Round Table: Heavy flavor suppression and transport properties

chairs:	Nora Brambilla
members:	Yukinao Akamatsu; Miguel A. Escobedo; Seyong Kim; Antonio Vairo; Zebo Tang and Livio Bianchi.

Experimental questions I

What have we learned about the quark-gluon plasma from heavy flavor observables?

Speaker: Zebo Tang

Experimental questions

How has the situation changed from RHIC to LHC? How will it change from LHC Run1 to Run2? Can we compare in two different kinematical regions?

Speaker: Zebo Tang

1. What have we learned about the quark-gluon plasma from heavy flavor observables.

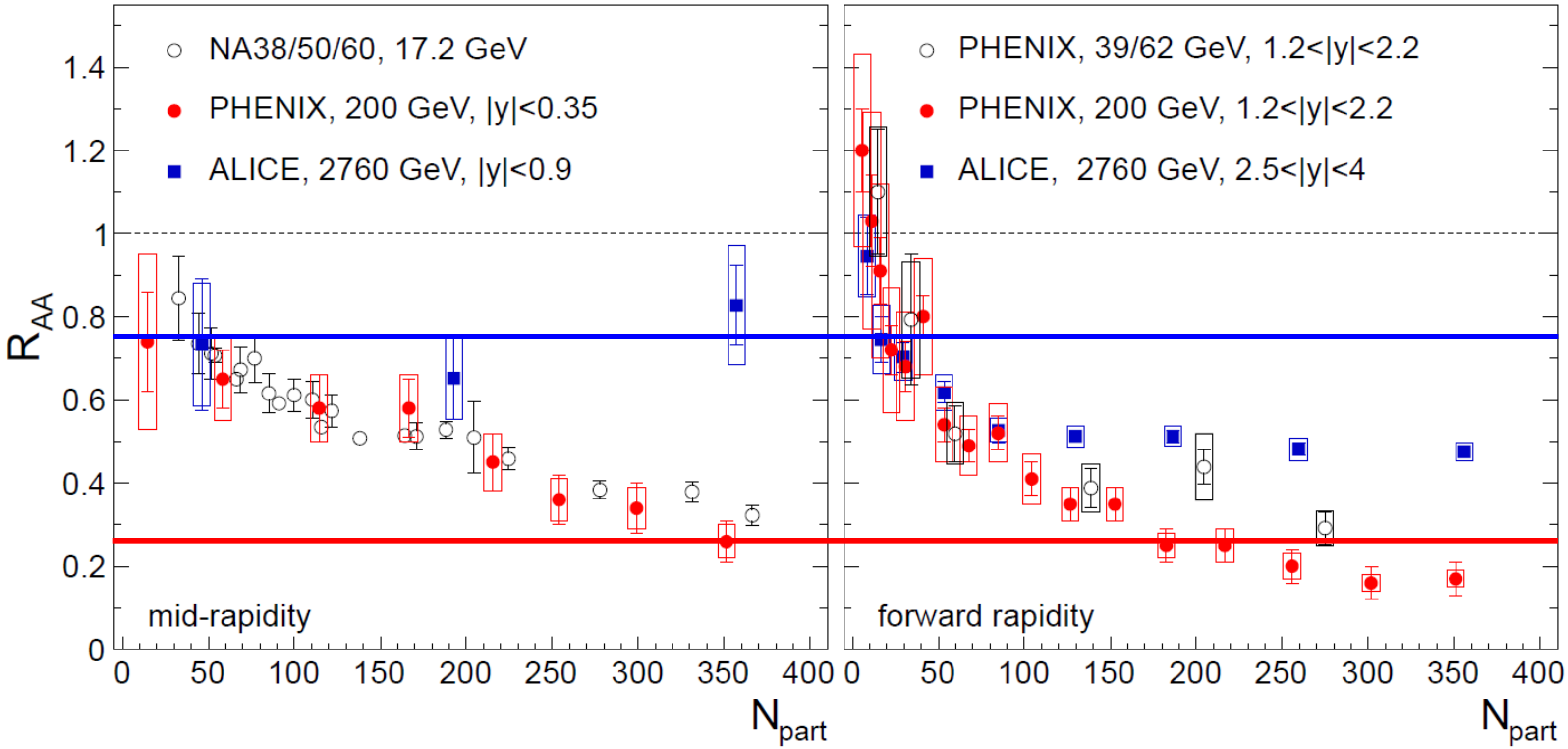
2. How has the situation changed from RHIC to LHC? How will it change from LHC Run1 to Run2? Can we compare in two different kinematical regions?

Zebo Tang (唐泽波)

Department of Modern Physics

University of Science and Technology of China (USTC)

Heavy Flavor is the most direct probe of "free quarks" in QGP

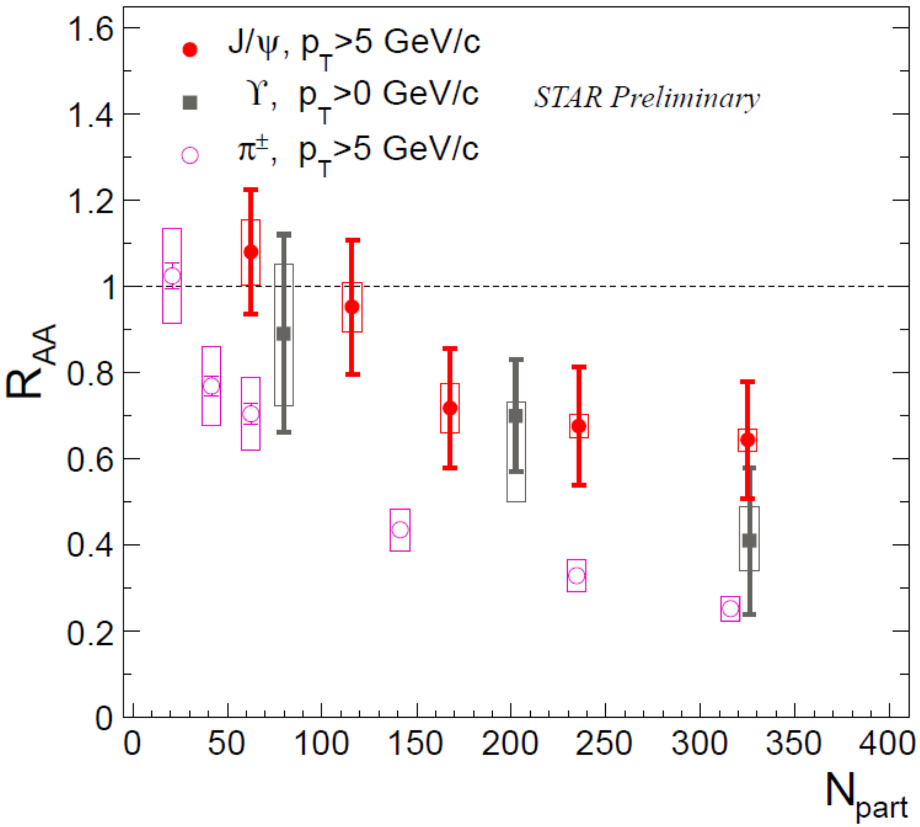


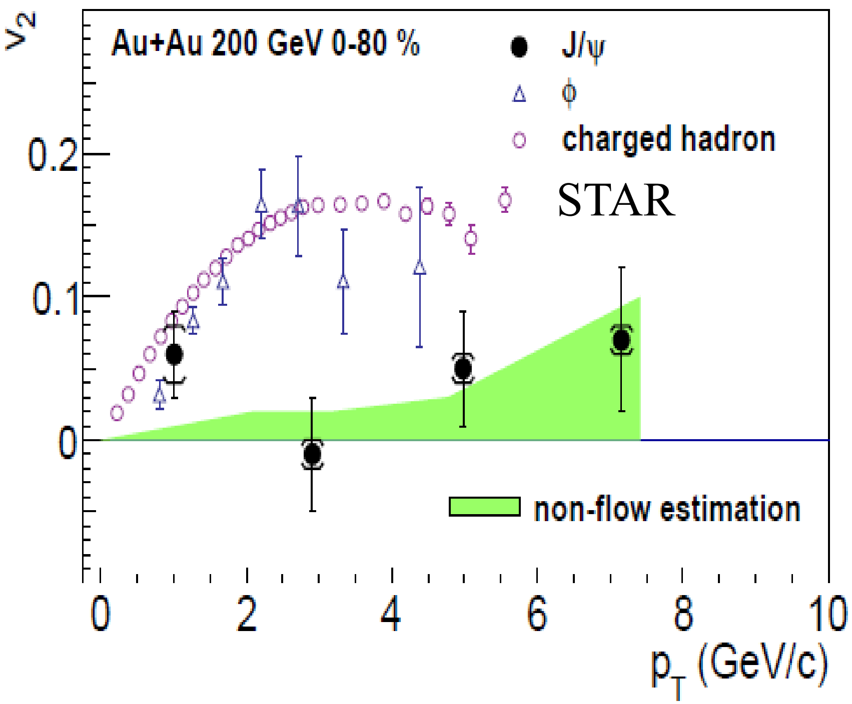
SPS→RHIC: similar, RHIC→LHC: significant increase

Stronger suppression at forward-rapidity

} **Recombination /Regeneration**

1. What have we learned about the quark-gluon plasma from heavy flavor observables.



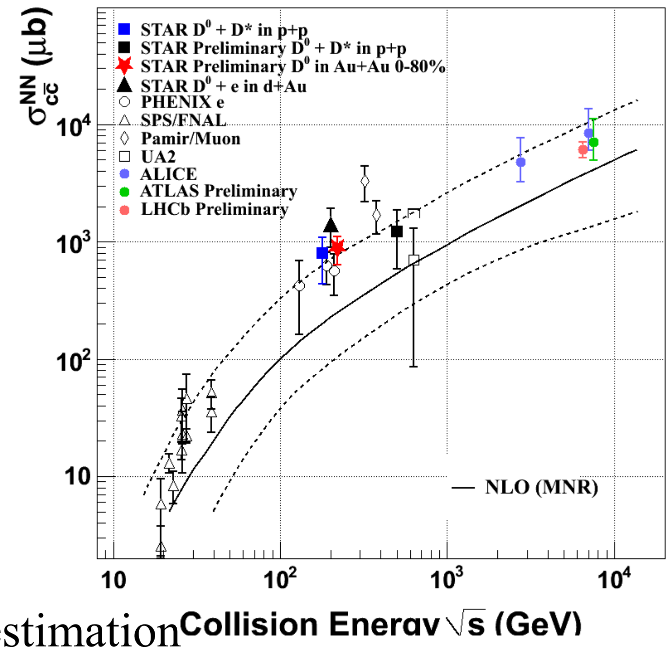


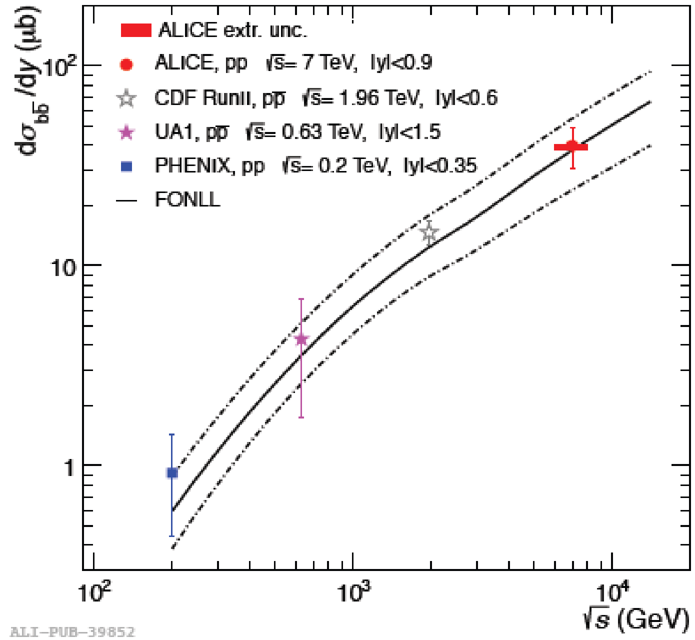
Cleaner Probes, consistent with Color-screening effect

J/ψ R_{AA} and v_2 very different from other hadrons

Empirically, J/ψ is the only measured hadron at RHIC with significant suppression in R_{AA}, but no elliptic flow and radial flow

2. How has the situation changed from RHIC to LHC? How will it change from LHC Run1 to Run2? Can we compare in two different kinematical regions?





Rough estimation

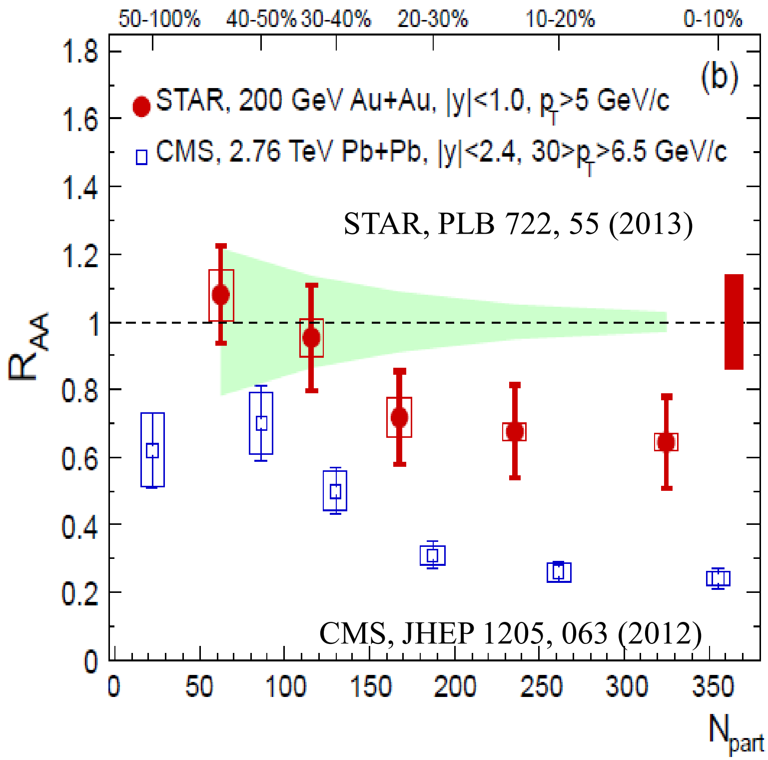
	$\sqrt{s_{NN}}$ (TeV)	$c\bar{c}$ (pairs)	(J/ψ) / $c\bar{c}$	$b\bar{b}$(pairs)	$\Upsilon/b\bar{b}$
Au+Au	0.2	15	~1%	0.1	~0.3%
Pb+Pb	2.76	60		2	
Pb+Pb	5	120		4	

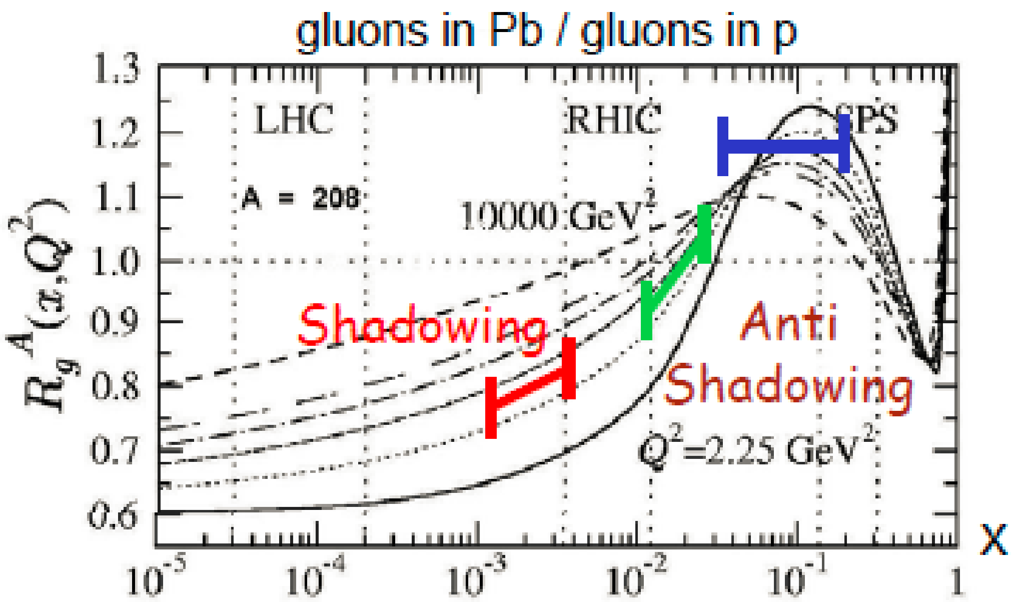
Regeneration contribution: Increase with collision energy.

For Low-p_T J/ψ RHIC: significant vs. LHC: dominant

For Upsilon RHIC: negligible vs. LHC: likely to be similar to J/ψ at RHIC

2. How has the situation changed from RHIC to LHC? How will it change from LHC Run1 to Run2? Can we compare in two different kinematical regions?





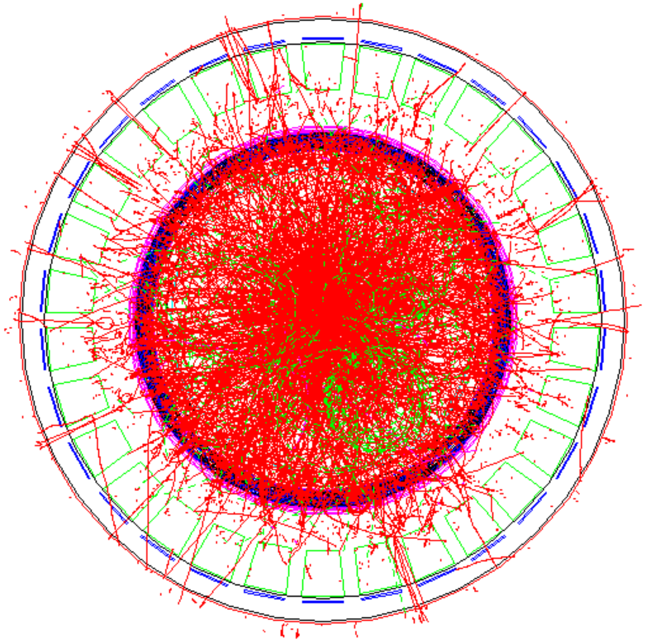
Shadowing effect could play an important role at LHC.

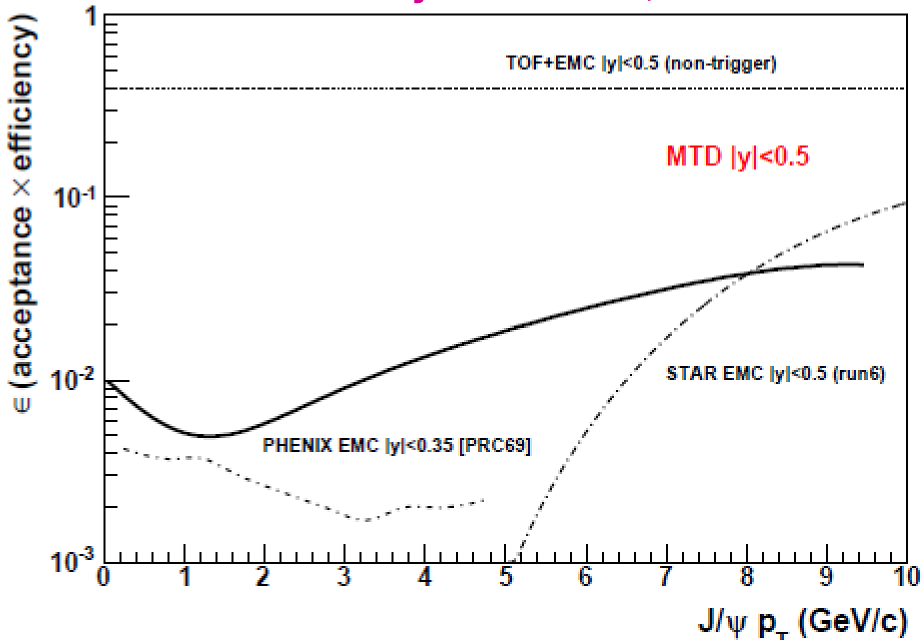
RHIC with MTD (large area muon detector at mid-rapidity, p_T>1.5-2 GeV/c):

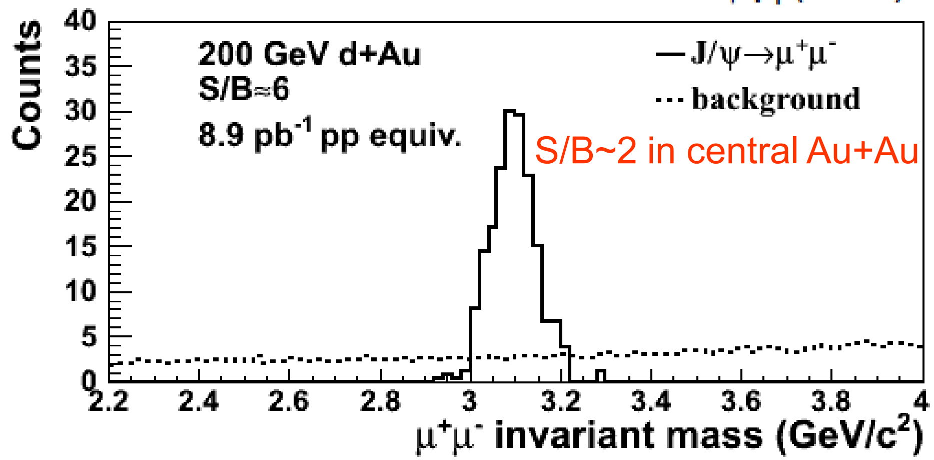
Detail study of J/ψ v_2, spectra and Upsilons states suppression

Muon Telescope Detector (MTD)

Lijuan Ruan, QM2011







Advantages over electrons

no γ conversion

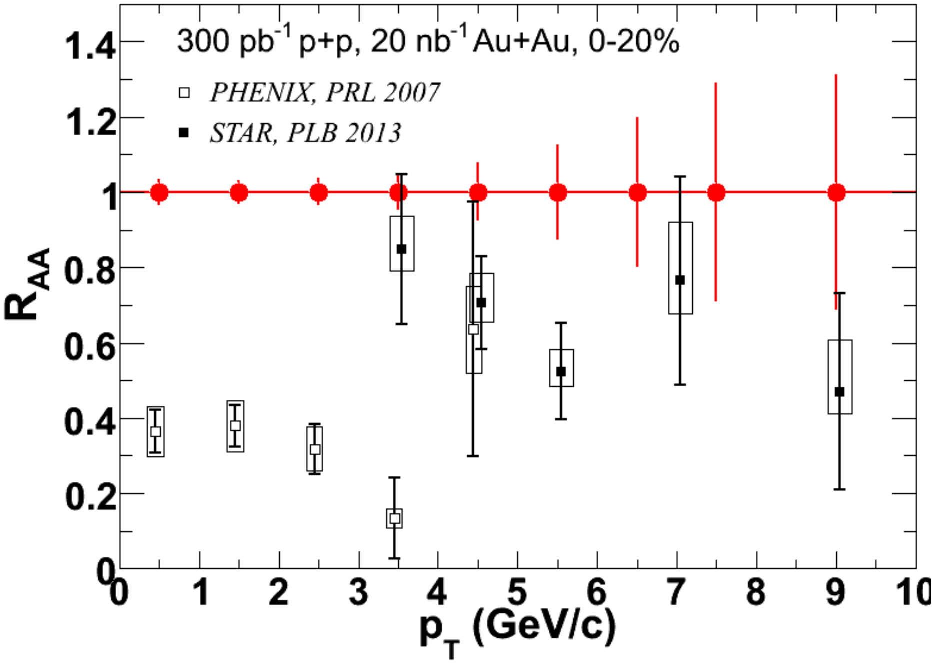
much less Dalitz decay contribution

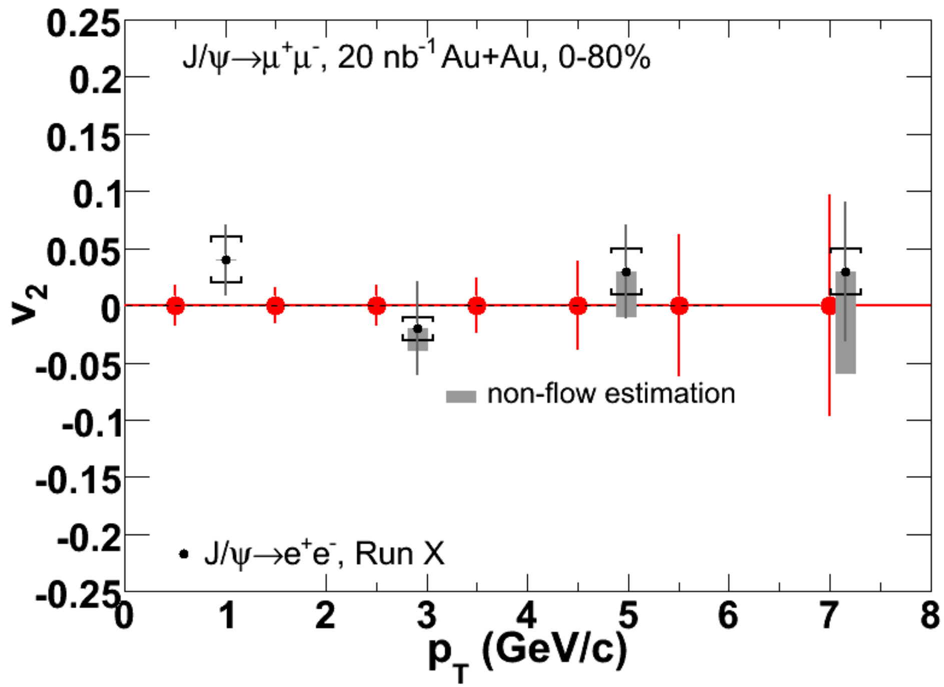
less affected by radiative losses in the materials

Trigger capability for low to high p_T J/ψ in central Au+Au collisions

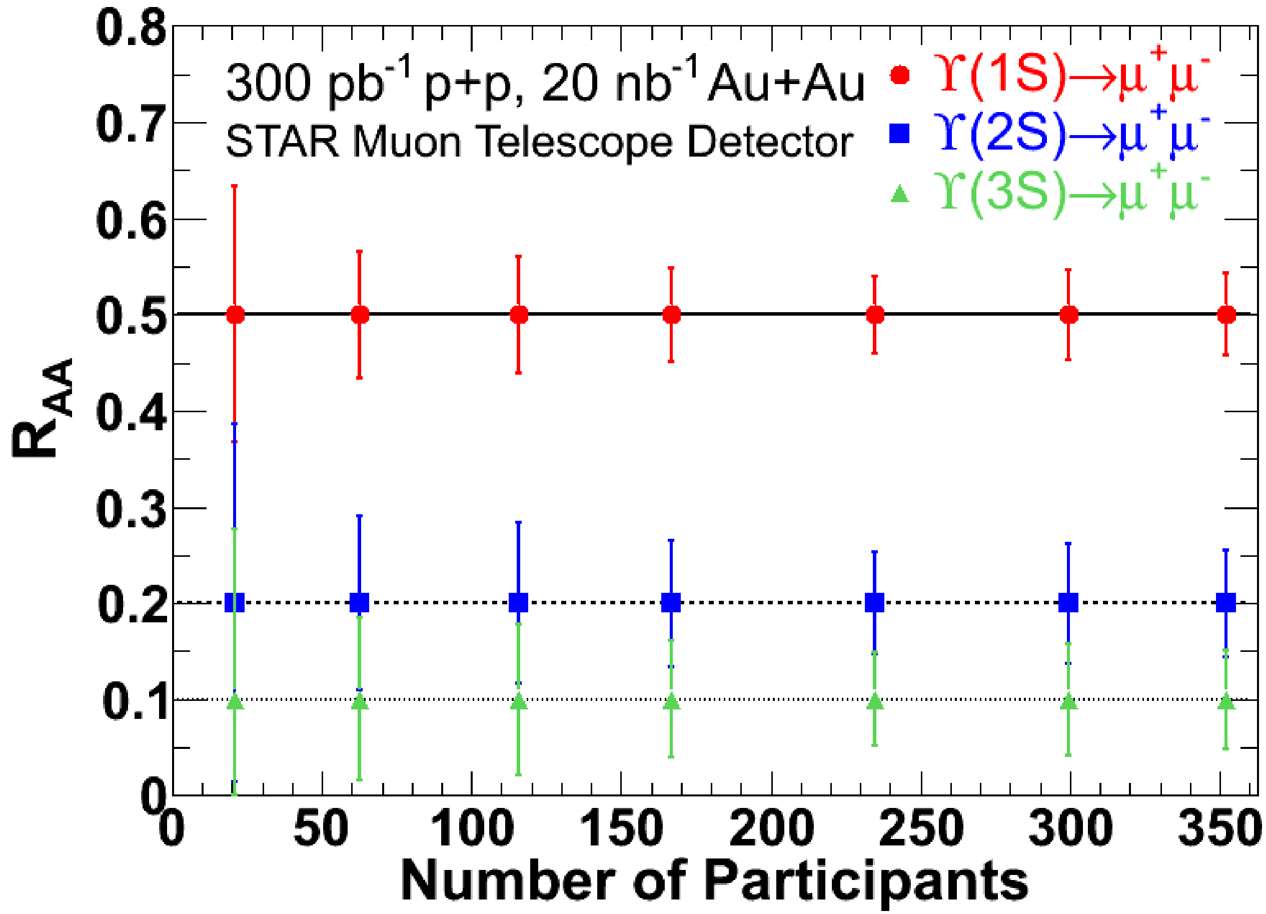
High μ/hadron enhancement

J/ψ with MTD projection



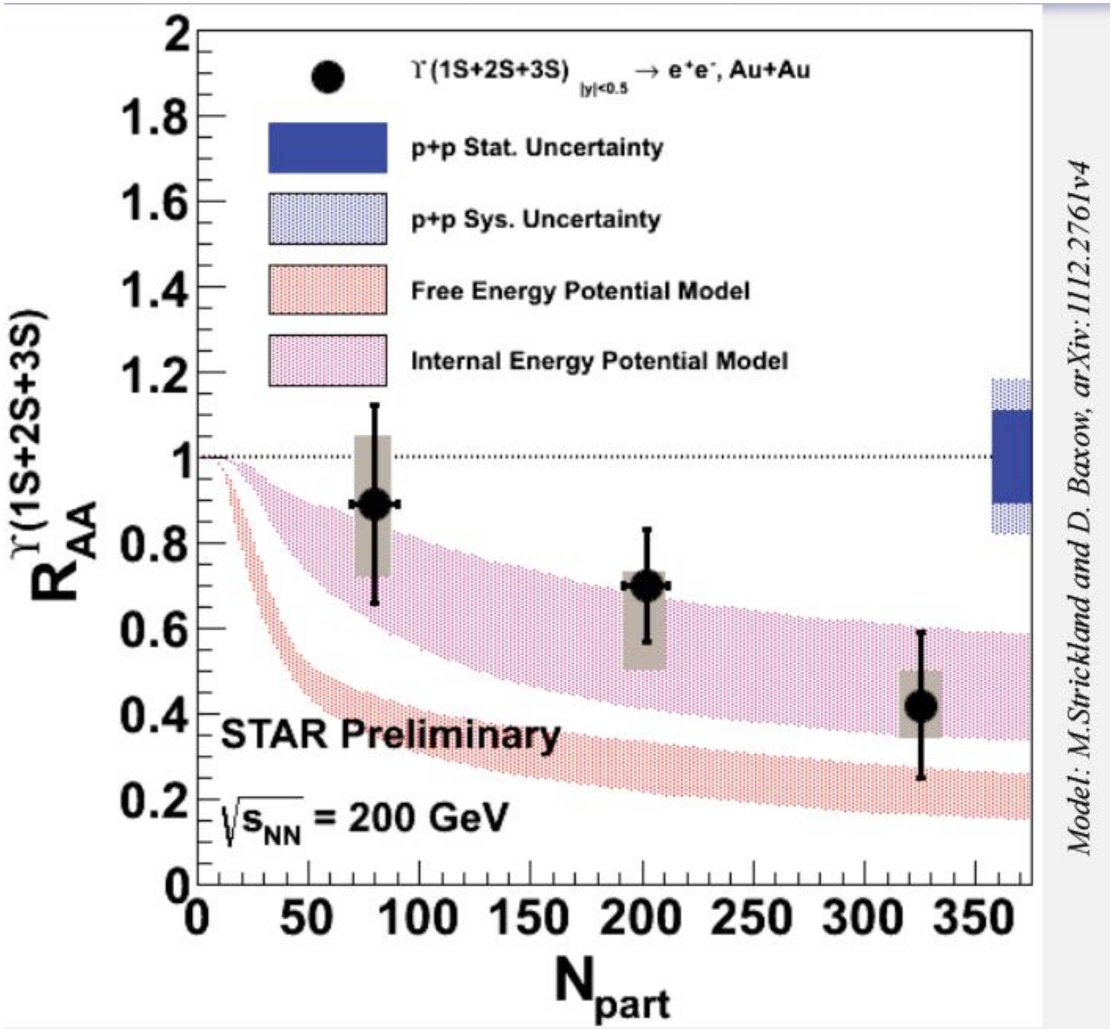


Upsilon with MTD projection



Separate different Upsilon states

Upsilon at STAR



- recombination can be neglected at RHIC
- Final state co-mover absorption is small.
- More suppression in more central collisions
- Consistent with prediction from a model requiring strong 2S and complete 3S suppression.

Cold nuclear matter and how to extract relevant information from experiments

Is Quarkonia versus Open flavor a theoretically clearer observable? What are the prospects for an experimental measurement?

Speaker: Livio Bianchi

Cold nuclear matter and how to extract relevant information from experiments

How important are cold nuclear matter effects quantitatively to understand suppression? And to understand the P_T, rapidity and centrality dependence of this suppression? Can we understand experimental results from pA collisions, as for example $\Psi(2s)$ in Phenix?

Speaker: Livio Bianchi

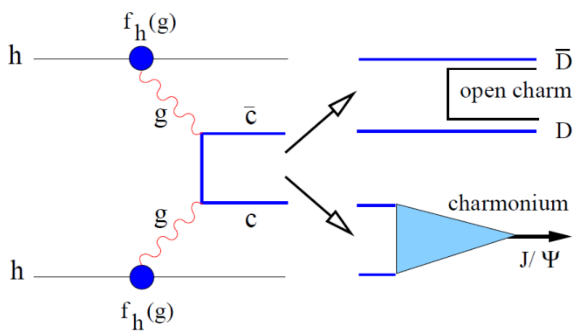
Round table: Heavy flavor suppression and transport properties

Livio Bianchi

QWG 2013

Beijing – P. R. China

22-26 April 2013

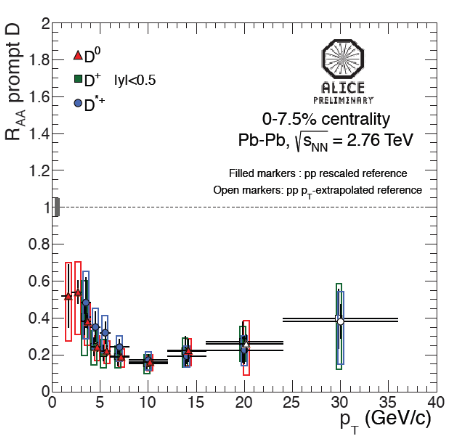


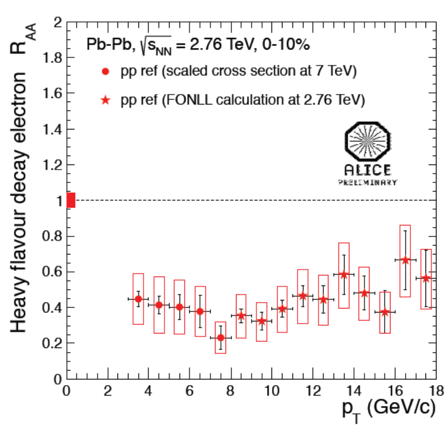
In order to simply quantify the suppression/enhancement scenarios we should be able to answer the questions:

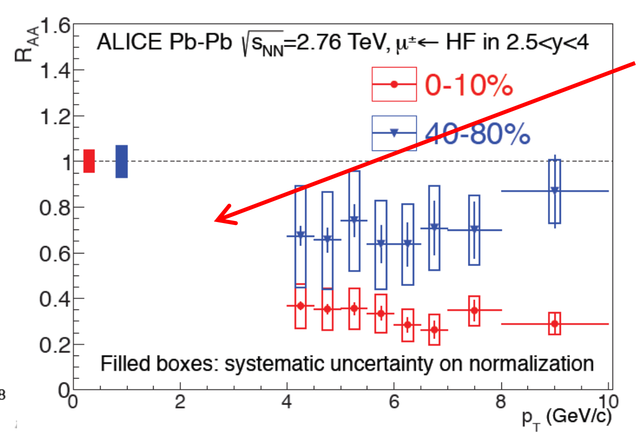
- Does the hot medium change the fraction of $c\bar{c}$ ($b\bar{b}$) pairs going to hidden vs open charm (bottom)? → **Normalize to open charm?**
- Does the hot medium change the relative fraction of $c\bar{c}$ ($b\bar{b}$) going to different hidden states? → **Sequential suppression**

Baseline: being able to make precise measurement of open charm down to zero p_t

Are we able to do that?





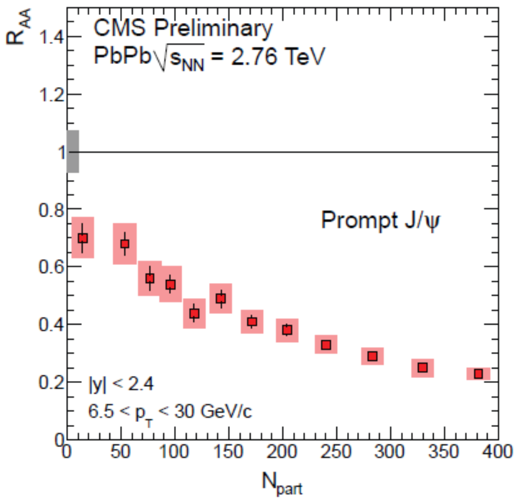


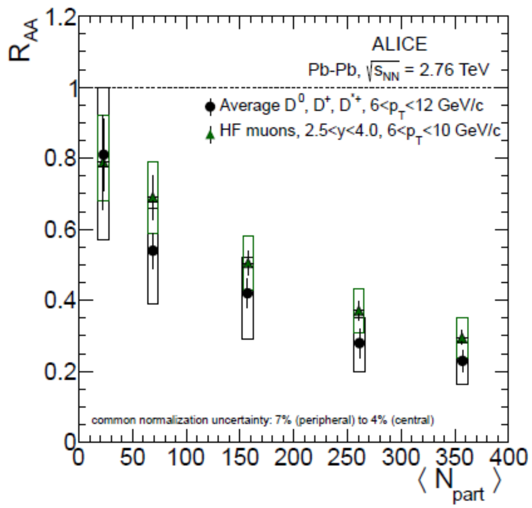
The forward muon tracker (ALICE upgrade) will help in reaching lower p_t with the discrimination of the secondary vertex

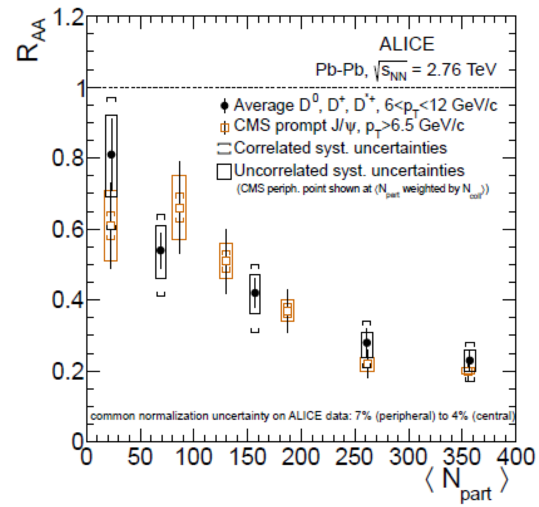
Normalization to open charm? (II)

Livio Bianchi
QWG 2013
23rd April 2013

Even being able…







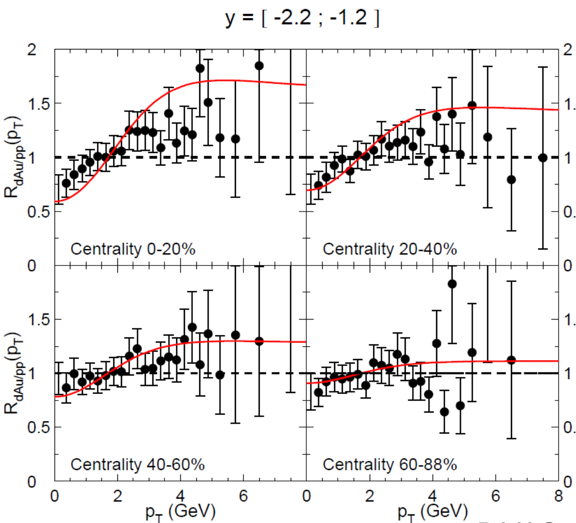
High-p_t J/ψ and D mesons at LHC show similar R_{AA} patterns.

But what can we learn from this?

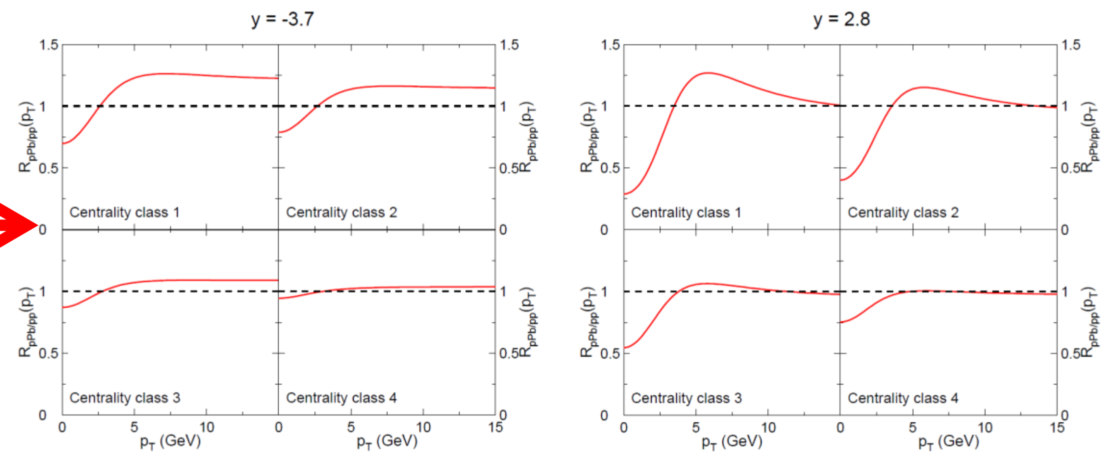
Making the ratio of the curves is not correct
since we are comparing quantities which have different meanings (quarkonium R_{AA}: suppression/enhancement – D-mesons R_{AA}: energy loss of the charm)

First question: how much important are CNM effects? How much at the LHC?

Arleo et al., arXiv:1304.0901v1



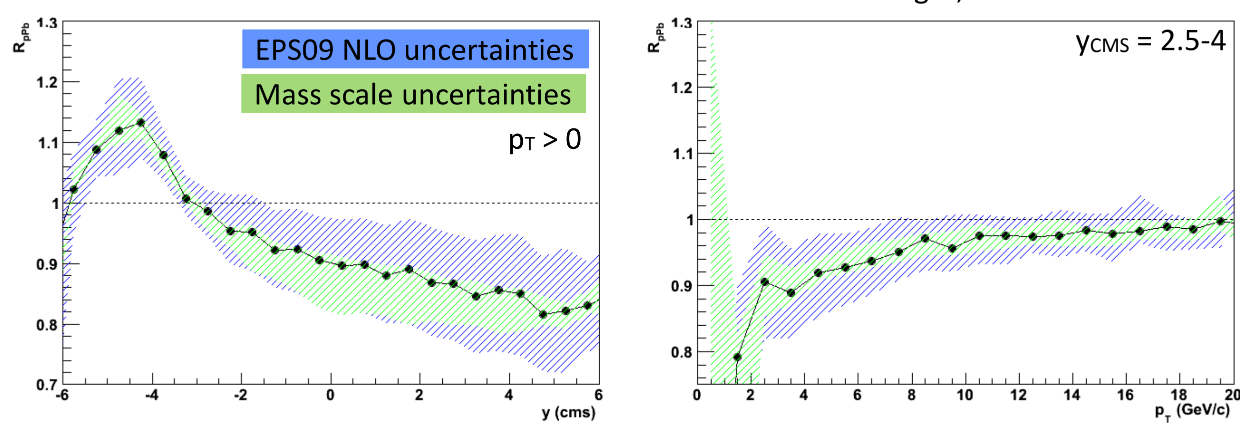
RHIC



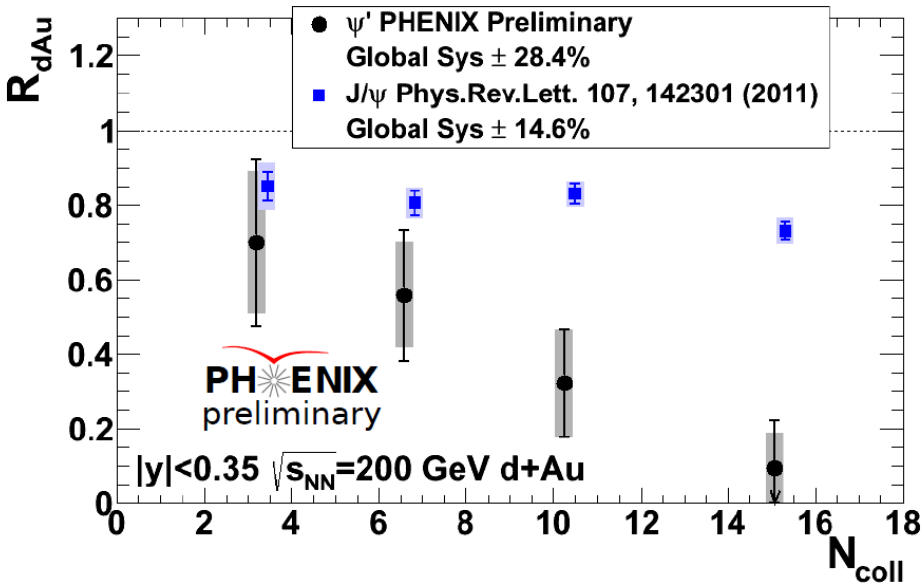
LHC

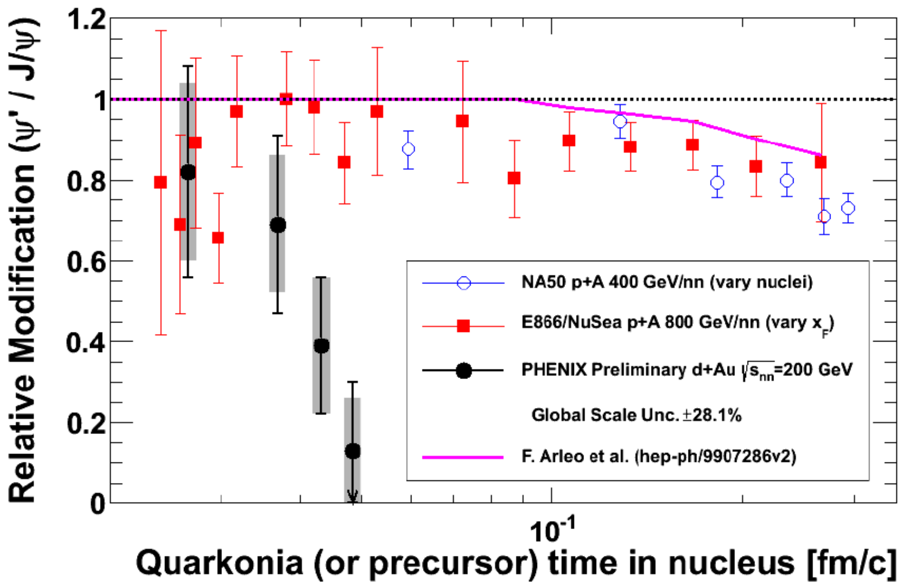
R. Voght, arXiv:1301.3395

They are VERY important!
in particular at low p_t and at forward/backward rapidity



Second question: do we understand everything up to now?





Puzzling result shown by PHENIX in QM2012:

Much stronger suppression of ψ(2S) wrt J/ψ

But naively we expect that CNM effects should be nearly the same for the two resonances: same shadowing and time passed by the $c\bar{c}$ pair in the nucleus very small!

Comovers? Should be more important at the LHC?

Definition of the potential and consequences of the imaginary part I

What do we know about the finite temperature potential? Is it well defined? Can we accurately compute it non-perturbatively?

Speakers: Antonio Vairo and Miguel A. Escobedo

Definition of the potential and consequences of the imaginary part I

What is the experimental impact of the imaginary part of the potential?

Speakers: Antonio Vairo and Miguel A. Escobedo

Heavy Flavour Suppression
- round table -

Antonio Vairo

Technische Universität München

What do we know about the finite temperature potential?

The potential is the interaction describing the quarkonium time evolution in an EFT that follows from QCD by integrating out all modes of energy larger than the binding energy:

$$i\frac{\partial}{\partial t}\phi = \left[\frac{\mathbf{p}^2}{m} + V(\mathbf{r}, \mathbf{p}, T, \dots) + \text{low-energy interactions}\right]\phi$$

We distinguish two regimes:

- Weak coupling: all scales are perturbative, i.e. larger than $\Lambda_{\rm QCD}$.
- Strong coupling: some scales are of order $\Lambda_{\rm QCD}$.

Weak coupling

Temperature	Potential (LO)	Thermal Width	Dissociation Mechanism
$T \gtrsim mg$	screened	$\Gamma \sim \alpha_{\rm s} T \times (m_D a_0)^2 > E_{\rm bin}$	screening
$mg \gg T \gtrsim mg^{4/3}$	Coulomb	$\Gamma \sim \alpha_{\rm s} T \times (m_D a_0)^2 > E_{\rm bin}$	inelatic parton scattering
$mg^{4/3} \gg T \gtrsim mg^3$	Coulomb	$\Gamma \sim \alpha_{\rm s} T \times (m_D a_0)^2 < E_{\rm bin}$	inelastic parton scattering
$mg^3 \gg T$	Coulomb	$\Gamma \sim \alpha_{\rm s} T \times (E_{\rm bin} a_0)^2 < E_{\rm bin}$	gluodissociation

$a_0 \sim 1/(mg^2) =$ Bohr radius
$E_{\rm bin} \sim mg^4 =$ binding energy
$m_D \sim gT =$ Debye mass

Strong coupling

- Analysis based on lattice calculations at different Euclidean times. See talk by A. Rothkopf.

- Such an analysis is important because we know from weak-coupling studies that the real part of the potential cannot be extracted from the Wilson loop free energy or from the correlator of Polykov loops. Moreover, it is crucial to obtain also the imaginary part of the potental.

- Ideally one would like to be able to express the real and imaginary part of the potential and its relativistic corrections in terms of expecation values of non-perturbative operators. A program that has been realized for quarkonium at zero temperature.

What is the experimental impact of the imaginary part of the potential?

- A specific weak-coupling case that could be tested at LHC could be the $\Upsilon(1S)$:

$$m_b \approx 5 \text{ GeV} \; > m_b\alpha_s \approx 1.5 \text{ GeV} \; > \pi T \approx 1 \text{ GeV} \; > m_b\alpha_s^2 \approx 0.5 \text{ GeV} \; \sim m_D \gtrsim \Lambda_{QCD}$$

- Can we have measures of the thermal width ($\sim$ number) of the $\Upsilon(1S)$ at different temperature? In this case:

$\Gamma \sim T$ (for gluodissociation) and $\Gamma \sim T^3/m^2$(for inelastic parton scattering dissociation).

What is the experimental impact of the imaginary part of the potential?

- Real part of the potential modifies position of the energy levels.
- Imaginary part of the potential modifies life time of the state.
- Both modify the wave function.

Consequences

- More suppression that only with real part. In the perturbative limit we can have suppression with a Coulomb potential plus a imaginary part.
- Fireball lives $\tau \sim 10$ fm, If the decay width is always bigger than $\Gamma \sim 20$ MeV we are going to see a very big suppression.
- The peak might exist and even be at the same position as at $T = 0$, but is not important for previous argument.

What is the experimental impact of the imaginary part of the potential?

Could it be a weak-coupling effect?

- Hints that it is present in Lattice computations. Works by Burnier, Rothkopf, Hatsuda and Sasaki.
- Interaction Quarkonia-Media can be seen as an open system. This is also so in strong coupling, and this produces an imaginary part. Works by Akamatsu.

Real question is the size, still open.

Definition of the potential and consequences of the imaginary part II

Is there a relation between the imaginary part of the potential and diffusion properties?

Speaker: Yukinao Akamatsu

Definition of the potential and consequences of the imaginary part II

What do we know about heavy quark damping and the mechanism responsible for it?

Speaker: Yukinao Akamatsu

Is there a relation between the imaginary part of the potential and diffusion properties?

Clear in LO perturbation

- Fluctuation → Decoherence → Imaginary part

$$\left\langle \xi^a(x)\xi^b(y)\right\rangle = -D(\vec{x}-\vec{y})\delta(x^0-y^0)\delta^{ab}$$

$$\Psi_{Q\bar{Q}}(t+\Delta t,\vec{x},\vec{y})$$

$$= \exp\left[-i\begin{pmatrix} 2M + \mathrm{Re}\,V(\vec{x}-\vec{y})[t_a\otimes(-t_a^*)] \\ +\xi^a(t,\vec{x})[t_a\otimes 1] + \xi^a(t,\vec{y})[1\otimes(-t_a^*)]\end{pmatrix}\Delta t\right]\Psi_{Q\bar{Q}}(t,\vec{x},\vec{y})$$

May not be general enough

Correlated fluctuation
→ *r*-dependent decoherence

$$i\frac{\partial}{\partial t}\left\langle \Psi_{Q\bar{Q}}(t,\vec{x},\vec{y})\right\rangle_\xi$$

$$=\left[2M - iC_F D(0) + \left(\mathrm{Re}\,V(\vec{x}-\vec{y}) + iD(\vec{x}-\vec{y})\right)[t_a\otimes(-t_a^*)]\right]\left\langle \Psi_{Q\bar{Q}}(t,\vec{x},\vec{y})\right\rangle_\xi$$

Clear in LO perturbation

- Fluctuation → Random force → Drag force

$$\left\langle \xi^a(x)\xi^b(y)\right\rangle = -D(\vec{x}-\vec{y})\delta(x^0-y^0)\delta^{ab}$$

$$\vec{f}^a(x) \equiv -\vec{\nabla}\xi^a(x), \vec{f}(x) \equiv t^a(t)\vec{f}^a(x),$$

$$\text{(conventional) constraint } t_a(t)t_a(t) = C_F$$

$$\left\langle f_i(x)f_j(x)\right\rangle = (C_F/3)\nabla^2 D(\vec{0})\delta(x^0-y^0)\delta_{ij}\delta^{ab}$$

Fluctuation dissipation theorem gives the drag force

What do we know about heavy quark energy loss and the mechanism responsible for it? Do they also affect quarkonia?

Energy loss mechanisms

- Elastic process (collisional energy loss)
  - Important for slow HQ
  - Perturbative: t-channel scattering dominant
  - Non-perturbative: Resonant scattering?? Analogy to Kondo problem??

- Inelastic process (radiative energy loss)
  - Important for fast HQ
  - Ask jet experts…, similar technique (CTP) used.

Lattice QCD observables

What new observables can be measured in the lattice that will give us relevant information about quarkonia in media?

Speaker: Seyong Kim

What new observables can be measured in the lattice that will give us relevant information about quarkonia in media?-Kim

- Lattice can in principle calculate N-point correlation functions in medium.
- In near future, lattice calculation with relativistic charm in medium will be more advanced $\rightarrow$ charm quark related transport properties can be studied on lattice.
- Ground state properties of S-wave quarkonium channel in medium can be investigated further in lattice NRQCD.
- if quarkonium decay in medium can still be described as four-fermion contact interactions as in zero temperature lattice NRQCD, further development is possible

Out of equilibrium and finite momenta

What properties can we extrapolate from thermal equilibrium and zero momentum to the non-equilibrium and finite momentum realized experimentally?

Speaker: Seyong Kim

What properties can we extrapolate from thermal equilibrium and zero momentum to the non-equilibrium and finite momentum realized experimentally?-Kim

- In lattice gauge theory, small departure from thermal equilibrium can be considered using Kubo formulae.
- Various transport coefficients have been calculated (viscosity, conductivity, diffusion coefficients, etc) and will be refined further
- Quarkonium moving in medium will be investigated further in lattice NRQCD
- How can the thermal width be measured experimentally?

Out of equilibrium and finite momenta

What properties can we extrapolate from thermal equilibrium and zero momentum to the non-equilibrium and finite momentum realized experimentally?

Speaker: Miguel A. Escobedo

What properties can we extrapolate from thermal equilibrium and zero momentum to the non-equilibrium and finite momentum realized experimentally?

It is surely non-equilibrium because of time evolution.

- Lifetime of fireball $\tau \sim 10$ fm.
- $1/E$ for $\Upsilon(1S)$ is around 0.5 fm.

Adiabatic approximation reasonable for $1S$, but $2S$? $3S$? Can we go beyond adiabatic approximation?

Anisotropy

- Leading order effect.
- Qualitatively similar (important is energy density) but quantitatively important.

What properties can we extrapolate from thermal equilibrium and zero momentum to the non-equilibrium and finite momentum realized experimentally?

Finite momentum. Are there effects?

- Have been seen in pQCD, AdS/CFT, T-matrix, some Lattice computations.
- Can be a source of additional suppresion.
- Qualitative features remain.

Relation with thermal equilibrium

- The basics physics seems to be the same. This can we learn by comparing computations/models with lattice QCD in thermal equilibrium.
- To compare with experiment all this has been included.
- At some extend this program is already in progress. Adiabatic approximation, finite momentum effects...