Calibrating the In-Medium Behavior of Quarkonia

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Wszystkiego najlepszego!

Alles Gute!

All the Best!
general:
Use in-medium charmonium behavior
to probe quark-gluon plasma

specific:
Use charmonium production in nuclear collisions
to probe QGP formation

basis:
Presence of produced medium
modifies $c\bar{c}$ binding to charmonia
charmonium production in $pp$ collisions

c$\bar{c}$ production: PDF’s $f_p(g) +$ perturbative QCD

$J/\psi$ binding? ...CEM, CSM, COM, ...

color evaporation “works”

$$\sigma_{hh \rightarrow J/\psi(s)} = g_{c\bar{c} \rightarrow J/\psi} \sigma_{hh \rightarrow c\bar{c}(s)},$$

partitioning of $c\bar{c}$ cake among eaters is energy-independent
Further consequence: energy-independent feed-down fractions

\[ J/\psi \] measured in \( pp \) collisions is approximately

60 % direct \( J/\psi(1S) \), 30 % \( \chi_c(1P) \) & 10 % \( \psi' (2S) \) feed-down

narrow resonances \( \rightarrow \) decay outside interaction region

medium sees traversal of higher resonances

• crucial question:

are these features

(hidden/open, relative quarkonium fractions)

changed in nuclear collisions?

NB:

the production dynamics in \( AA \) collisions is different from

that in \( pp \) collisions!
modifications in nuclear collisions:

- **initial state effects**
  - pdf modification (shadowing, antishadowing)
  - energy loss of incident parton (gluon)

- **final state effects**
  - energy loss of primary $c\bar{c}$
  - cold nuclear matter effect on (nascent) charmonium
  - secondary matter effect on (nascent) charmonium

previous analysis procedure:

- **measure production in $pp$ and $pA$**
  - determine pdf modification (shadowing, antishadowing)
  - determine parton energy loss
  - determine cold nuclear matter effect
• construct model for \( AA \)
  scale \( pp \) by number of collisions
  incorporate initial & cmn final state modifications
• compare to \( AA \) data: is there anomalous behavior?
  i.e., something not accounted for by model \( \rightarrow \) inconclusive

Theoretical Scenarios

• sequential suppression
  color screening dissociates charmonium states in QGP
  first higher excited states \((2S), (1P)\),
  then ground state \((1S)\)
• statistical enhancement
  all primary charmonia dissociated
  at high collision energy,
  overabundance of charm quarks
  equilibration, $c\bar{c}$ excess survives
  hadronisation by statistical
  combination

How to calibrate $J/\psi$ survival probability?
both scenarios claim that presence of medium modifies the
relative fraction of $c\bar{c}$ going into charmonia
neither says anything about how many $c\bar{c}$ pairs are produced
in $AA$ relative to scaled $pp$
more explicitly:

if the total number of $c\bar{c}$ pairs produced in $AA$ collisions is reduced by a factor two relative to scaled $pp$ rates, but as before, 90 % go into open charm, 10 % into charmonia (with same distribution among states), then

- the medium formed in $AA$ collisions leads neither to suppression nor to enhancement of $J/\psi$ production;
- the crucial question is what happens to the produced $c\bar{c}$ pairs, not how many there are to begin with; the medium can only affect those that are there.
- the quantity

$$R_{AA}(J/\psi) = \frac{N_{AA}(J/\psi)}{n_c N_{pp}(J/\psi)}$$

is reduced by a factor two.
Conclude:
the correct calibration is hidden to open charm, so that the relevant observable is

\[
S_{J/\psi} = \left( \frac{N_{AA}(J/\psi)}{N_{AA}(c\bar{c})} \right) / \left( \frac{N_{pp}(J/\psi)}{N_{pp}(c\bar{c})} \right) = \frac{1}{g_{c\bar{c} \rightarrow J/\psi}} \left( \frac{N_{AA}(J/\psi)}{N_{AA}(c\bar{c})} \right)
\]

In the observable

\[
\frac{N_{AA}(J/\psi)}{N_{AA}(c\bar{c})},
\]
if measured over all phase space, initial state effects cancel out, and one can check if the result is different from

\[
\frac{N_{pp}(J/\psi)}{N_{pp}(c\bar{c})} = g_{c\bar{c} \rightarrow J/\psi}.
\]
i.e., if the medium has had an effect on charmonium binding.
NB: the often used observable $R_{AA}(J/\psi)$ alone
is at best inconclusive, at worst misleading

need to compare hidden to open charm,
so must compare $R_{AA}(J/\psi)$ to $R_{AA}(c\bar{c})$;
if they are equal: neither suppression nor enhancement

specifically, use double ratio

$$\frac{R_{AA}(J/\psi)}{R_{AA}(c\bar{c})} = \frac{N_{AA}(J/\psi)}{n_c N_{pp}(J/\psi)} \frac{N_{AA}(c\bar{c})}{n_c N_{pp}(c\bar{c})} = S_{J/\psi}$$

to get $J/\psi$ survival probability.

have to specify:
what does $N(c\bar{c})$ mean? cannot measure total open charm
relative abundances of light hadrons in high energy collisions
“statistical hadronisation” at universal temperature $T_f$

$$\frac{N_i}{N_j} = \left(\frac{d_i}{d_j}\right) \left(\frac{m_i}{m_j}\right)^2 \frac{K_2(m_i/T_f)}{K_2(m_j/T_f)} \approx \left(\frac{d_i}{d_j}\right) \left(\frac{m_i}{m_j}\right)^{3/2} \exp\left\{-(m_i-m_j)/T_f\right\},$$

rate of $c\bar{c}$ production is not statistical, but in $e^+e^-$, $pp$, $p\bar{p}$
the distribution among open charm states is: each open charm state gets fixed piece of total $c\bar{c}$
expect same for $AA$, but need to check! If OK:

$$N(c\bar{c}) \sim \text{const. } N(D^+) \Rightarrow R_{AA}(c\bar{c}) = R_{AA}(D^+)$$

must measure only one specific channel, e.g., $D^+$ production
apply to data – illustration only so far, kinematics...
Data from ALICE & CMS: $J/\psi$ vs. open charm production at intermediate & high transverse momenta
(thanks to Zaida Conesa del Valle)

in $AA$, as many $c\bar{c}$ pairs make $J/\psi$ as in scaled $pp$,
but there just are fewer now to begin with

here neither $J/\psi$ suppression nor enhancement; \textbf{low $P_T$?}
Data from PHENIX & STAR: $J/\psi$ vs. open charm production at high & low transverse momenta
(thanks to Torsten Dahms)

at high $p_T$, as at LHC;
at low $p_T$, up to 80 % $J/\psi$ suppression:
here $\exists$ no medium effect on $c\bar{c}$ production,
only on charmonium binding.
Complementary aspect: so-called “RHIC puzzle”

“more $J/\psi$ suppression” in forward than in central production, based on $R_{AA}$

Could it be that there are just fewer $c\bar{c}$ pairs produced at forward than at mid rapidity?
Check by looking at open charm production in \( pA \) collisions

Rapidity dependence of open charm production in \( pA \) at 800 GeV, with parametrization \( \sigma_{pA} = A^\alpha \sigma_{pp} \).

(thanks to Mike Leitch)

The puzzle seems not so puzzling with correct calibration; but need to check quantitatively
Additional Probe

ratio of excited to ground state in $AA$: $\Upsilon(1S) : \Upsilon(2S) : \Upsilon(3S)$

does the presence of a medium change this from $pp$?

initial state effects cancel here as well; example

Higher excited states suppressed, feed-down to ground state gone

Seems evidence of sequential suppression...see CMS paper.
Conclusions

Only measurements of hidden/open heavy flavor production, measurements of excited/ground state quarkonium production in $pp$, $pA$, $AA$

can provide model-independent answers to model-independent questions.
Wszystkiego najlepszego!

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