J/ψ suppression in relativistic heavy-ion collisions

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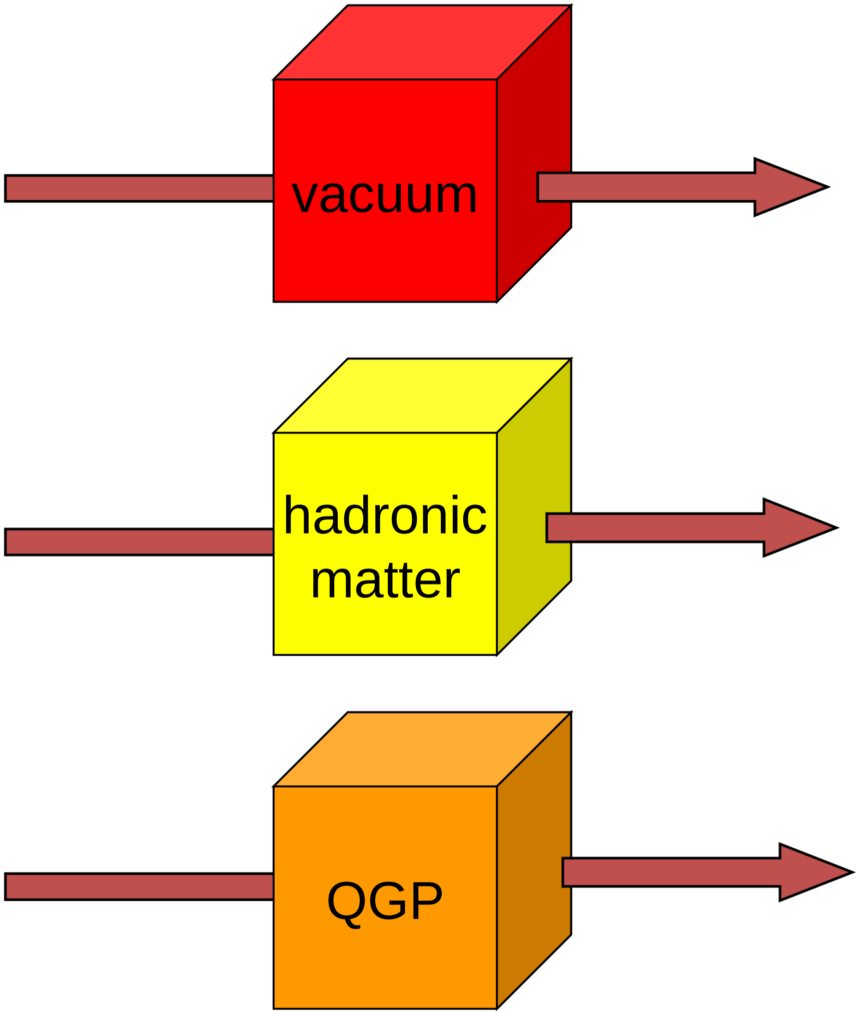
Challenge: find the good probes of QCD matter



The good QCD matter probes should be:

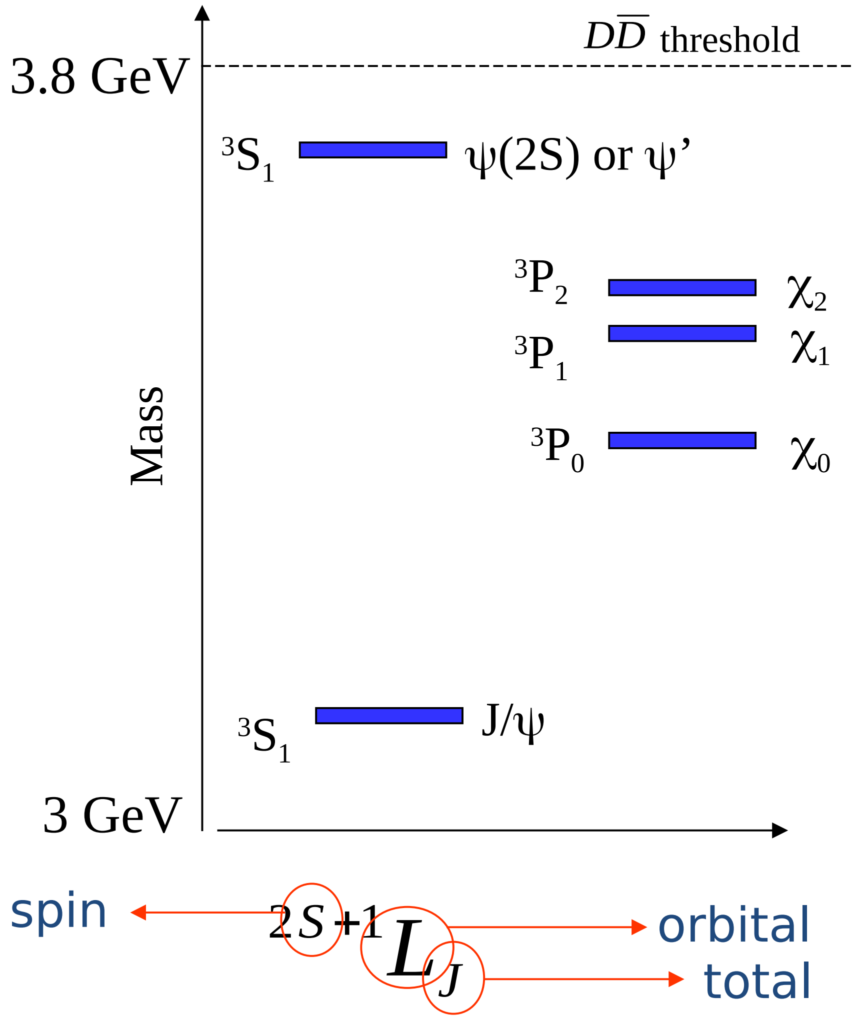
” Well understood in “pp collisions

Slightly affected by the hadronic matter, *<u>in a well understood way, which can be accounted for</u>*

Strongly affected by the deconfined QCD medium...

***Heavy quarkonia* (J/ψ, ψ’, Υ, Υ’, etc) are very good QCD matter probes !**

Charmonium states



Charmonium → cc-bar bound state

$m<2m_D$ → stable under strong decay

Relative motion is non-relativistic (β~0.55)→treated with non-relativistic Potential theory

The binding of the c and c-bar quarks can be expressed using the Cornell potential:

$$V(r) = -\frac{\alpha}{r} + kr$$

Coulomb contribution, induced by gluon exchange between q and qbar

Confinement term

The story begins …

PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

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ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

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One of the most famous paper in our field (>2000 citations!)

Keywords

1)Hot quark-gluon

2)Colour screening

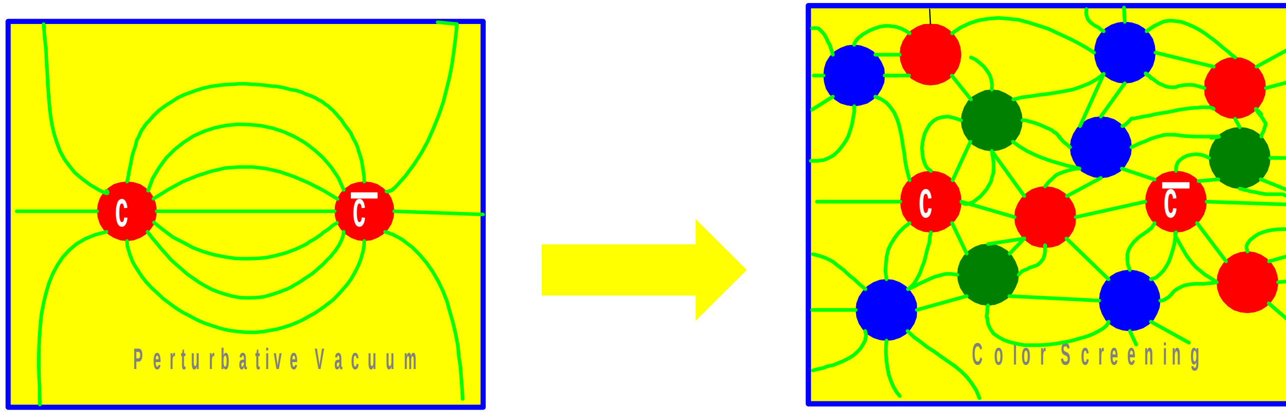
3)Screening radius

4)Dilepton mass spectrum

Unambiguous signature of QGP formation

Fate of a cc-bar bound state in a de-confined medium

Screening of strong interactions in a QGP



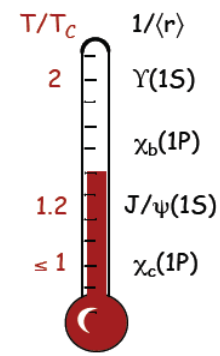
- Different states, different sizes and binding energies
- Screening stronger at high T

∀λ_D → maximum size of a bound state, decreases when T increases

Dissociation temperatures
(Lattice QCD, Potential Model)

state	J/ψ (1s)	χ_c (1P)	ψ' (2s)
T_d/T_c	2.1 (1.2)	1.16 (~1)	1.12 (~1)

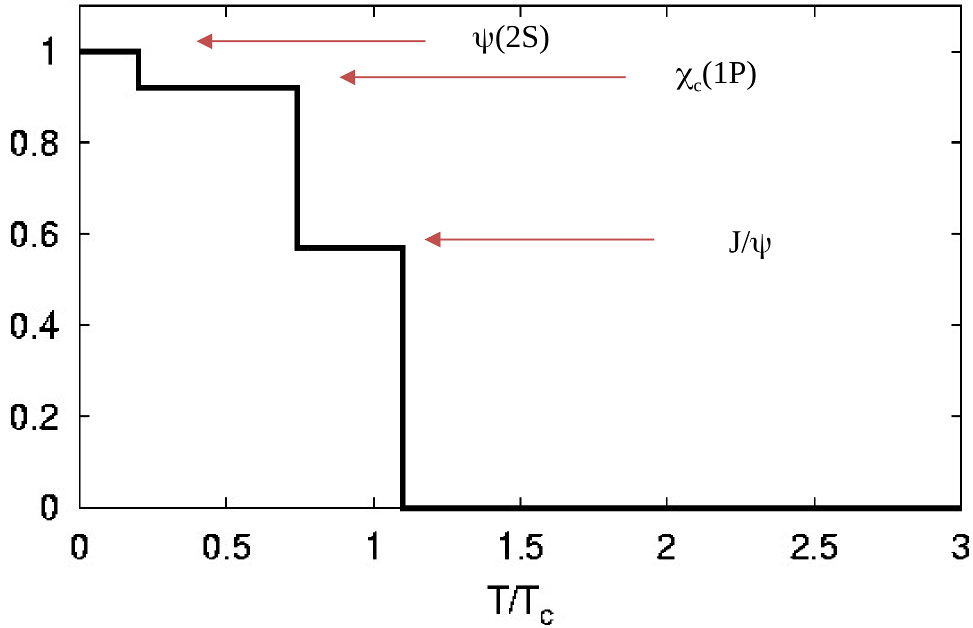
Resonance melting



QGP thermometer

Suppression hierarchy: sequential melting

- Each resonance has a typical dissociation threshold
- Consider the cc-bar resonances that decay into J/ψ : Feed down



S. Digal et al., Phys.Rev. D64(2001)094015

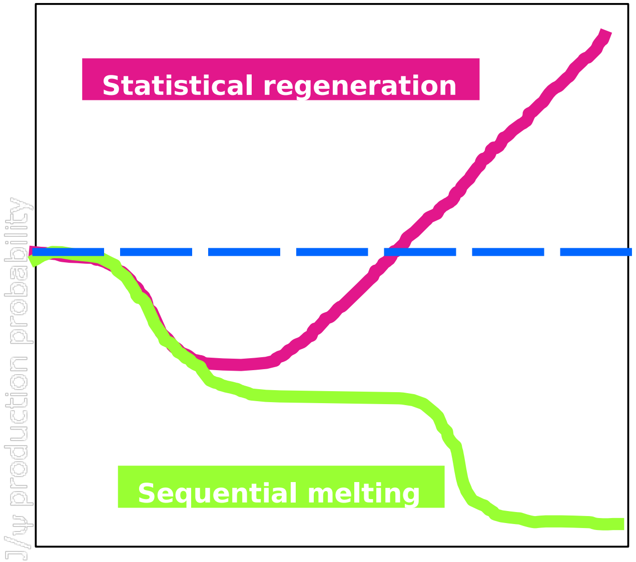
The J/ψ yield should exhibit a step-wise suppression when T increases (e.g. comparing A-A data at various √s or centrality)

From suppression to (re)generation

(Re)combination

Increasing the collision energy the cc-bar pair multiplicity increases

Most central AA collisions	SPS 17 GeV	RHIC 200GeV	LHC 2.76TeV	LHC 5.02 TeV
N_{ccbar}/event	~0.2	~10	~75	~ 115



enhanced charmonium production via (re)combination of exogamous cc-bar pair during:
QGP stage (kinetic model)
and/or at hadronization (SHM)

SHM: P. Braun-Muzinger,J. Stachel, PLB 490(2000) 196
Kinetic model: R. Thews et al, Phys.Rev.C63:054905(2001)

…but the story is not so simple

Do we understand charmonium production in elementary collisions ?

Are there any other effects, not related to colour screening, that may induce a suppression of quarkonium states ?

- Is it possible to define a “reference” (i.e. unsuppressed) process in order to properly define quarkonium suppression ?

Which elements should be taken into account in the design
of an experiment looking for qurkonium suppression?

Do experimental observations fit in a coherent picture ?

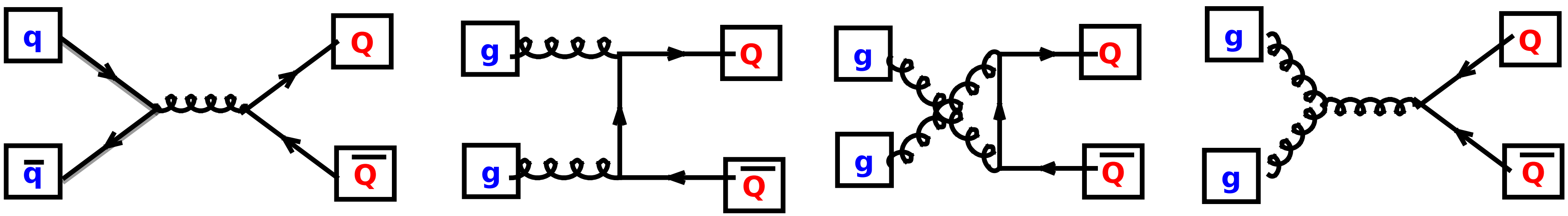
None of these questions has a trivial answer….

J/ψ production in elementary (pp) collisions

Generally assumed as a factorizable two step process:

(i)Production of a cc-bar pair
(ii)Formation of resonance

(i) Production of charm-anticharm (cc) pair



Qurk-antiquark annihilation

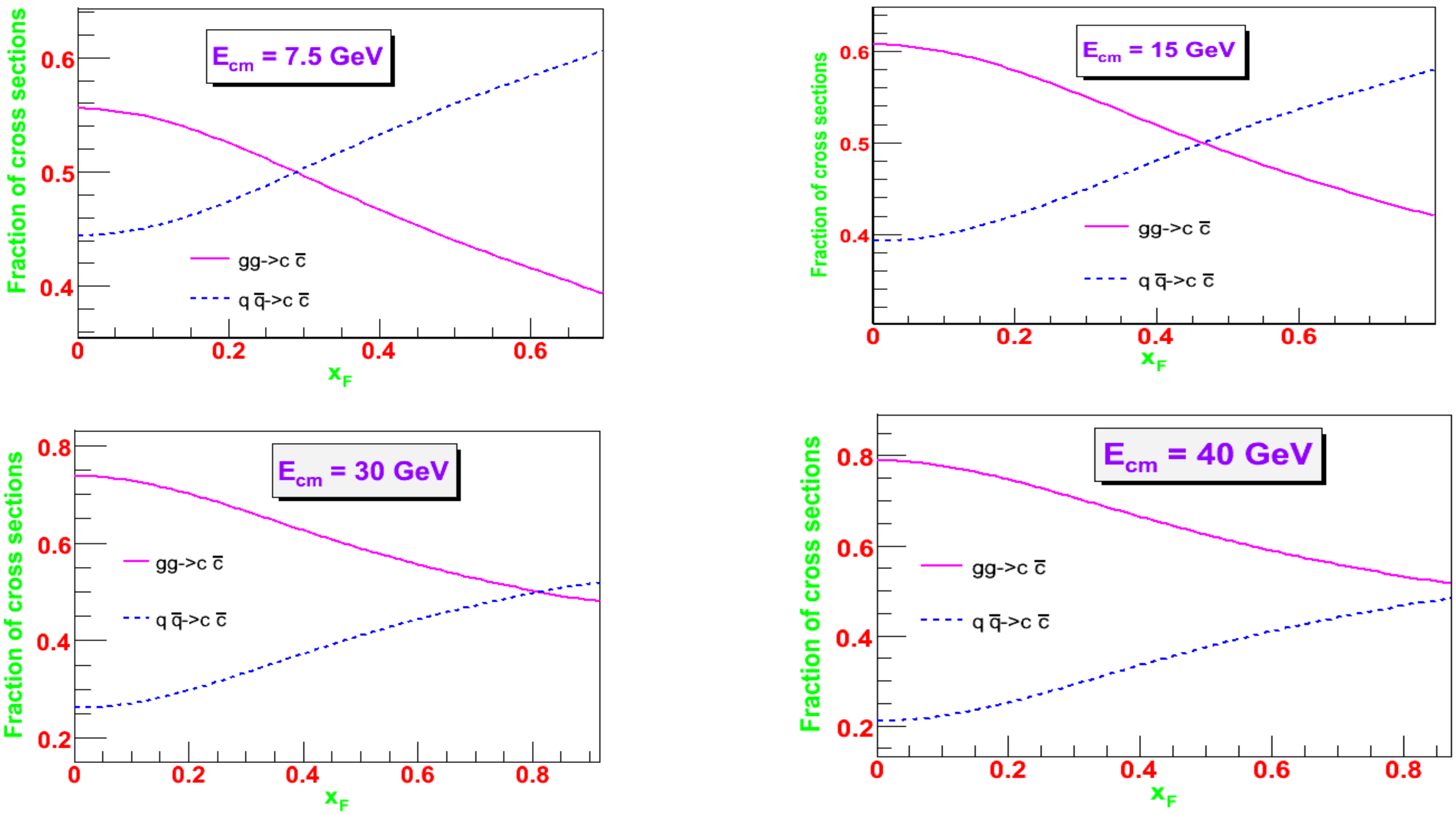
Gluon fusion

Perturbative in nature due high mass of charm quarks

Contribution of intrinsic charm is negligible.

At high energies gg fusion is the only dominating process, at low energy qq-bar annihilation also becomes important.

Relative size of the two sub-processes



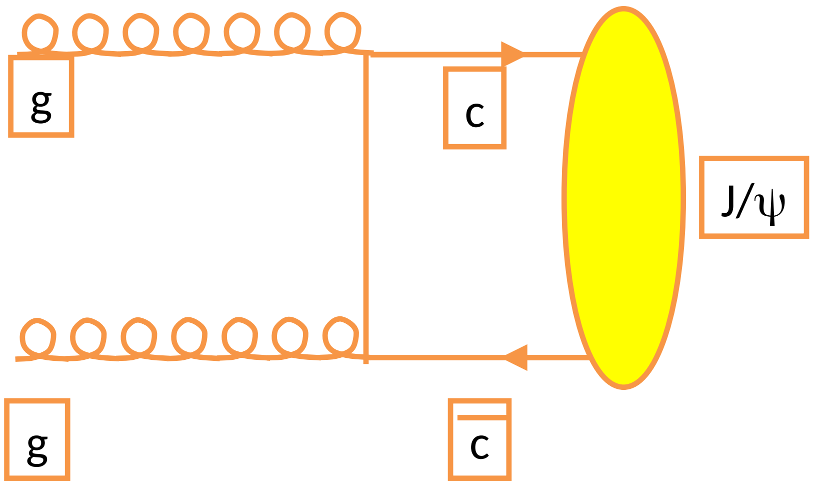
PPB, A. K. Chaudhuri and S. Chattopadhyay, Phys. Rev. C 84, 054914 (2011)

- Lower x_F gluon fusion dominates
- Higher x_F quark annihilation dominates
- High energy collisions (RHIC, LHC) : reliable description from gg fusion alone
- Low energy collisions (FAIR, NICA): significant contribution from quarks

Hadronization of the QQ pair into physical bound state

No unique theoretical description : Different models :

1. Color Singlet Model (CSM)
2. Color Octet Model (COM)
3. Color Evaporation Model (CEM)



CSM:

Requires the cc pair to be produced in a color singlet state, with the same quantum nubers of the charmonium state under study

CEM:

The cross section for the production of a certain charmonium state is a fixed fraction F of the production cross section for cc pairs with $m<2m_D$

COM:

cc-bar pairs are produced in a color octet state; subsequent color neutralization occurs by radiation of soft gluons

J/ψ production in p+A collisions: CNM effects

In p+A collisions, production is influenced due the presence of the target nucleons. Collisions provide a tool to probe the effect of confined matter.

Measurements till date unanimously reported that at fixed collision energy rate of J/ψ production per target nucleon decreases with increasing target mass

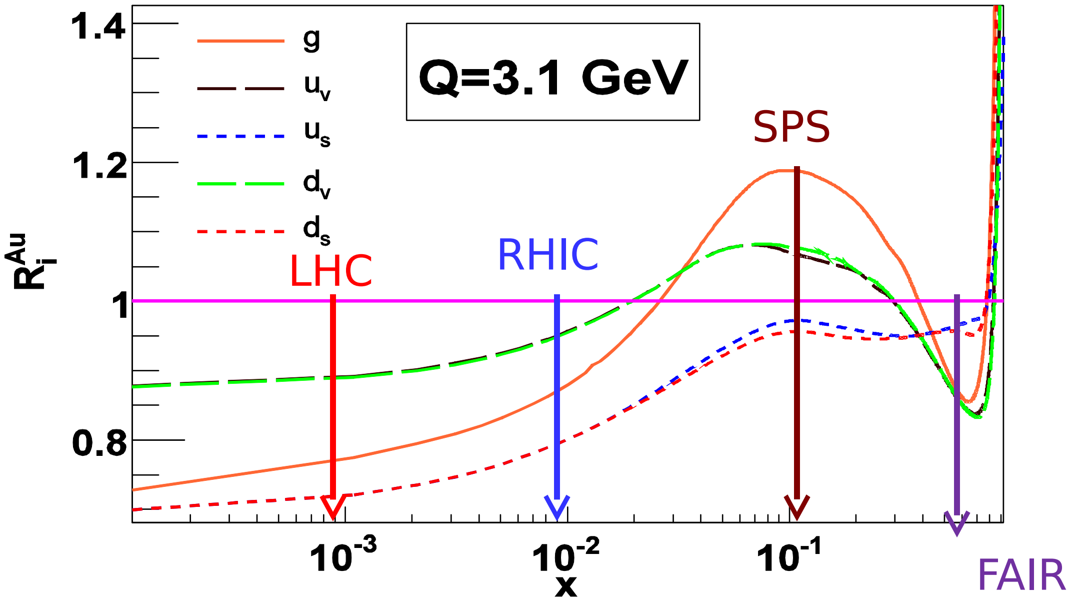
Observed reduction is due to interplay of variety of physical processes (nuclear effects) collectively known as ***cold nuclear matter (CNM)*** effect.

Nuclear effects can come into play throughout the entire evolution period of production:

Modification of initial state pdf's due to presence of other nucleons inside the nucleus: enter in the perturbative cc-bar production cross section :
⇨ decrease (shadowing) or increase (anti-shadowing) in production rate

Once produced cc-bar pair suffers successive interactions with target nucleons
⇨ absorption in the pre-resonance or resonance stage

Initial state shadowing



- PDF in a nucleus is the sum of the proton & neutron parton densities:

$$f_i^A = Z \; f_i^{p/A} + (A - Z) \; f_i^{n/A}$$

- DIS & Drell-Yan measurements showed parton densities inside a nucleus are significantly different relative to a free proton
- Depletion (shadowing) or enhancement (anti-shadowing) depends on (x,Q^2,A)

Nuclear absorption

- Once the J/ψ has been produced, it must cross a thickness L of nuclear matter, where it may interact and

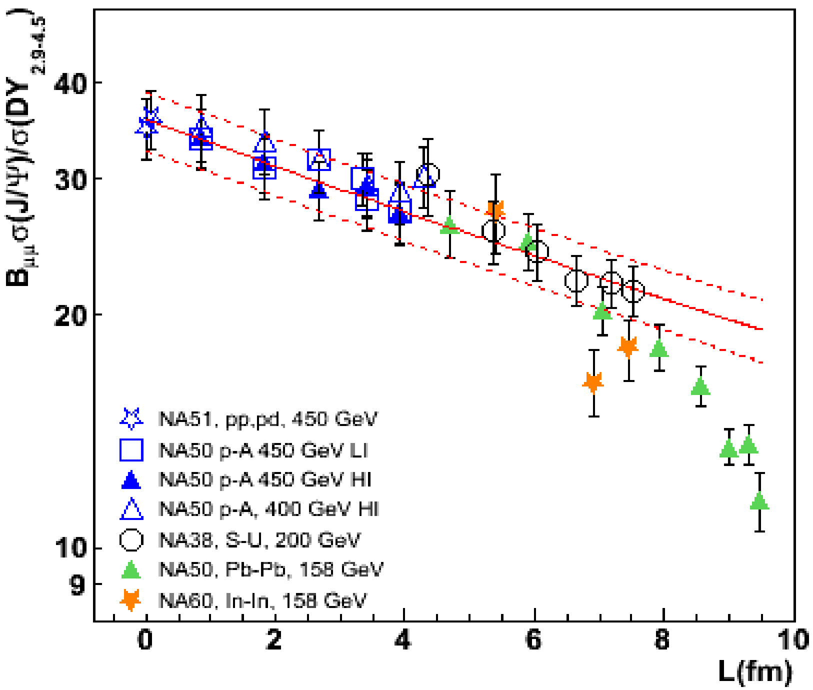
If the cross section for nuclear absorption is $\sigma_{abs}^{J/\psi}$, one expects

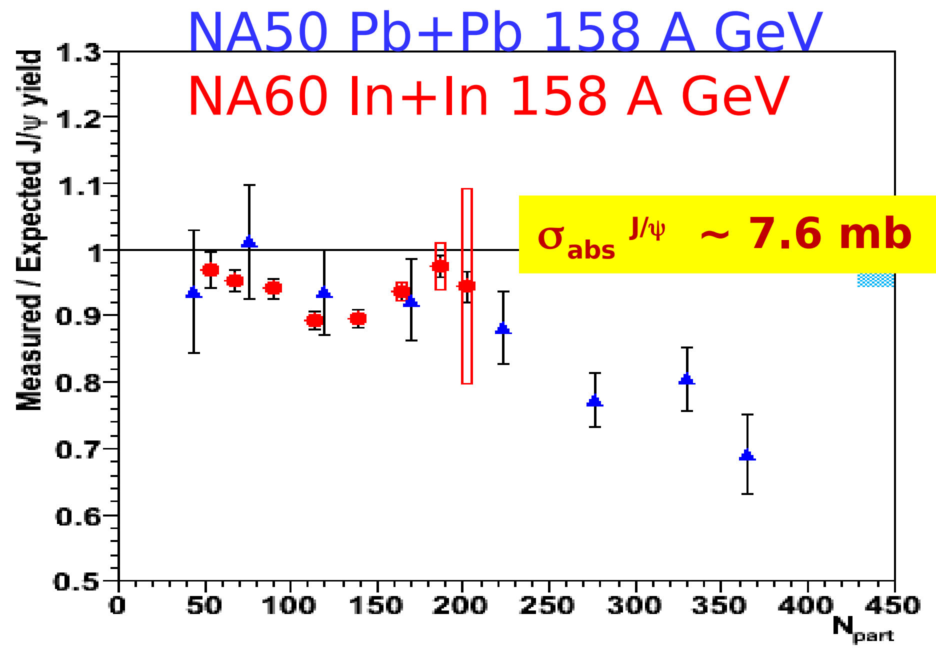
$$\sigma_{pA}^{J/\psi} = A\sigma_{pp}^{J/\psi} e^{-\sigma_{abs}^{J/\psi}\rho L}$$

- L can be calculated in the frame of the Glauber model (geometrical quantity)

J/ψ suppression at SPS

(NA38, NA50, NA60)

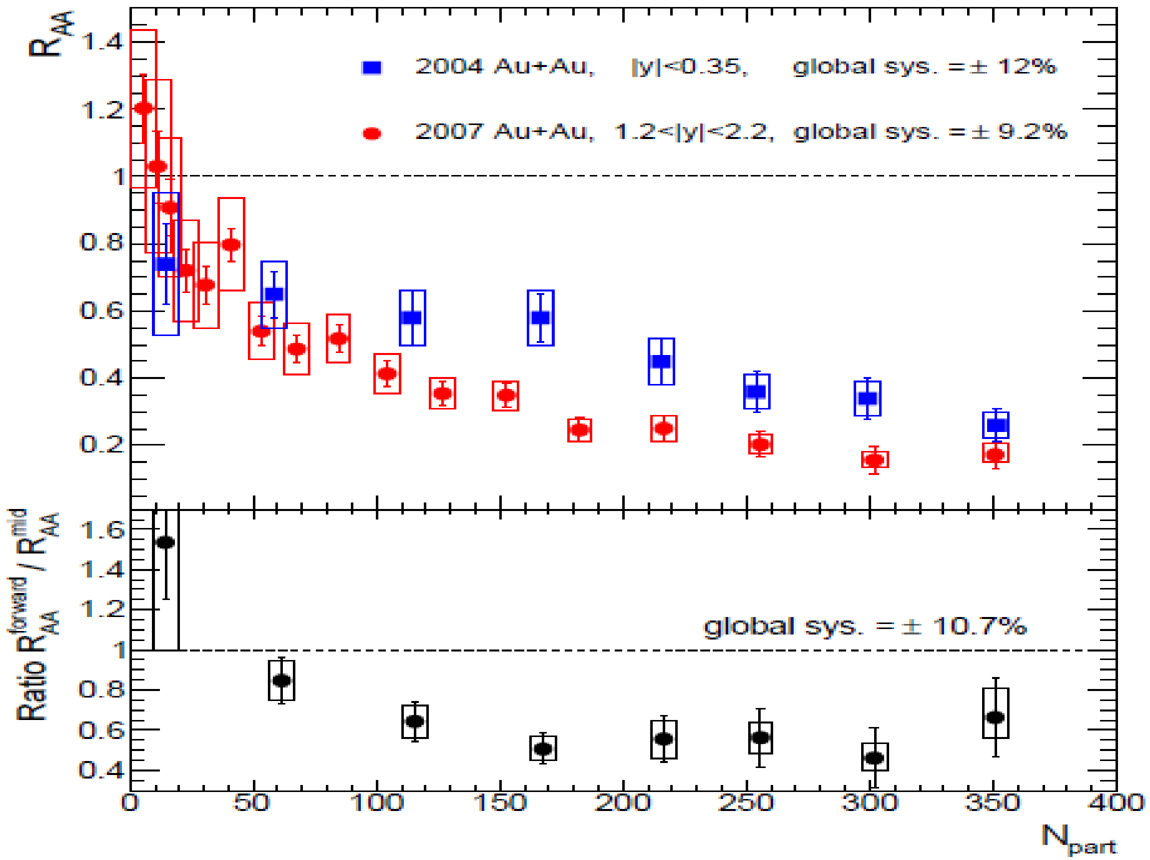




First evidence of anomalous suppression at SPS by NA50 in 158 A GeV Pb+Pb collisions

Data found to be explained by a variety of models w and w/o partonic phase

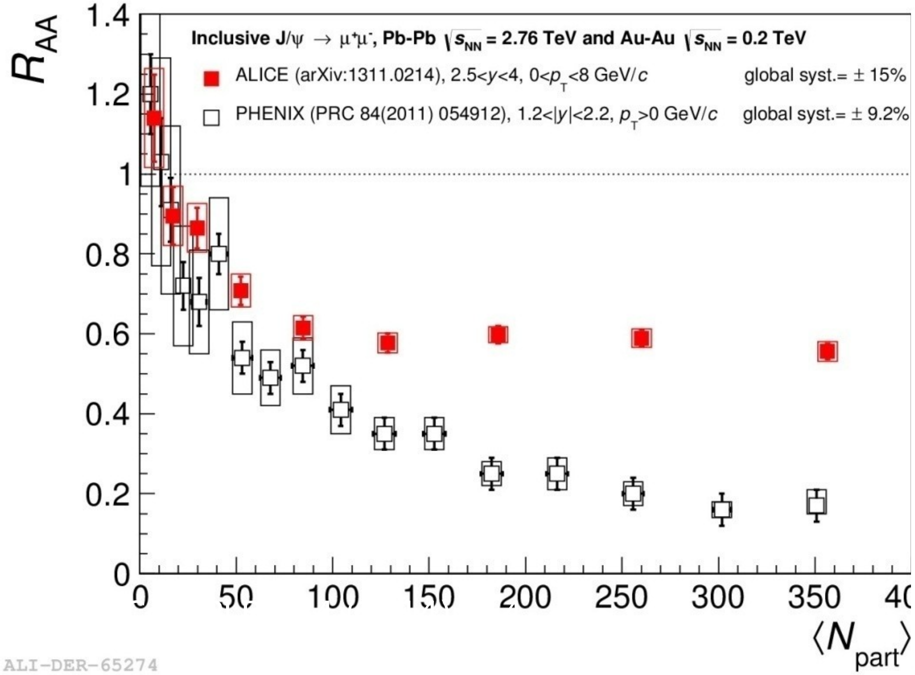
J/ψ suppression at RHIC



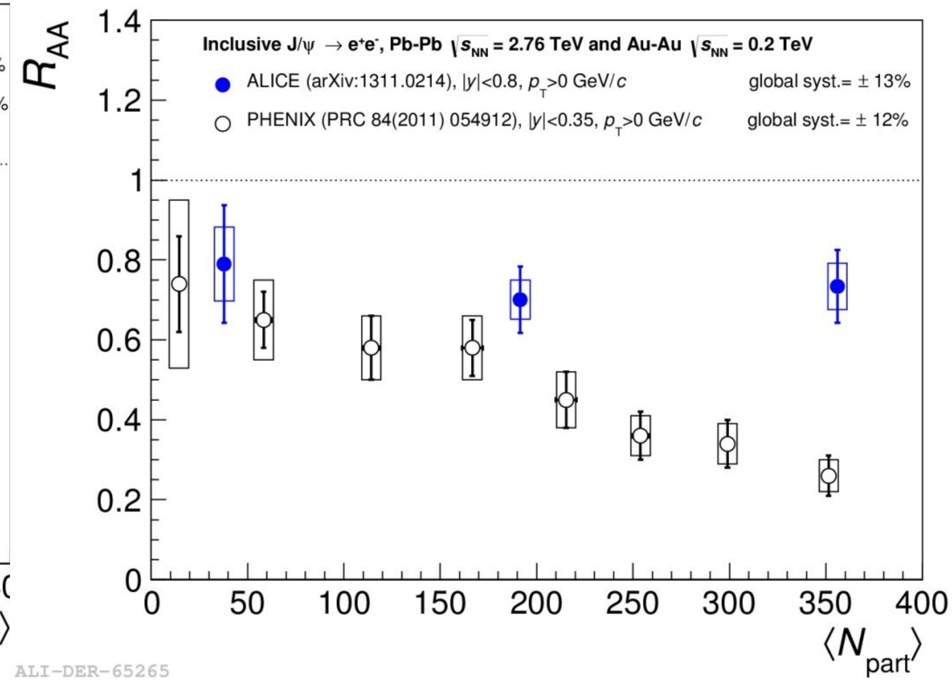
•Data published in terms of nuclear modification factor
•More suppression at forward rapidity than at mid-rapidity
•Hint of recombination process at work

J/ψ suppression at LHC: centrality dependence

ALICE $2.5<y_{J/\psi}<4$
PHENIX $1.2<|y_{J/\psi}|<2.2$



ALICE $|y_{J/\psi}|<0.8$
PHENIX $|y_{J/\psi}|<0.35$

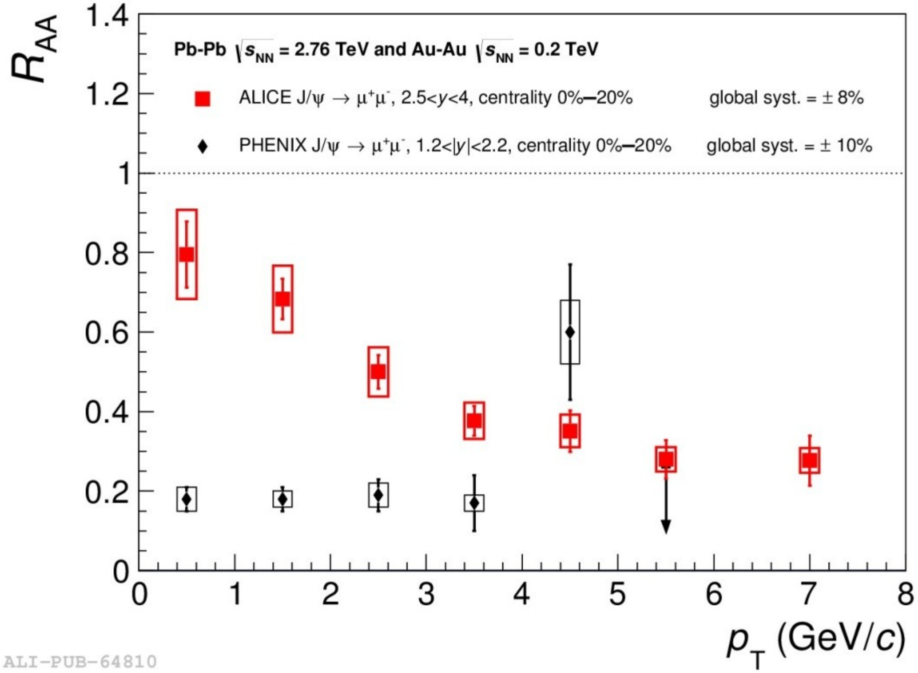


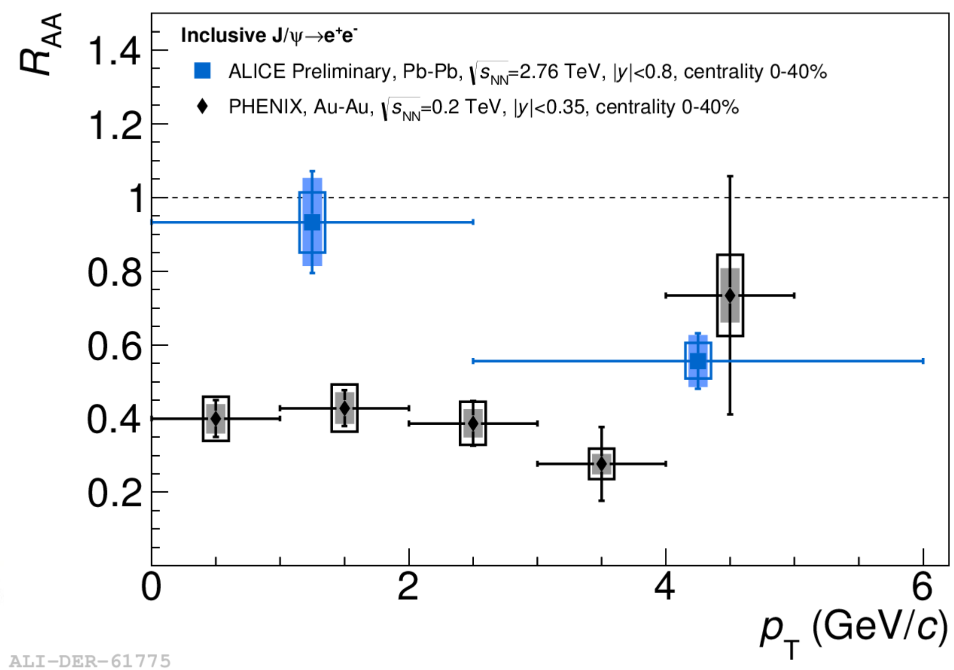
Comparison with PHENIX:
ALICE results show weaker centrality dependence and smaller suppression for central events

Behaviour expected in a (re)combination scenario

J/ψ R_{AA} vs transverse momentum

J/ψ production via (re)combination should be more important at low transverse momentum





- Different suppression for low and high p_T J/ψ
- Smaller R_{AA} for high p_T J/ψ in both rapidity ranges. Striking difference between RHIC and LHC patterns
- Supports recombination picture

Facility for Antiproton and Ion Research (FAIR)

FAIR Modularized Start Version (MSV) :

SIS-100: protons up to 30 GeV, heavy-ions up to 12 (15) A GeV

FAIR Phase -II

SIS-300: protons up to 90 GeV heavy-ions up to 35 (45) A GeV

Intensities:

protons: up to 10^{13}/s

heavy-ions: up to 10^{9}/s

Nucleus-nucleus collisions: **Compressed Baryonic Matter (CBM)**

Physics cases:

- baryonic matter at highest densities
- phase transitions and critical endpoint
- in-medium properties of hadrons

Existing data for J/ψ production data close to threshold energies scenario

Expt.	p_{Lab} (GeV/c)	System	Channel	σ_{in} (nb)
CERN-PS	24	p-p	e^+e^-	0.56 +/-0.16
CERN-PS	24	p-C	e^+e^-	7.2+/-1.8
CERN-PS	24	p-W	e^+e^-	74+/-20
AGS	30	p-Be	e^+e^-	0.1
WA39	39	p-p	$\mu^+\mu^-$	1+/-0.5
IHEP	70	p-Be	$\mu^+\mu^-$	32+/-8

- **Disperse data sets with proton beams**

- **Only measurement of inclusive cross sections (limited phase space, no differential measurements)**

- **No detailed study of target mass dependence, difficult to extract cold nuclear matter effects**

- **Absolutely no data on charmonium production in A-A collisions below top SPS energy (E_b = 160 AGeV)**

J/ψ measurement at CBM-FAIR: Uniqueness & Challenges

Uniqueness:

•No data in heavy-ion sector below top SPS energies, exploratory measurements around threshold energies

•Multi-differential and high precision measurements

Opportunities @ SIS-100:

•Detailed measurement of charm production and propagation in cold matter with beams of proton and light nuclei (C, Ni, ...)

•Test of pQCD inspired models at low energies

•Possibility to investigate sub-threshold production of charm with heavy-ion (Au) beams

Opportunities @ SIS-300:

•Production will be dominated by initial hard collisions, subsequent recombination effects is negligible

•Exact traces of the suppression pattern unlike higher energies

•Characterization of the dense baryonic medium

Challenges:

•Production cross sections are dramatically small

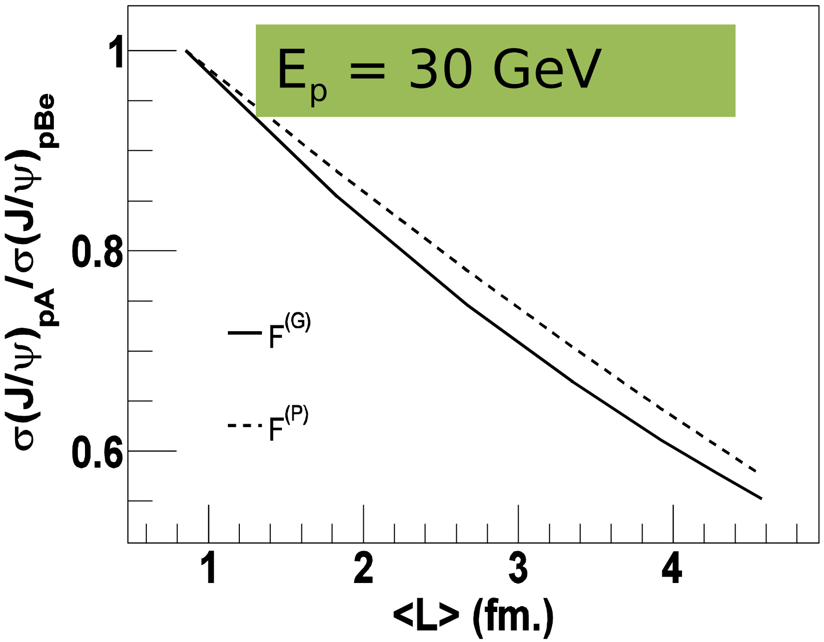
•Requires accelerators with unprecedentedly high beam intensities; with beam intensity for Au ions of 10^9/sec and 1 % λ_I peak event rate 10 MHz

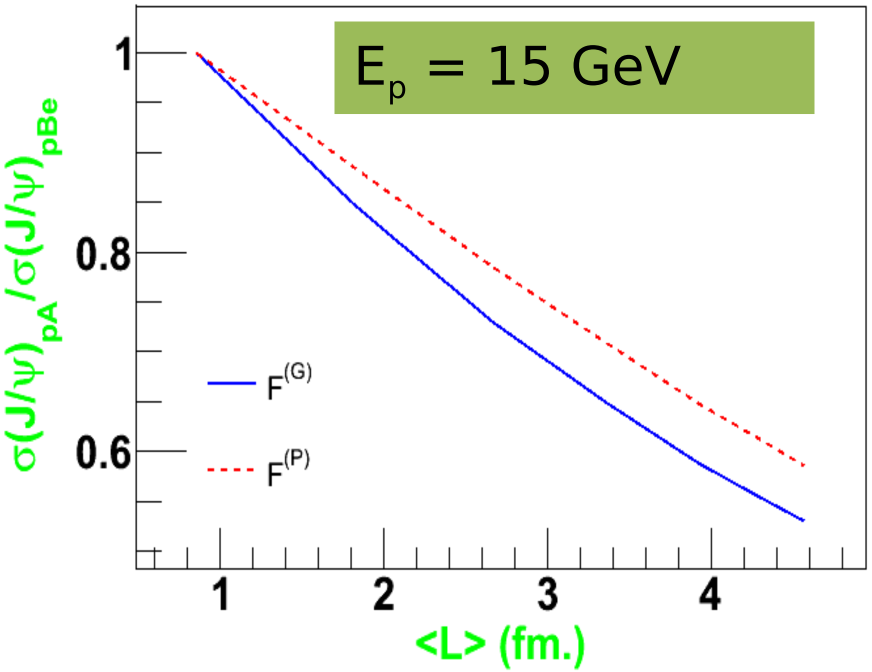
• Detectors with high rate capabilities

• On-line event selection to reduce the raw data rate down to recordable

Cold Nuclear suppression in p+A collisions: FAIR SIS-100

PPB, A. K. Chaudhuri and S. Chattopadhyay, Phys. Rev. C 84, 054914 (2011)





Larger suppression @ FAIR energy domain compared to SPS

Shadowing of the target parton densities in the initial state; larger dissociation in the final state (σ_{abs} ~ 10 - 12 mb @ 15 GeV)

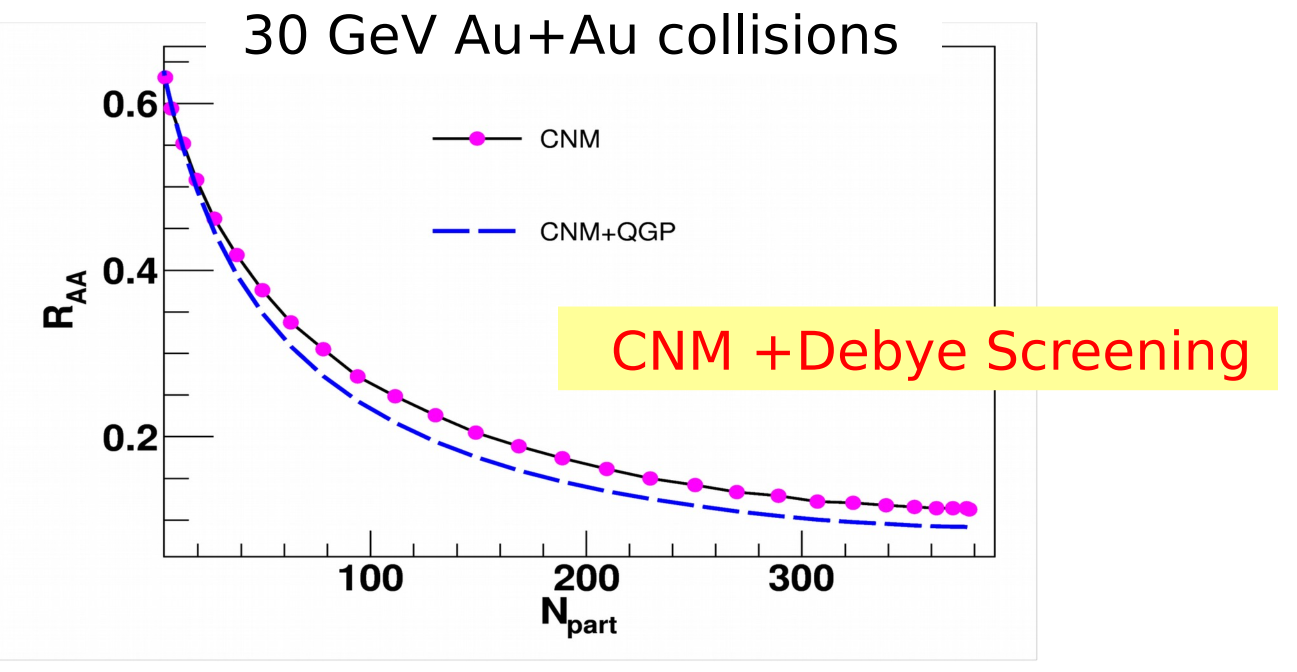
Lower be the beam energy higher is the difference between the amount of suppressions following two hadronization schemes

Can be tested with high statistics data from SIS-100 p+A measurements

Prediction at FAIR SIS-300

J/ψ suppression due to screening inside the plasma

PPB, A.K. Chaudhuri and S. Chattopadhyay,
Phys. Rev. C 85, 064911 (2012) ; Phys. Rev. C 88, 061902 (2013)Phys. Rev. C 89, 044912 (2014)



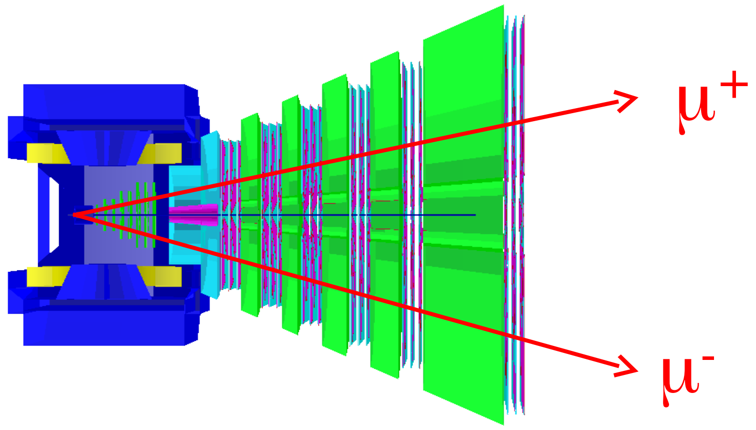
Cold matter effects are more vigorous @ FAIR compared to SPS:
i)Effective shadowing of the nuclear pdfs
ii)Larger final state dissociation

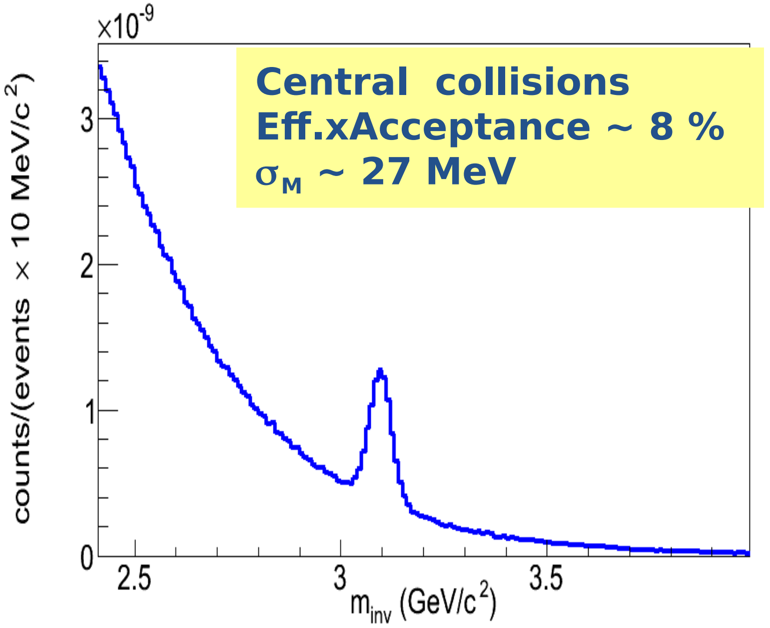
Dominant contribution from CNM effects (~ 90 %)

Debye screening causes much weaker effects (~ 10 – 15 %)

Invariant mass spectra: SIS-300 Au+Au collisions @ 25 A GeV

Operation at maximum rate (10 MHz)
Trigger logic for online event selection





•Clearly identified peak over the background: highly feasible detection

•Background from Drell-Yan and semi-muonic open charm decays are negligibly small

•About factor of 4 better mass resolution (~ 100 MeV for 158 A GeV Pb+Pb collisions @ NA50)

•Mass shape fitted with symmetric Gaussian

Summary

J/ψ suppression considered for a long time as a prominent signature for QGP formation.

A very careful study (and a corresponding theoretical effort) necessary to understand cold nuclear matter effects

At LHC clear signal of regeneration has been seen via:

- Centrality and p_T dependence of R_{AA}
- Non-zero v_2

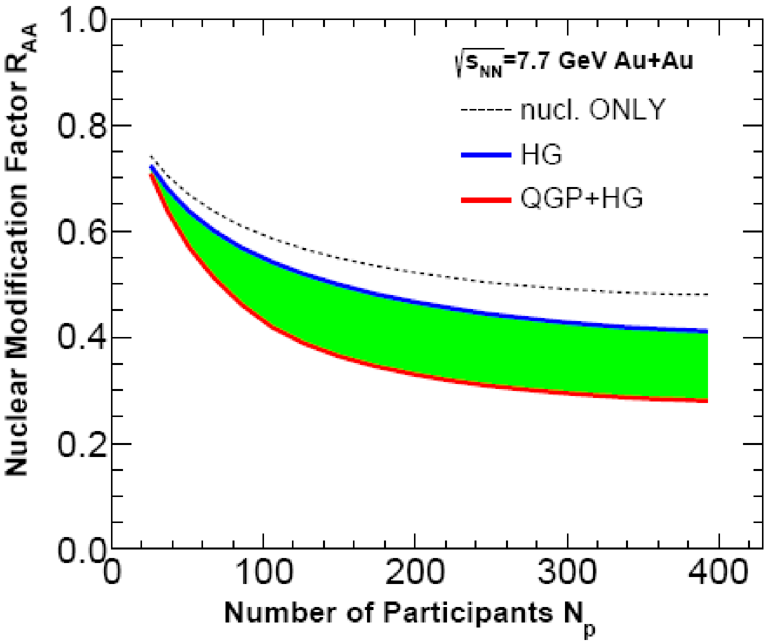
At low energies (FAIR)

- No recombination at work: clean signature of suppression
- CNM suppression becomes more crucial
- Much weaker effect due to Debye screening
- Needs high precision data

Thank you

Anomalous suppression @ FAIR:III

Bayoi Chen, arXiv:1510.07902v2



Dynamics of charmonium from Boltzmann equation

Medium evolution via (2+1) ideal hydrodynamic equation with EOS with 1st order p.t.

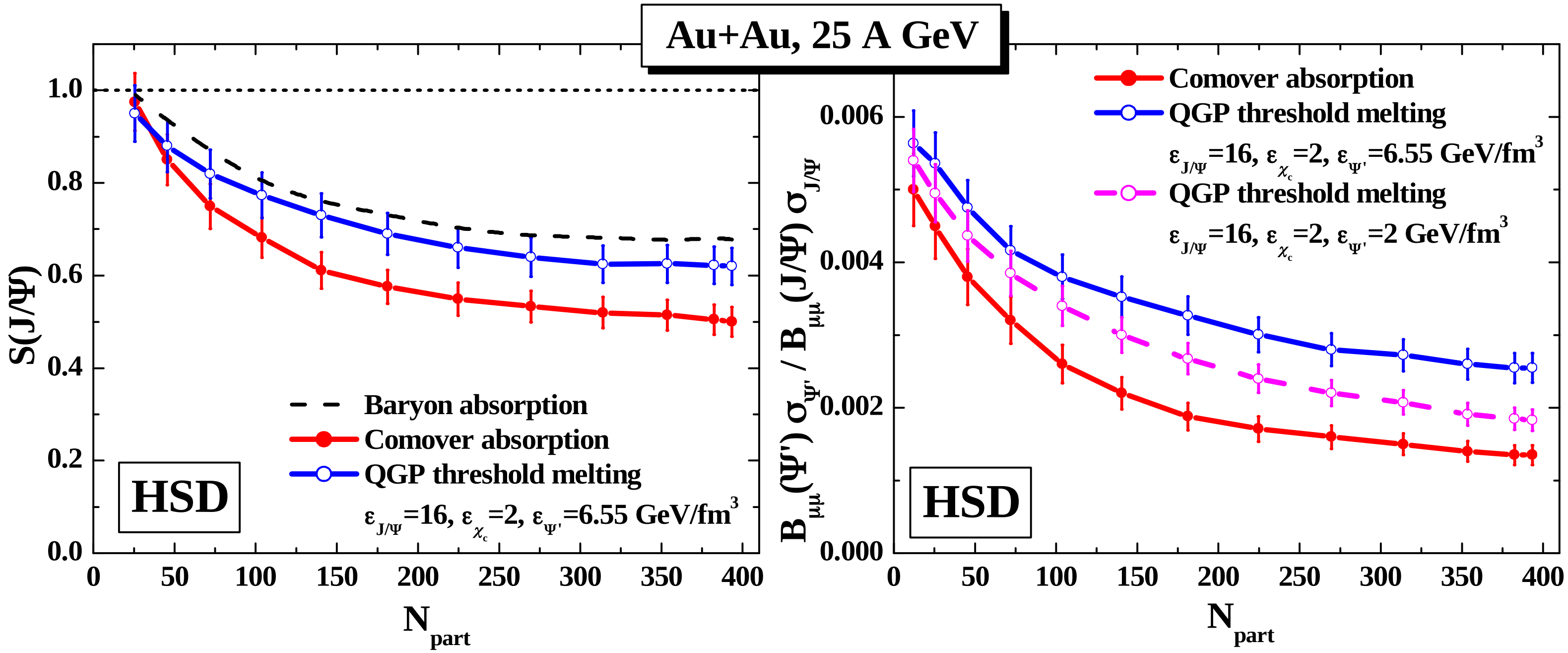
Suppression due to screening + gluo-dissociation in the plasma phase

Suppression in the thermalized hadronic medium (hot hadron gas)

No contribution from recombination effects in either phase

More suppression in the plasma phase compared to hadronic phase

HSD predictions for charmonium suppression at FAIR



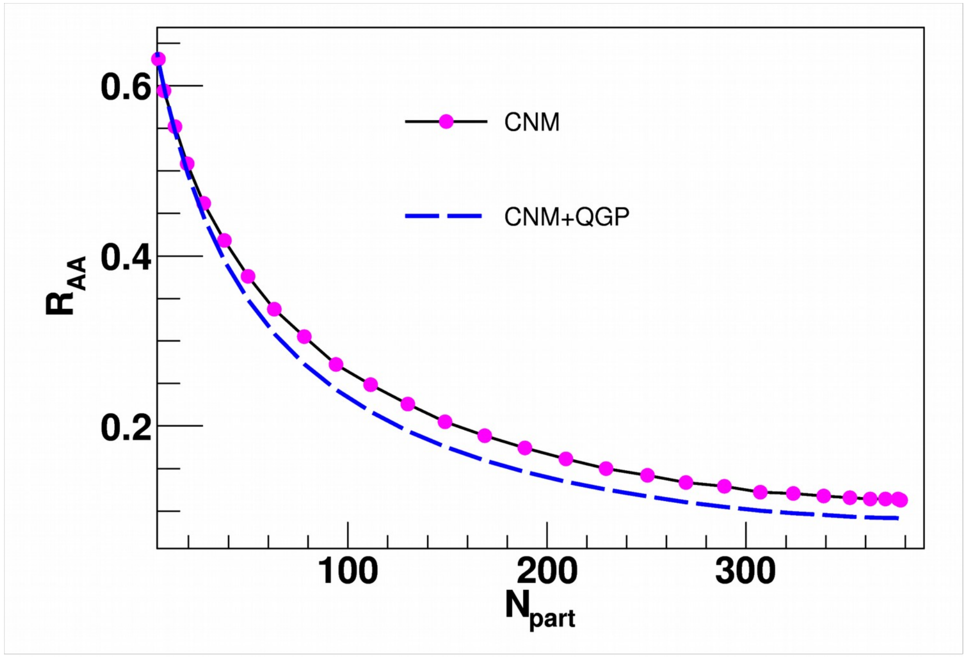
Olena Linnyk et al., arXiv:nucl-th/0612049, Nucl. Phys. A786:183 – 200,2007.

- CNM suppression employed via Glauber model, with σ_{abs} ~ 4.5 mb (the then available value)
- Different scenarios can be distinguished already at FAIR energies:

  Ψ´ over J/Ψ ratio and survival probability are lower in the comover absorption model since the average comover density decreases only moderately with lower bombarding energy whereas the energy density decreases rapidly
- No collisional dissociation in the plasma phase

Model prediction for J/ψ suppression due to screening inside the plasma

30 A GeV Au+Au collisions



❖**Total suppression is obtained assuming factorization, $R_{AA}=R_{AA}^{CNM} \times S^{QGP}$**

❖**Dominant contribution from CNM effects (~ 90 % : initial state shadowing ~ 15 % final state dissociation of the pre-resonant cc-bar pairs ~ 75 %)**

❖**Debye screening causes much weaker suppression (10 -15 %)**

❖**Collision dissociation (thermal and pre-thermal) with hard partons neglected**

❖**Require high precision data to isolate the QGP effects**

Charmonium (bottomonium) states

Various cc and bb bound states have very different binding energy and dimensions

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

Strongly bound states are smaller

The $r_0 > r_D$ condition can be met at different temperatures for the various resonances

Try to identify the resonances which disappear and deduce the temperature reached in the collision