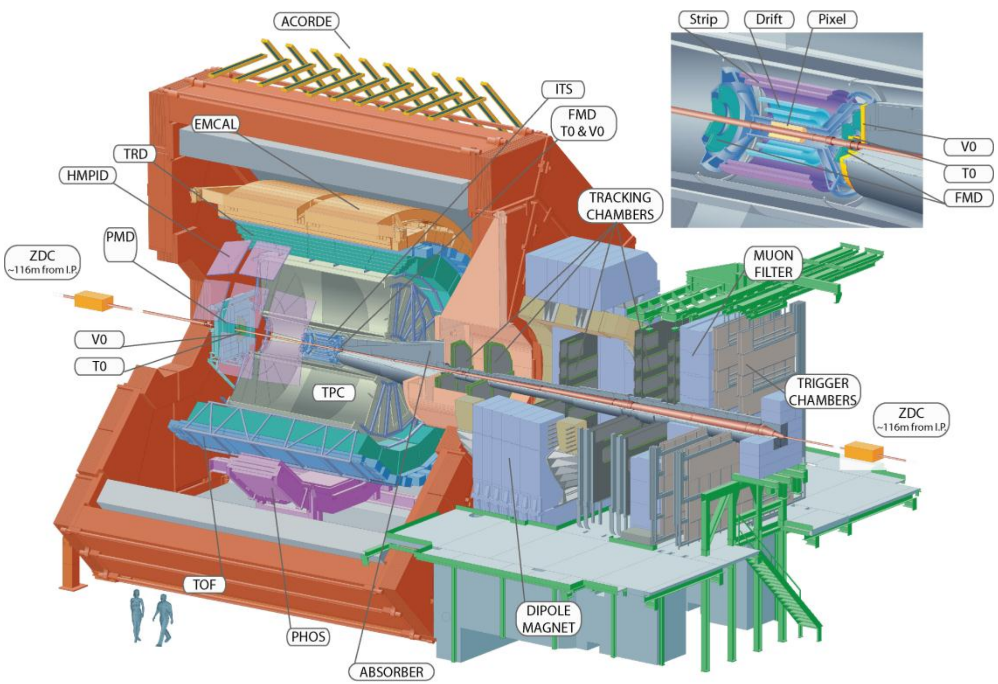
Context

Four experiments on the LHC at CERN: ALICE, ATLAS, CMS and LHCb

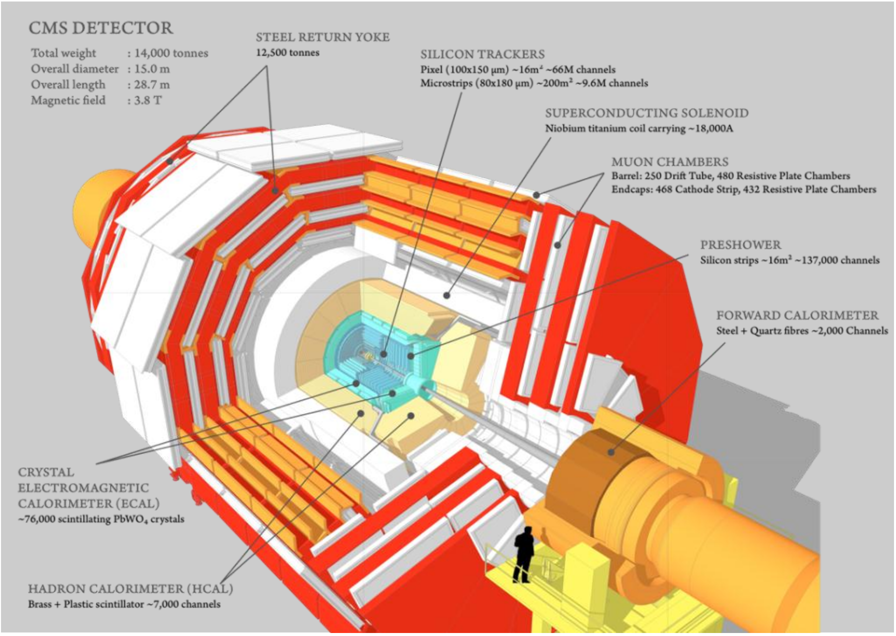
Colliding species: p+p, p+Pb (and Pb+p), Pb+Pb

Collision Energy: $\sqrt{s_{NN}}$ = 2.76 TeV (14 x RHIC)

ALICE



CMS



Differences with respect to past experiments

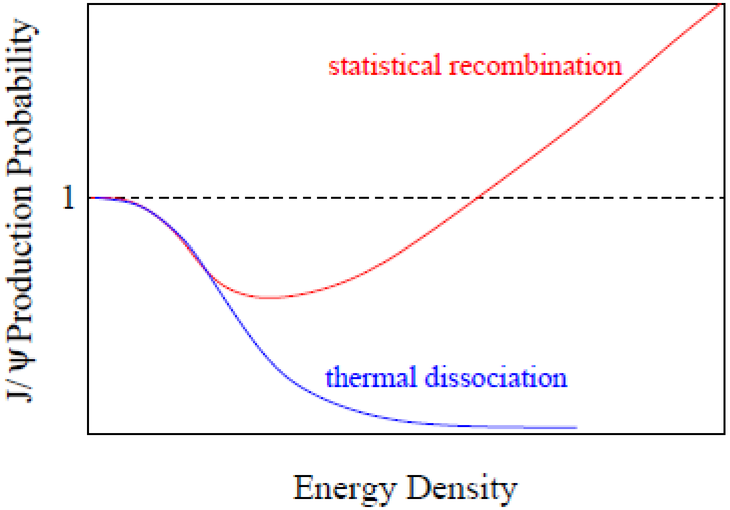
J/ψ resonances are more abundant → precise measurements
Possibility to also study ψ’ in more details
Upsilon resonances become accessible (with high enough statistics)

Cold nuclear matter effects:
There should be no nuclear absorption/break-up
To be confirmed when results from p-Pb run become available
Gluons shadowing/saturation are probed in different x, Q^2 regime

QGP effects:

Higher temperature: smaller screening radius
More heavy quarks → more J/ψ produced by recombination, and at larger p_T
see talk by Massimiliano

Possible sizeable J/ψ elliptic flow v_2
see talk by Laure



More resonances are accessible
→ further test sequential suppression, notably in Upsilon sector
see talk by Nicolas

Afterwords

There are two talks in this session which I have not introduced:

Ultra Peripheral Collisions in ALICE (by Daniel)

Look at J/psi produced by the diffraction of a (virtual) photon on gluons from the target nuclei, for collisions with large impact parameter.
Unaffected by QGP
Provides information about gluon distribution functions in the Nucleon/Nucleus

Light Di-muon Resonances in ALICE (by Antonio)

Look at the production of low mass vector mesons (ρ, φ and ω) in the di-muon channel, at forward rapidity.
Provides information on the QGP via the study of in medium modifications of these resonances due to (for instance) chiral symmetry restoration