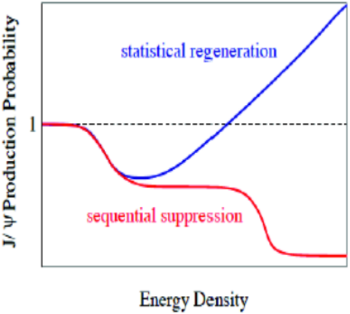
# Lecture 19
# Quarkonia in QGP (part II)

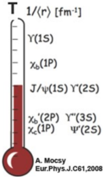



From J.Satchel

In this lecture, we will see other mecanisms for suppression and production, as well as data on quarknonia

# Quarkonia in expanding QGP

If $T \searrow$ in a static hot environment, quarkonia are suppressed sequentially




At very high T, all melted and at low T, only large ones melted

## How is this modified by expansion?

Quarkonia formation is a two-step process:
1) pQCD based models describe $Q\bar{Q}$ pair production: fast almost ponctual process $\Delta x \sim \Delta t \sim 1/(2m_Q)$ (ex. $\sim 0.1$ fm for $c\bar{c}$)
2) $Q$ and $\bar{Q}$ form a bound state via non perturbative interactions.
Crude estimate for time scale: $Q$ and $\bar{Q}$ separate in a time

$\tau_{form} = r_{bound}/v_{relat} = r_{bound} E_{Q\bar{Q}}/p_{Q\bar{Q}}$ in pair rest frame

$t_{form} = \tau_{form}\gamma = \tau_{form}\sqrt{1 + p_\perp^2/M^2}$ in the lab.

### Limit for $p_\perp$ due to QGP cooling time

$t_{form}$ is large for large $p_\perp$ and the QGP may have cooled down below the dissociation temperature $T_d$ before $t_{form}$.

$\Rightarrow$ upper limit for $p_\perp$ in order to have dissociation

This limit is:
$t_{form} = t_d \Rightarrow p_\perp^{max1} = M\sqrt{(t_d/\tau_{form})^2 - 1}$

To get an order of magnitude, using the Borken model (at mid-rapidity): $t_d = t_0(T_0/T_d)^3$, so $t_d$ can be computed from the initial conditions.

$\tau_{form}$ can be obtained by solving a Shrödinger equation. The table below shows an exemple of such results ($\tau_F \equiv \tau_{form}$).

| | $J/\psi$ | $\psi'$ | $\chi_c(1P)$ | $\Upsilon(1S)$ | $\Upsilon(2S)$ | $\chi_b(1P)$ |
|---|---|---|---|---|---|---|
| $M$ (GeV) | 3.07 | 3.698 | 3.5 | 9.445 | 10.004 | 9.897 |
| $r$ (fm) | 0.453 | 0.875 | 0.696 | 0.226 | 0.509 | 0.408 |
| $\tau_F$ (fm) | 0.89 | 1.5 | 2.0 | 0.76 | 1.9 | 2.6 |

From R.Vogt

Exercise:

Compute $t_d$ and $p_\perp^{max1}$ for $J/\Psi$ at SPS assuming $\tau_0$= 1 fm and $T_0$ = 300 MeV for the Bjorken model.

Using values in lectures 1 and 18: $t_d = 1 \times (300/(154 \times 1.17))^3$=4.6 fm

$p_\perp^{max1} = 3.1\sqrt{(4.6/0.89)^2 - 1} \sim 16$ GeV.

## Limit for $p_\perp$ due to QGP finite size

A pair spends a finite time inside a transverse slice of matter: $t_{inside} \sim < r > (m_\perp / p_\perp)$

If $t_{form}$ is larger than $t_{inside}$, the pair forms outside and is not screened.

$\Rightarrow$ another upper limit for $p_\perp$ in order to have dissociation

This limit is:

$$t_{form} = t_{inside} \Rightarrow p_\perp^{max2} = M(< r > / \tau_{form})$$

We expect the average distance to be traveled to be $< r > \sim R$

It depends on the radial profile of the matter, the location and direction of travel of the pair.

Exercise:

Compute an order of magnitude for $p_{\perp}^{max1}$ for a $J/\Psi$ in a a gold nucleus.

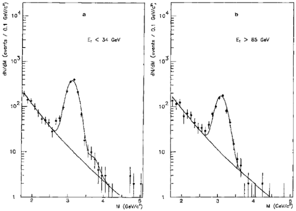
$p_{\perp}^{max2} \sim 3.07 \times 7/0.89$=24 GeV

# Other mechanisms that suppress quarkonia

- Quarkonia can interact with hadrons in the medium: nuclear absorption
  Approximatively: $\sigma_{hA\to C}/\sigma_{hN\to C} \sim exp(-\eta A^{1/3})$ (absorption depends on path length)
- Quarkonia can interact with hadrons produced along with it (comovers)
  Approximatively: $\sigma_{hA\to C}/\sigma_{hN\to C} \sim exp(-\beta A^{1/3})$ (after approximations)
- Some $p_t$ broadening in hA collisions (Cronin effect)

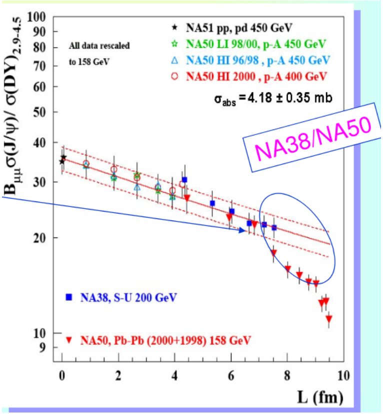
These mechanisms were enough to explain the $J/\Psi$ suppression observed initially at SPS (O+U 1986 and S+U 1987).

For historical perspectives at SPS see H.Satz arXiv:hep-ph/9806319 and L.Kluberg Eur. Phys. J. C (2005) 20245-6



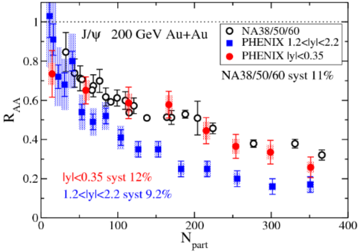
## $J/\Psi$ suppression in Pb+Pb at the SPS (at last)

In central Pb+Pb, an anomalous suppression not explained by hadronic effects appeared (NA50 1996) and hinted at color deconfinement




Then what to expect at RHIC? Higher energy densities so more suppression?

# $J/\Psi$ suppression at RHIC



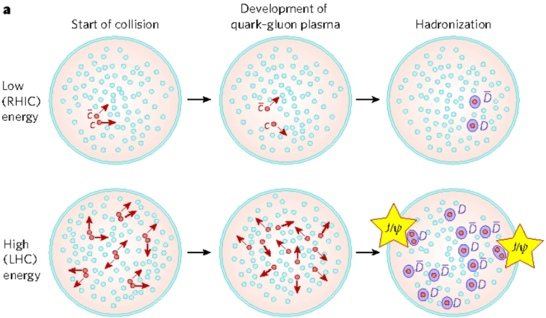

- Suppression is observed: OK
- Similar to SPS at mid-rapidity: strange
- Larger at forward rapdity where energy density is smaller: stranger

$R_{AA}$ is a comparison to p+p accounting for higher number of nucleon-nucleon collisions

Nuclear absorption effect (again)? Mechanism increasing $J/Psi$ production (see next slide)?

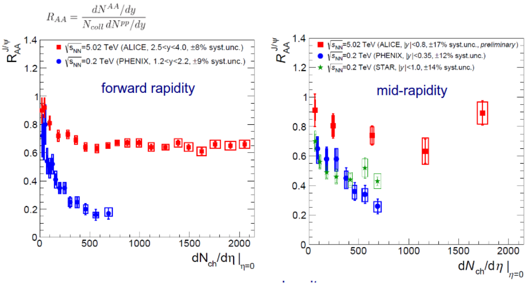
## A prediction: mechanisms that produce quarkonia

- At SPS, about $\sim$ 1 $c\bar{c}$ produced per 10 Pb+Pb collisions (and $\sim$ 1 $J/\Psi$ per 500 collisions).
- At RHIC, about $\sim$ 10 $c\bar{c}$ pairs produced per Au+Au collisions.
- At LHC, $\sim$ 100 $c\bar{c}$ pairs per central collisions. So in addition to directly produced $J/\Psi$, some additional production could occur later.



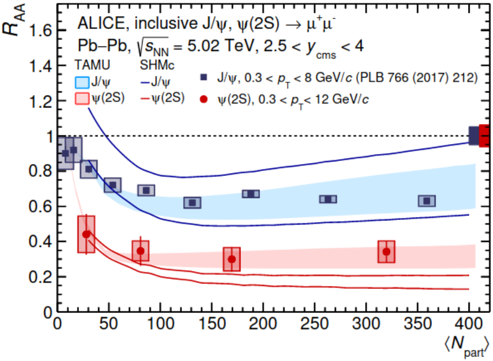

Regeneration: Create charmonium states by recombining at hadronization (P.Braun-Munzinger and J.Stachel, PLB 490 (2000) 196) or during QGP evolution (Thews et al., PRC 63 (2001) 054905)

## $J/\Psi$ at LHC




From RHIC to LHC, no additional melting, rather enhancement (regeneration) of $J/\Psi$

# $\Psi'$ at LHC

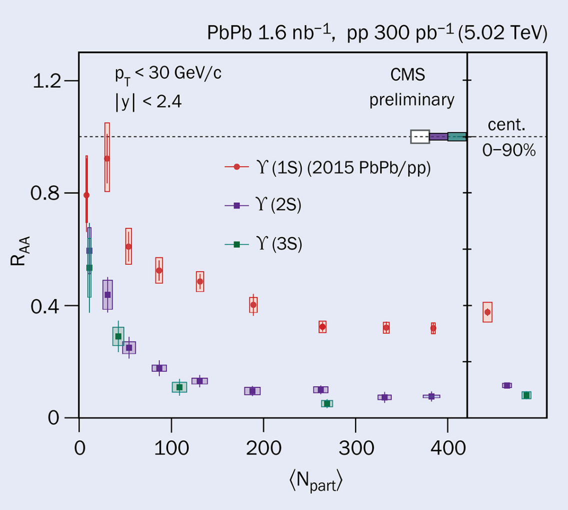



$\Psi'$ is more suppressed that $J/\Psi$ as expected (which does not preclude recombination). Results seem in somewhat better agreement with transport model TAMU rather than Statiscal Hadronization Model

Recent results from ALICE arXiv:2210.08893

# How about the $\Upsilon$?

$\Upsilon$ is $b\bar{b}$. Due to its heavy mass, it is not very sensitive to regeneration. One expects a more clear sequential suppression. This seems to be the case (very recent result).



Homework

Redo the two exercises for $\Psi'$

Other references on this topic

- J.-P.Blaizot & J.-Y.Ollitrault in “Quark Plasma 1”
- R. Vogt’s book item R.Vogt “Cold Nuclear Matter Effects on Open and Hidden Heavy Flavor Production at the LHC” arXiv:1508.01286