J/ψ suppression in a baryon rich QGP

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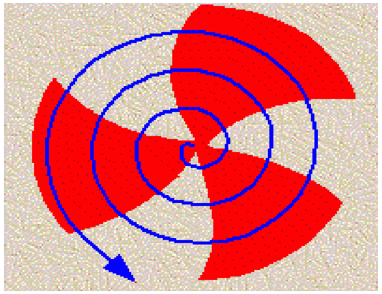
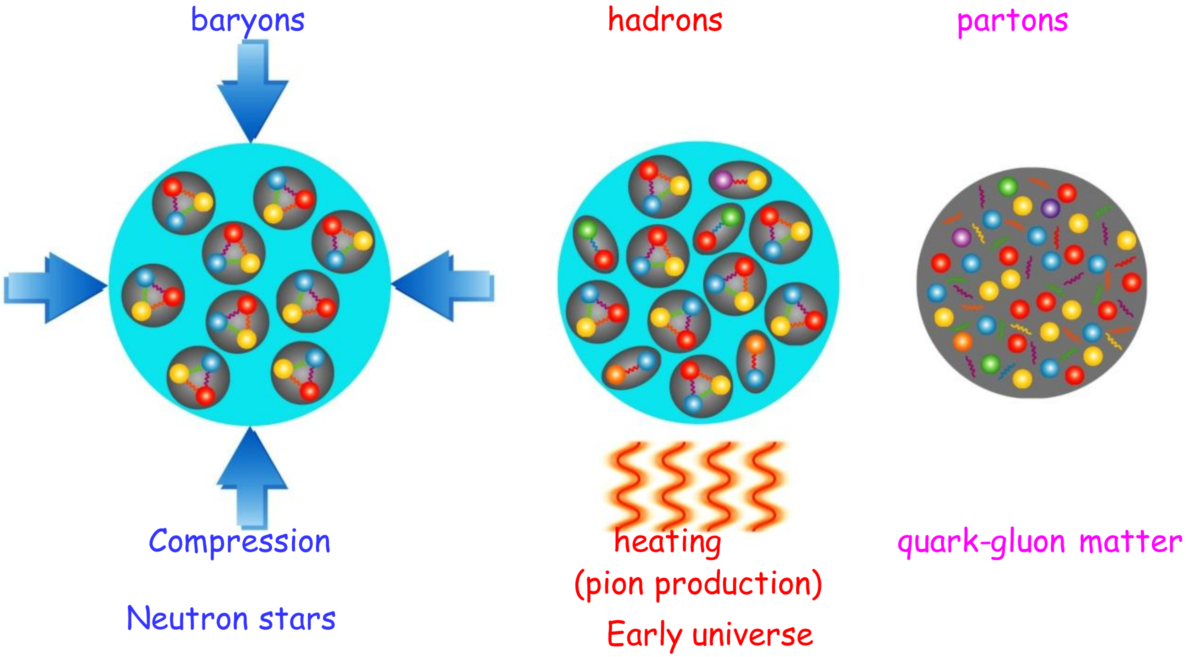


FAIRNESS-2014
Vietri Sul Mare, Salerno, Italy

Introduction

- Different states of matter, their defining features and transition between them always been one of the fundamental issues of physics. Strongly interacting matter opens up a new chapter for such studies.

- Statistical QCD predicts at high temperature and/or densities, strongly interacting matter will undergo a transition from color neutral hadronic phase to a state of de-confined color charged quarks & gluons- QGP

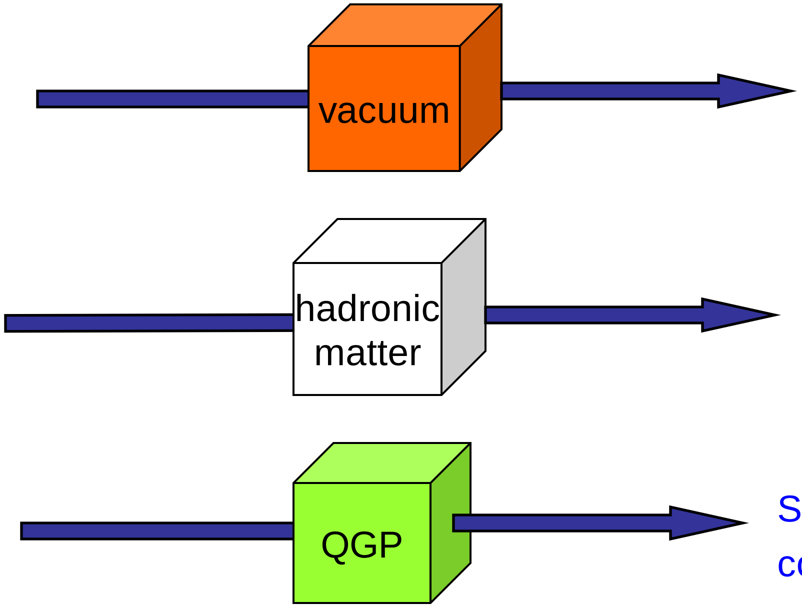


➢Collisions of heavy nuclei at relativistic energies endows us with the opportunity to create and investigate hot and dense nuclear matter in the laboratory

➢However transient nature of the system renders its identification highly complex

➢Needs identification of unambiguous and experimentally viable probes that would clearly indicate the occurrence of the phase transition

The good QCD matter probes should be:



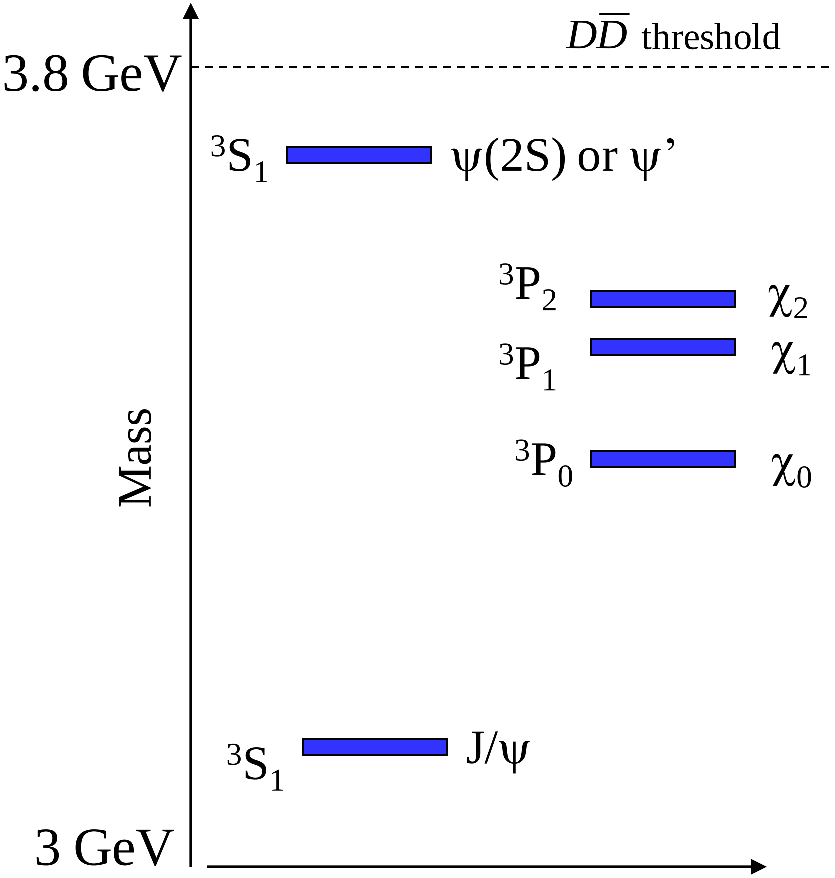
Well understood in “pp collisions”

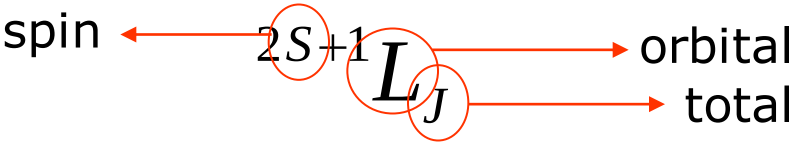
Slightly affected by the hadronic matter (pA collisions),
in a well understood way, which can be accounted for

Strongly affected by the deconfined QCD medium (A+A collisions) **…**

- Till date relentless efforts have been invested both theoretically & experimentally to find suitable probes to indicate color de-confinement in nuclear collisions
- *“Anomalous”* charmonium suppression was long predicted as a ***“smoking gun”*** signature for the de-confinement phase transition
- Due to their high mass they are produced in the early stages of the nuclear collisions

Charmonium states





Charmonium → cc-bar bound state

If $m<2m_D$ → stable under strong decay

Relative motion is non-relativistic (β~0.6)→ non-perturbative treatment

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 q-bar

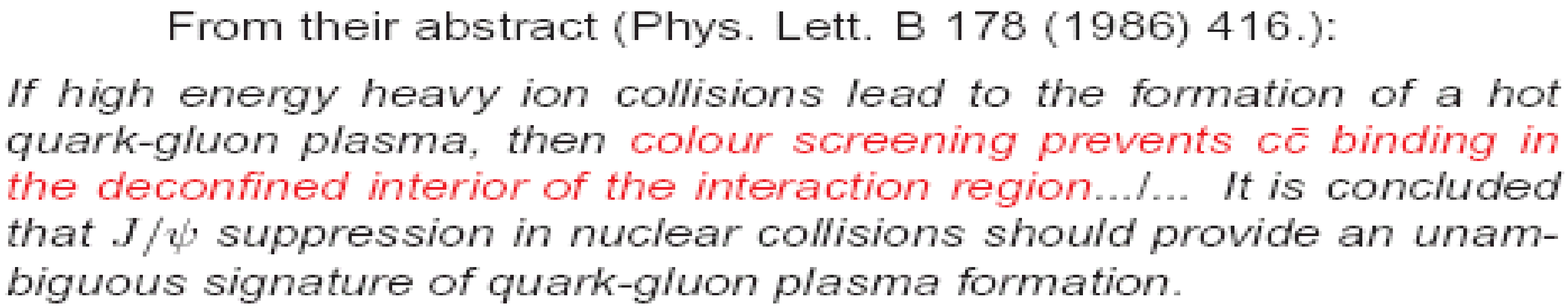
Confinement term

The beginning …

Matsui and Satz prediction (1986) at the origin of the whole field

First paper on the topic
→ 1986, Matsui and Satz

(> 2000 citations!)



From their abstract (Phys. Lett. B 178 (1986) 416.):

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…/… It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

***Subsequent experimental investigations observations*:**

- **Considerable reduction of charmonium production present in p-A collisions compared to scaled hadronic collisions.**
- **Formation of secondary (de-confined) medium is not generally possible.**
- **Effect of the primary medium; existing nuclear matter-> normal nuclear suppression**
- **Offers a robust and well understood reference baseline, in A-A collisions, with respect to which we can clearly and unambiguously identify patterns specific to the high-density medium produced in high-energy nuclear collisions**

...but the story is not so simple

❖Nuclear dissociations are conventionally analyzed within Glauber model framework with the "normal" suppression quantified by an effective absorption cross section σ_{abs}

❖The first set of heavy-ion data on J/ψ production in S+U collisions @ 200 A GeV by NA38 collaboration was found compatible with the Glauber suppression

❖First significant "anomalous" suppression beyond the conventional nuclear suppression was observed @ SPS by NA50 collaboration in Pb +Pb collisions @158 A GeV

❖Data can be explained by a variety of models with & with out incorporating the color de-confinement: additional suppression due to

hadronic (mesonic comovers) dissociation
partonic (gluons + Debye screening) dissociation

No unique answer so far obtained

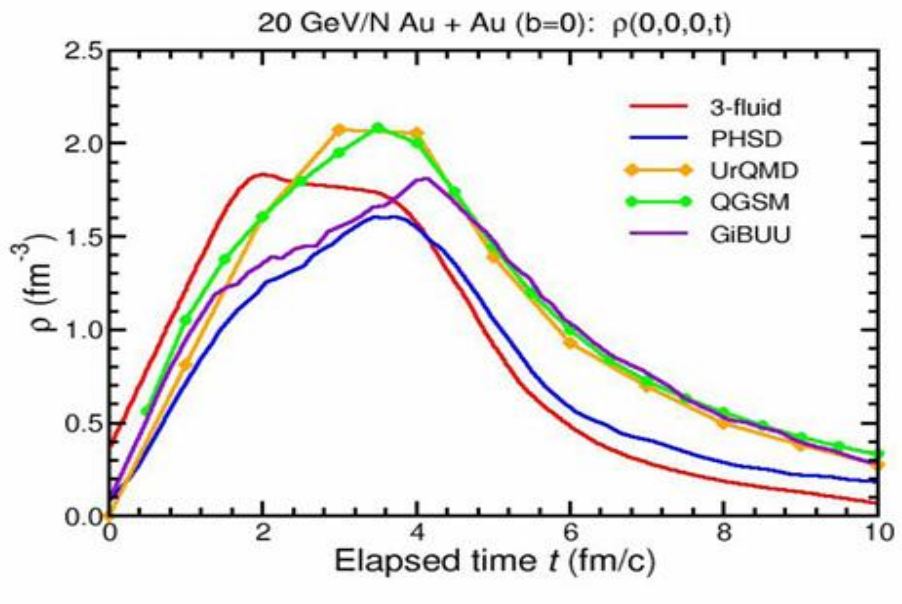
❖ Later NA60 collaboration also observed anomalous suppression in In+In collisions @ 158 A GeV; none of the above models could satisfactorily explain the data

❖Subsequent p+A measurements by NA560 @ 158 A GeV revealed no anomalous suppression in In+In collisions only 25-30 % anomalous suppression in central Pb+Pb collisions

❖At RHIC (E_{cm} = 200 GeV) in Au+Au collisions more suppression at forward rapidity compared to mid-rapidity: suppression is masked by regeneration effects (exogamous production at the phase boundary)

… till date we do not have a clear picture

J/ψ production in nuclear collisions at FAIR



- ❖In nuclear collisions at FAIR a moderate temperature high baryon density medium is anticipated
- ❖Maximum net baryon densities from 5 - 40 AGeV ~ 1 - 2 fm^{-3} ~ (6 – 12) ρ_0 (ρ_0 ~ 0.15 fm^{-3})
- ❖ Remarkable agreement between different models
- ❖Experimental observables are expected to be sensitive to density as well as temperature.
- ❖ Charmonium production might get modified in a baryon rich medium
- ❖High baryon density might lead to de-confinement
- ❖Charmonium production might probe the confining status of the medium; depending on the structure of the medium the charmonium suppression pattern/spectra can be completely different.

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

❖Till date no measurements on J/ψ production in heavy-ion collisions below 158 A GeV

❖In low-energy nuclear collisions, production cross sections are dramatically small

❖Measurements require accelerators with very high beam intensities and detectors with very high rate capabilities

❖At FAIR energies (E_b = 10 – 35 (45) A GeV), charm production will occur close to the kinematic production threshold.

❖Too low production cross sections (@ E_b = 25 A GeV $\sigma_{NN} \sim 0.1$ nano barn) ; small branching ratio to the di-lepton channel (~ 6 %)

❖Charmonia are *rare probes* in the low energy collisions (Yield=$B_{\mu\mu}$ x Mult ~ 10^{-7} for 25 A GeV Au+Au)

❖CBM is the only modern heavy-ion facility to look for rare probes in nuclear collisions

❖Measurements will be realized with unprecedentedly high intensity beams delivered by FAIR

Maximum beam intensity for Au ions: 10^9 / s (factor of 1000 higher compared to SPS)

For a Au target of thickness 250 μm, peak event rate 10 MHz.

❖Requires very fast detectors that can be operated at MHz rates

We have developed a model based on color screening picture for estimation of charmonium suppression in a baryon rich QGP

Anomalous Charmonium suppression @ FAIR: theoretical formulation

We have developed a model based on color screening picture for estimation of charmonium suppression in a baryon rich QGP

Suppression due to color screening are generally implemented in literature within threshold picture

Suppression is either total or absent depending on some critical value

In-medium screening mass $m_D(T,\mu_q)$ is used the decide fate of a charmonium state implanted in the expanding plasma

$$m_D(T,\mu_q) = g(T,\mu_q)T\sqrt{N_c/3 + N_f/6 + N_f/2\pi^2(\mu_q/T)^2}$$

m_D estimated from LO pQCD (T. Toimela, PLB 1983)

Medium dynamics from realistic UrQMD transport calculations

Color screening within threshold picture: general considerations

Central assumption of the theory is the existence of a characteristic threshold temperature T_d or energy density ($\varepsilon_d \sim T_d^4$) (T_d values from potential model or lattice correlator)

Encloses plasma volume inside which screening radius is smaller than the bound state radius

Resonance formation is forbidden for all cc-bar pairs inside the region at corresponding resonance formation time t_F (note in the plasma frame $t_F = \gamma t_F$)

Competition between t_F and finite volume and life time of the plasma would lead to characteristic p_T dependent survival probability at central rapidity smaller suppression at higher p_T

Common consideration is that medium attains thermal properties over a time comparable to the formation time of the cc-bar pairs in the plasma frame

Different situation @ FAIR due to different kinematical conditions

Anomalous Charmonium suppression @ FAIR: theoretical formulation

Intrinsic formation time: $\tau_{F,i}$ ~ 1-2 fm for different charmonium states

In the collision frame $t_{F,i} \sim \tau_{F,i}$ as $\gamma_i \sim 1$ (p_T very small mid-rapidity $p \sim p_T$)

Plasma formation time: $\tau_0 \sim t_{coll} \sim 2R_A/\gamma\beta \sim 3$ -4 fm

Plasma would encounter fully formed charmonium bound states

Debye screening would dissociate the bound states

Survival probability for the ith charmonium state can be modeled as:

$$S_i^{QGP}(b,s,\tau) = \Theta[r_i - r_D(b,s,\tau)]$$

r_i denotes the size of the particular charmonium state (0.5 fm for J/ψ, 0.72 fm for χ_c and 0.9 fm for ψ')

S_i^{QGP} can be experimentally compared with R_{AA}/R_{AA}^{CNM}

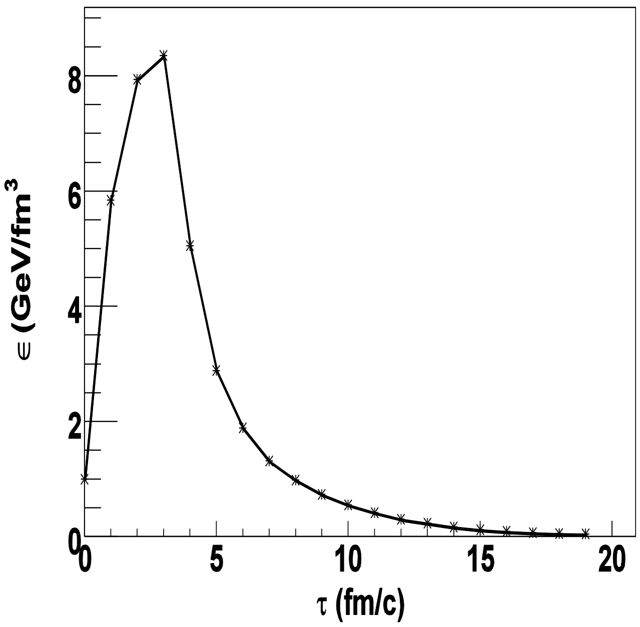
R_{AA}^{CNM} can be modeled from the p+A collisions

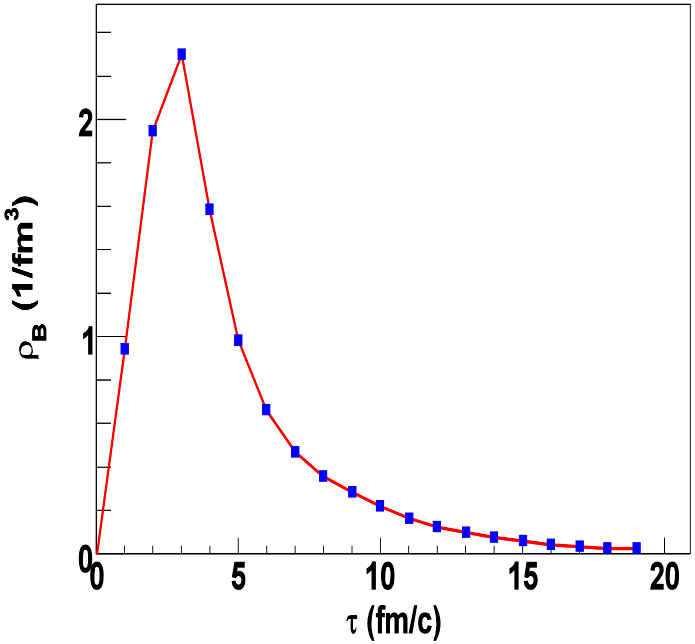
Inclusive survival probability is obtained by integrating over space time

Implement threshold energy density (ε_c ~ 1 GeV/fm^3) for plasma formation finite space-time extent of the plasma

Au + Au collisions @ 30 A GeV

I. C. Arsene *et. al*., Phys. Rev. C 75, 034902 (2007)





Time variation of central densities from UrQMD

Add spatial profile according to n_{part} (b,s)

$$\epsilon(\mathrm{b},\mathrm{s},\tau) = k_1\epsilon_0(\tau) \times n_{part}(\mathrm{b},\mathrm{s})$$

$$\rho_B(\mathrm{b},\mathrm{s},\tau) = k_2\rho_{B,0}(\tau) \times n_{part}(\mathrm{b},\mathrm{s})$$

Get space-time dependent densities

Plug densities into a suitable plasma EOS

Phenomenological QGP EOS proposed by Kapusta (*J. I. Kapusta, Phys. Rev. C 81, 055201 (2010)*)

Matches with the LQCD calculations at zero density and ground state nuclear matter at zero temperature

One input parameter T_0 can be identified with T_c at $\mu_B = 0$

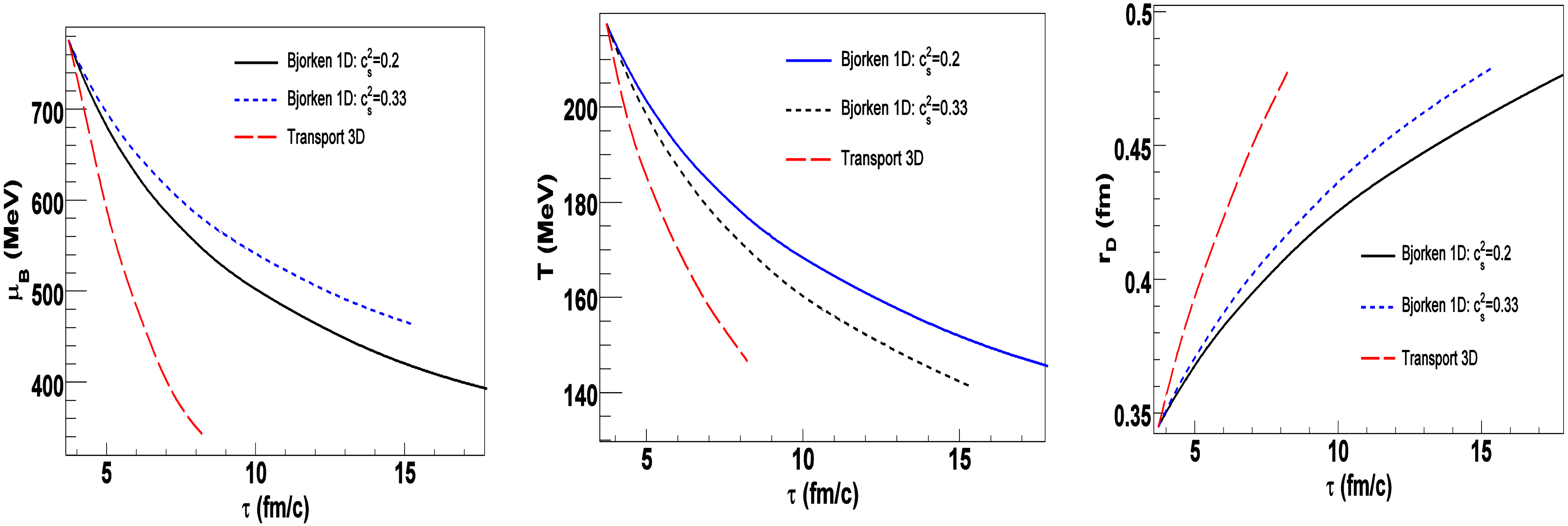
Get the critical density ε_C for plasma formation and assume it to be constant

Recent calculations indicate $T_c \sim 160$ MeV

Get the T, μ_B at each space time point

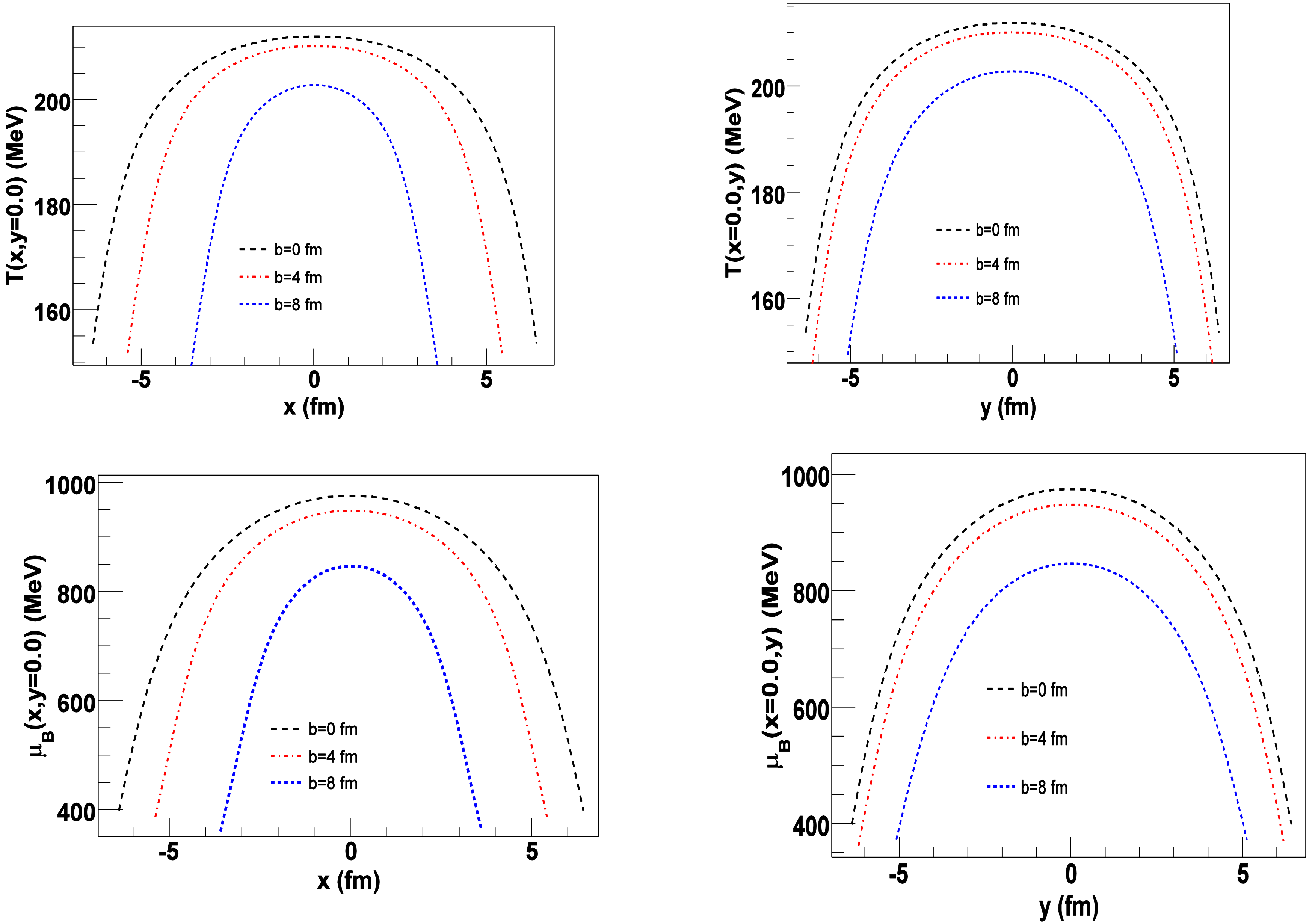
Calculate in medium $m_D(T, \mu_B)$

Temporal profile of the central cell in central collisions



- **Critical energy density for plasma formation ε_C ($N_f = 2$) ~ 0.8 GeV/fm^3**
- **Endows plasma with a finite space-time extent, evolution stops at $\varepsilon(s,\tau) = \varepsilon_c$**
- **Role of transverse dynamics: comparison between full (3+1)-D expansion and Bjorken boost invariant longitudinal expansion with different c_s^2**
- **Transverse expansion causes faster cooling and dilution of the fireball**

Spatial profile of T and μ_B in the transverse plane at τ_0



Determination of the limits of time integration

Lower limit assumes to coincide with the thermalization time τ_0

Calculated from the passing time of the two colliding nuclei

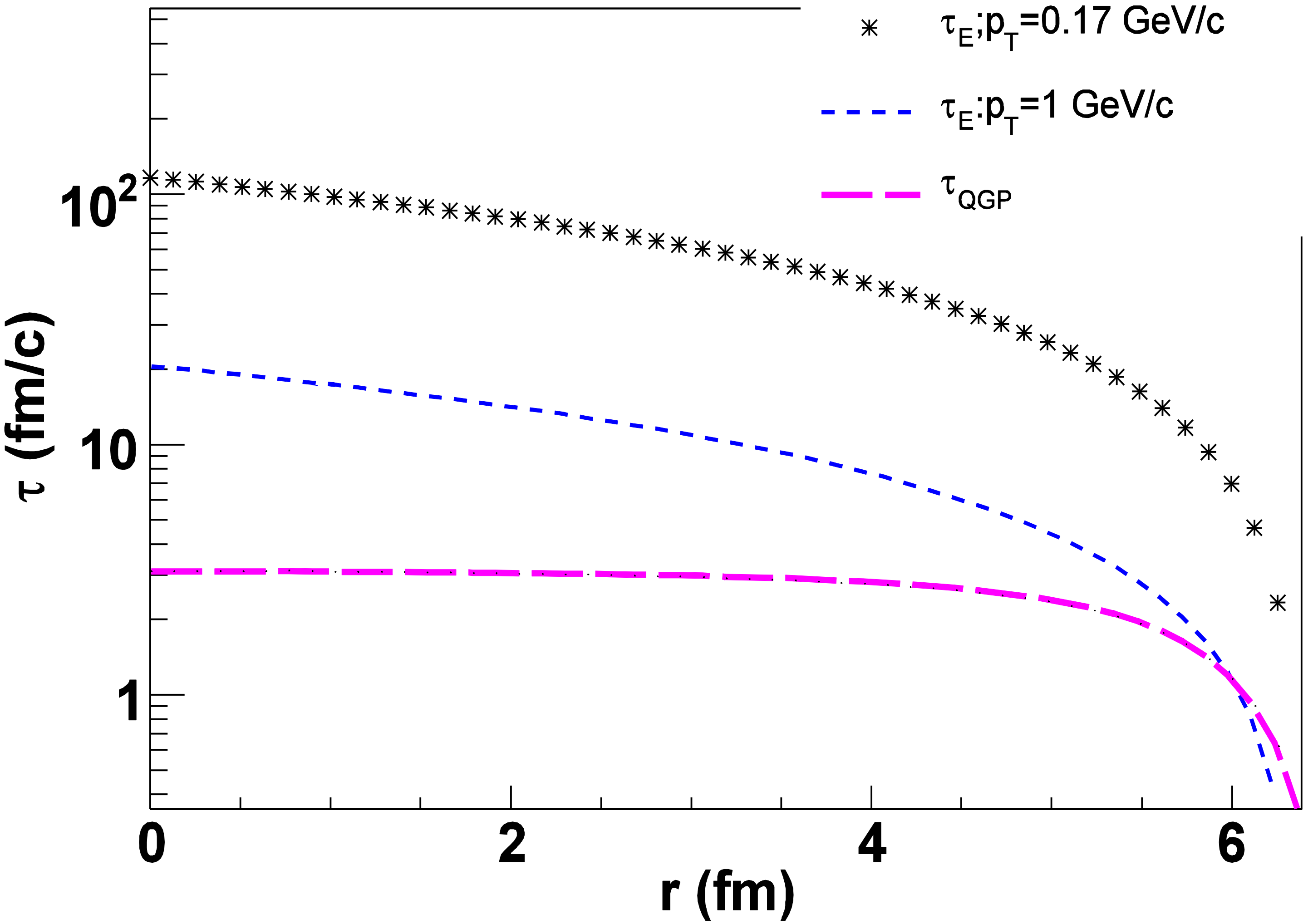
$$\tau_0 = 2R_A/\gamma\beta + \Delta z/2\beta \approx 3-4\,fm$$

Upper limit is decided by min (τ_E, τ_f); τ_E is the escape time and τ_F denotes plasma extinction time ($\varepsilon(r, \tau_F)=\varepsilon_c$)

$$d = -r\cos\phi + \sqrt{R^2 - r^2\sin^2\phi} \qquad \tau_E = M_T d / p_T$$

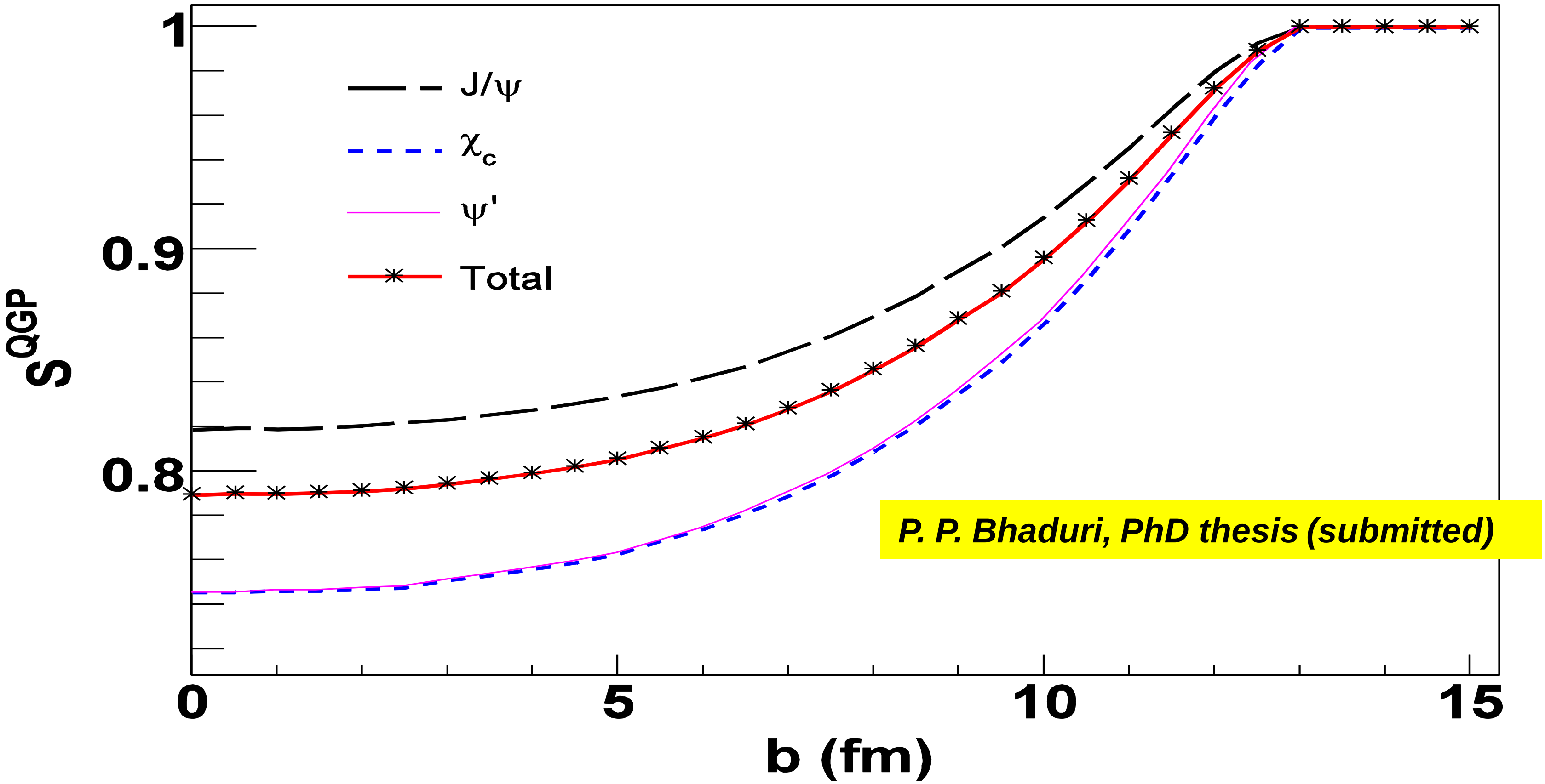
At FAIR energies the charmonium will have very low p_T

Screening remains operational throughout the life time of the plasma



p_T independent survival probability

Centrality dependence of inclusive survival probability



P. P. Bhaduri, PhD thesis (submitted)

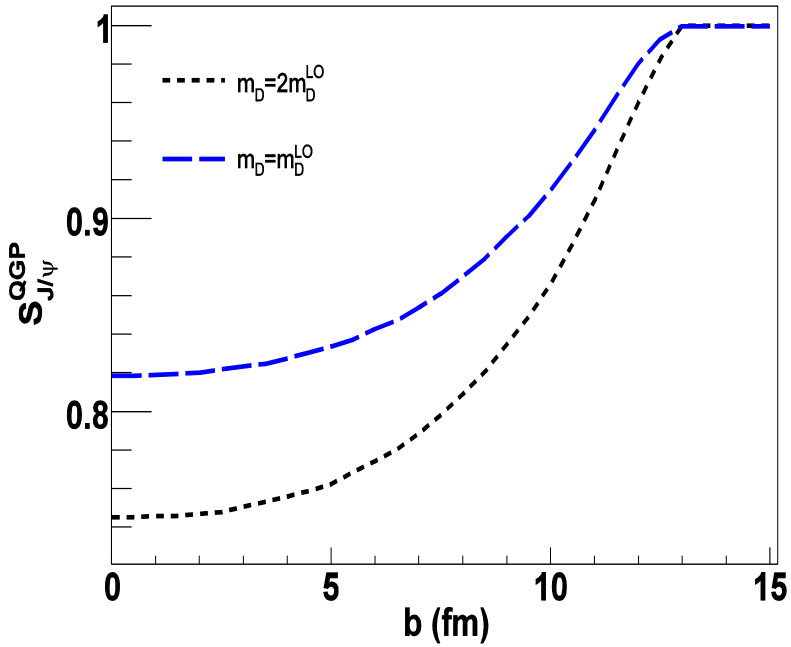
Effects of feed down is included: 30 % from χ and 10 % from ψ'

Stot=$0.6S_{J/\psi} + 0.3\ S_{\chi} + 0.1S_{\psi'}$

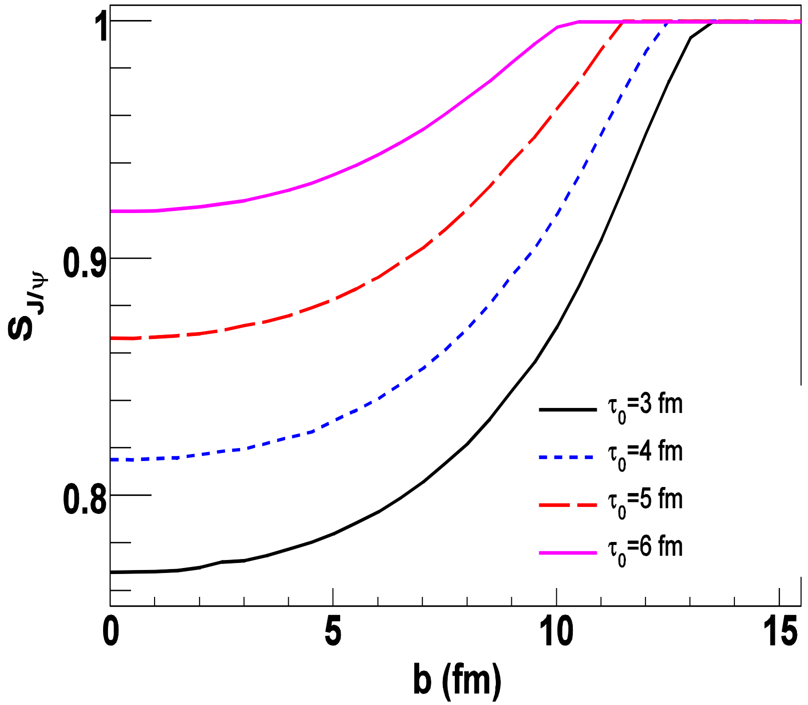
Maximum of ~ 20 % suppression due to color screening

Sensitivity to the model parameters

Debye mass



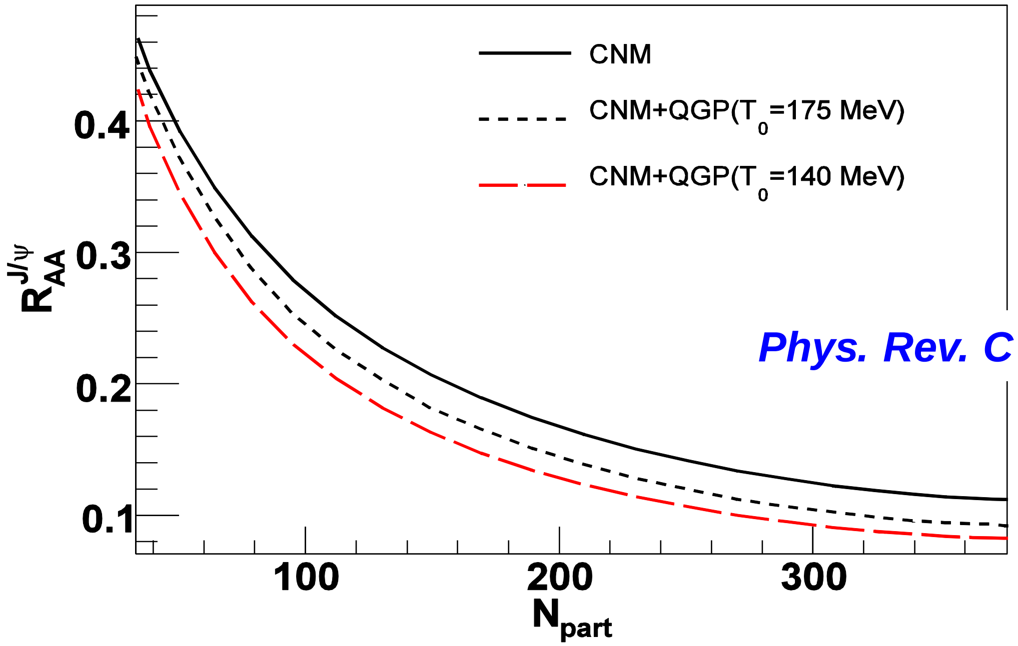
Thermalization time



- **Non-perturbative effects in screening mass are too meager to be detected for finite experimental resolution**

- **Late thermalization smaller anomalous suppression**

Model prediction for plasma suppression @ FAIR



Phys. Rev. C 88, 061902 (R) (2013)

- ❖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 %)

- ❖Plasma suppression is sensitive to the QGP EOS

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

- ❖Require high precision data to isolate the QGP effects

Summary

At FAIR energies, charmonium suppression should be a clean signal like upsilons at LHC

Production from initial hard collisions; suppression effects are not likely to be masked by subsequent regeneration effects

Charmonium suppression has been calculated using threshold model

Screening implemented through in-medium Debye mass

Medium evolution is obtained from UrQMD

Screening gives maximum 15% -20% suppression in the most central collisions

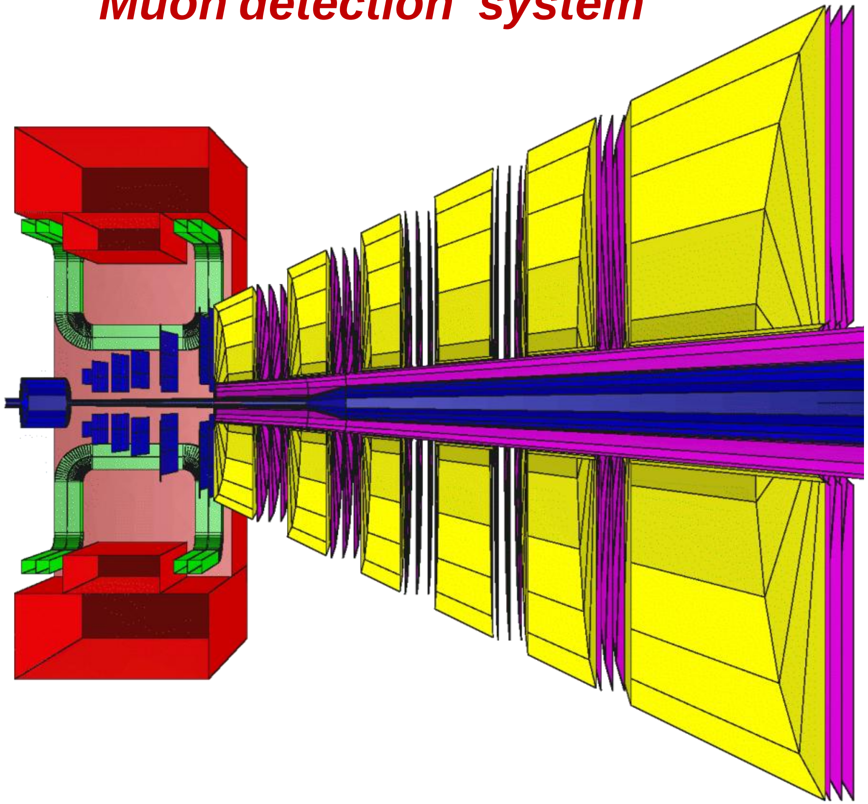
Lack of estimation of dissociation due to hard partonic collisions

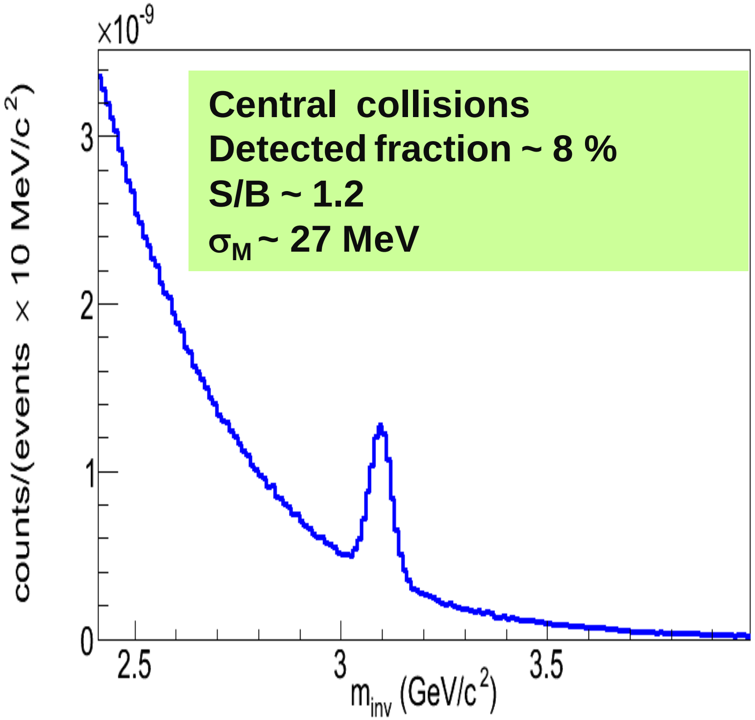
Probably large pre-equilibrium suppression due to late plasma formation time.

A better way to estimate the dissociation in the thermally and chemically equilibrated plasma phase is to calculate the in-medium decay width with a realistic potential model

Our efforts for J/ψ detection in Au+Au collisions @ FAIR (25 A GeV)

Muon detection system





Central collisions
Detected fraction ~ 8 %
S/B ~ 1.2
σ_M ~ 27 MeV

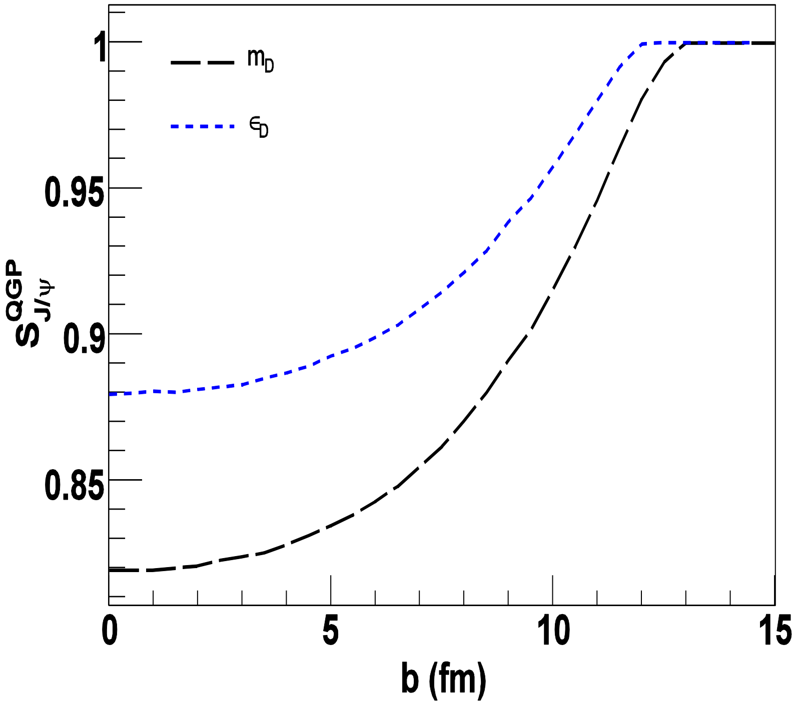
- Background represents the combinatorial one; calculated using Super Event (SE) analysis
- Clearly identified peak over the background: highly feasible detection
- About factor of 5 better mass resolution (~ 100 MeV for 158 A GeV Pb+Pb collisions @ NA50)
- Improved S/B for central collisions

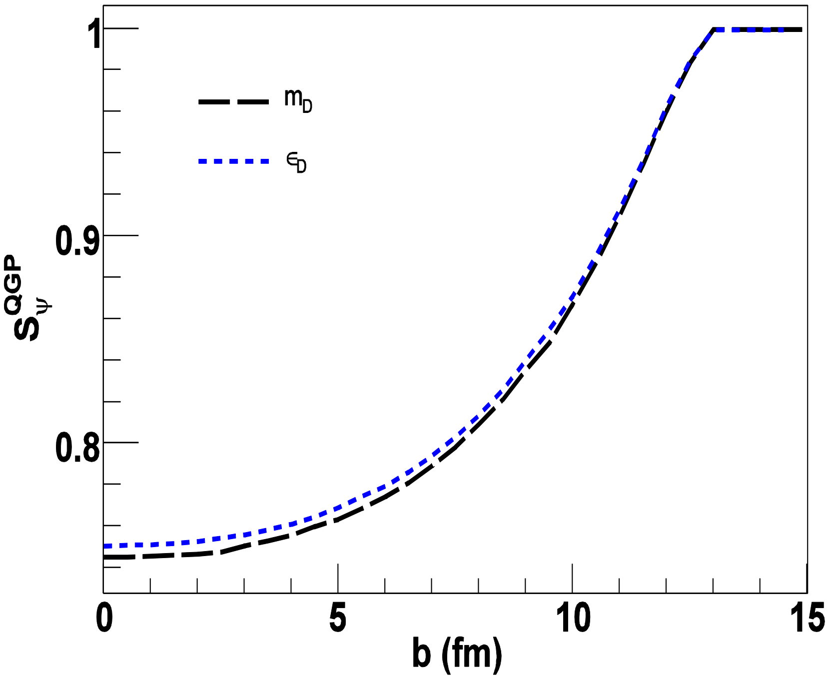
Thank You

Back ups

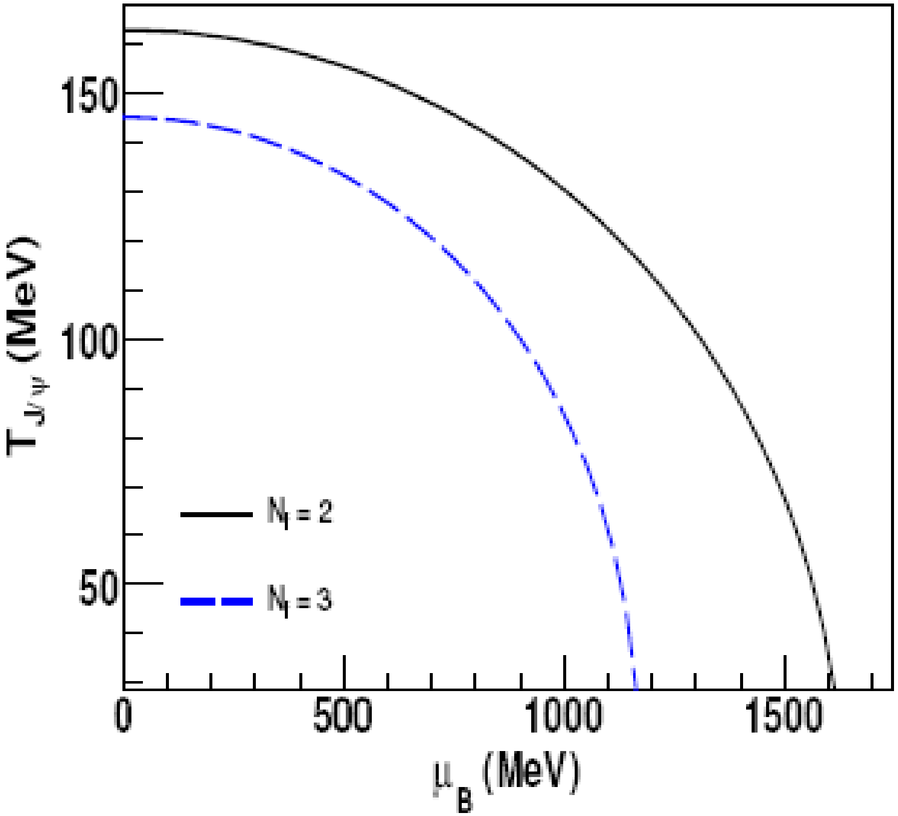
Modeling survival probability with energy density

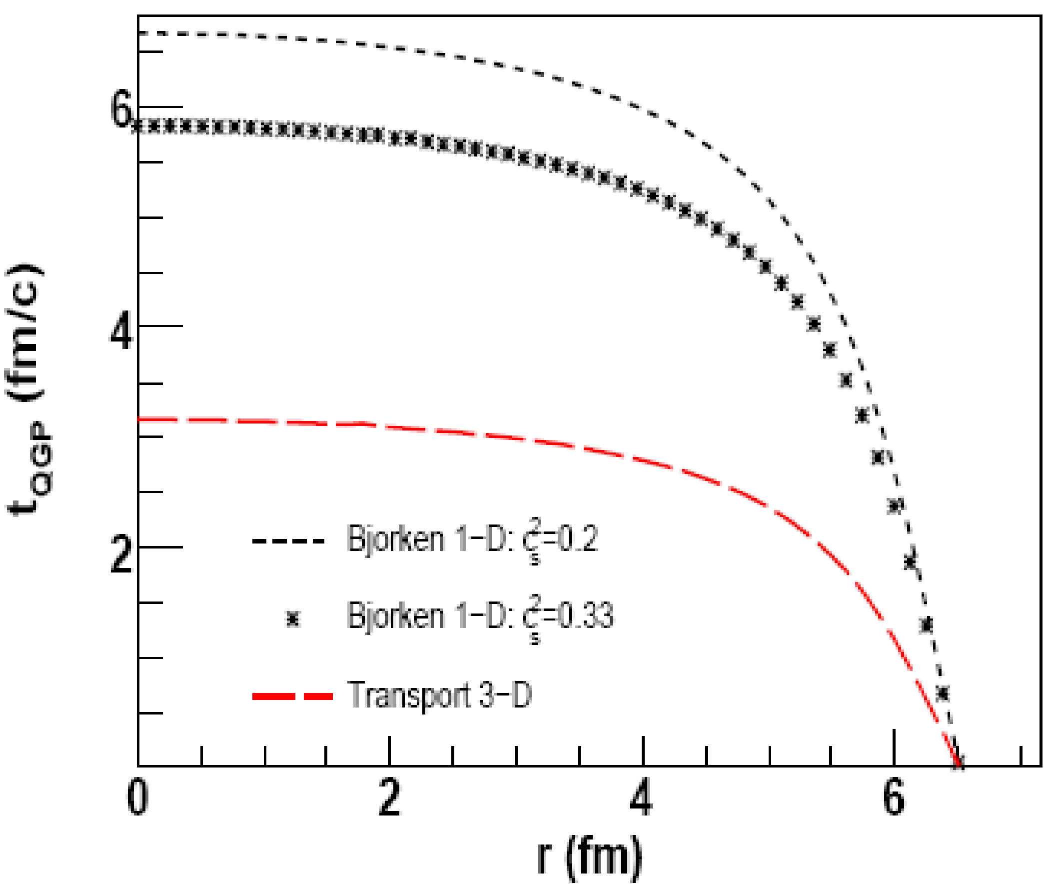
$$S_i^{QGP}(b,s,\tau) = \Theta[\varepsilon_D - \varepsilon(b,s,\tau)]$$





Weak binding scenario: $T_{J/\psi}$ = 1.2 T_c, $T_{\chi,\psi}$ =T_c


$T_{J/\psi}$ (MeV)
150
100
50
0
500
1000
1500
μ_B (MeV)
$N_f = 2$
$N_f = 3$


6
4
2
t_{QGP} (fm/c)
0
2
4
6
r (fm)
Bjorken 1-D: c_s^2=0.2
Bjorken 1-D: c_s^2=0.33
Transport 3-D

$$m_D(T,\mu_q) = g(T,\mu_q)T\sqrt{N_c/3 + N_f/6 + N_f/2\pi^2(\mu_q/T)^2}$$

$$r_D(T,\mu_q) = 1/m_D(T,\mu_q)$$

Charmonia in FAIR energy collisions

FAIR beam energy range: E_b = 8 – 40 A GeV

CBM is the dedicated relativistic heavy-ion collision experiment;

Aim is to explore the QCD phase diagram in the region of high net baryon densities and moderate temperatures

High baryon and energy densities are anticipated in central Au+Au collisions

Max. net baryon densities from 5 - 40 AGeV ~ 1 - 2 fm^{-3} ~ (6 – 12) ρ_0

Mutual agreement between different models

High baryon density might lead to deconfinement transition to a baryon rich QGP.

Charmonium suppression is one of the early probes of color deconfinement.

CBM has a dedicated program to measure charmonium production in heavy-ion collisions for the first time

No data till now available below top SPS energy (E_b = 158 A GeV)

We have calculated the survival probability of the charmonium states suffering dissociation due to screening in an evolving QGP medium based on threshold scenario

Threshold model

Original model (Blaizot and Ollitrault' 1996)

Static geometrical model; no dynamics involved

Local energy density of the medium assumed to be proportional to the local participant density $n_p(b,s)$

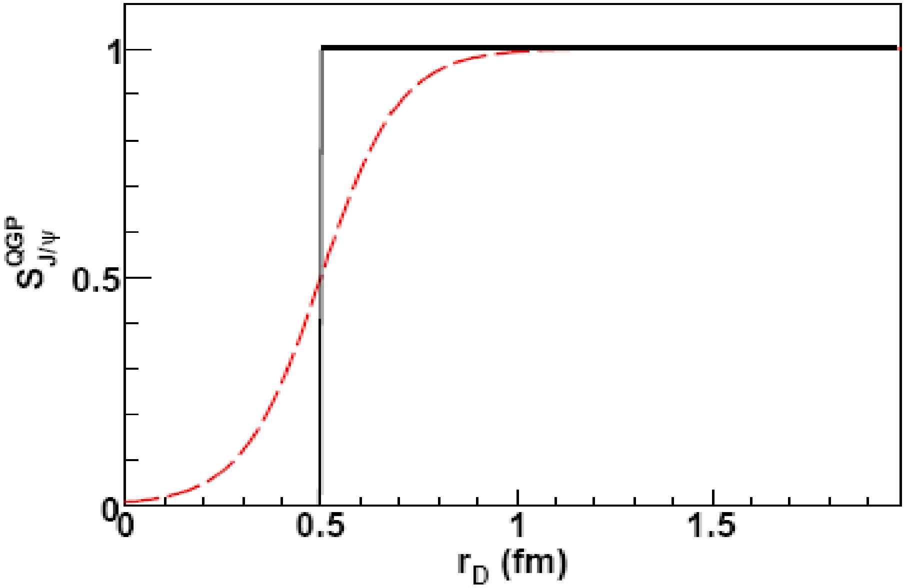
Total suppression above critical participant density (n_c)

Fixed from the NA50 Pb + Pb data on J/ψ suppression

$$S^{QGP}_{J/\psi}(b) = \int d^2\mathbf{s}\,\Theta(n_c - n_p(b,\mathbf{s}))$$

- **Static geometrical model**
- **Does not include medium dynamics**

Smearing the survival probability



The plasma equation of state (EOS)

$$\begin{aligned}
P &= \left[\frac{\pi^2}{90}\left(16+\frac{21N_f}{2}\right)T^4+\frac{N_f}{18}\mu^2T^2+\frac{N_f}{324\pi^2}\mu^4\right] \\
&- \left[CT^2+D\mu^2+B\right] \\
s &= \frac{4\pi^2}{90}\left(16+\frac{21N_f}{2}\right)T^3+\frac{N_f}{9}\mu^2T-2CT \\
\rho_B &= \frac{N_f}{9}\mu T^2+\frac{N_f}{81\pi^2}\mu^3-2D\mu \\
\varepsilon &= -P+Ts+\mu\rho_B
\end{aligned}$$

$$2C \approx 0.24,\ D \approx 0,\ B \approx T_0^4,$$