Heavy Flavor as a Probe of Quark-Gluon Plasma

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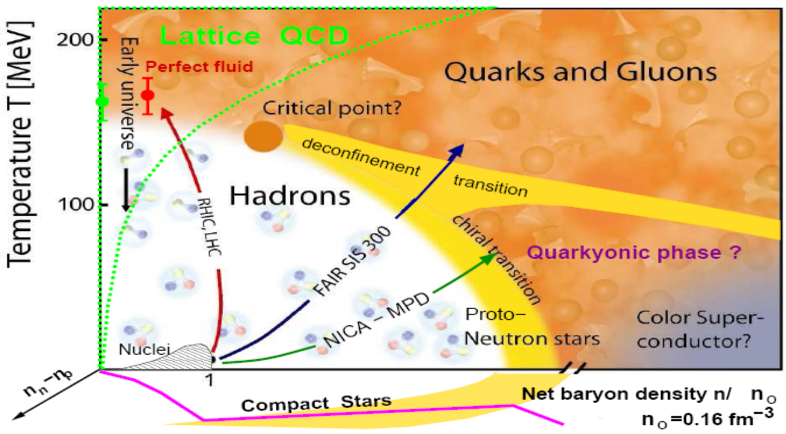
1. Introduction

1.1 QCD Phase Transitions and Heavy Ion Collisions

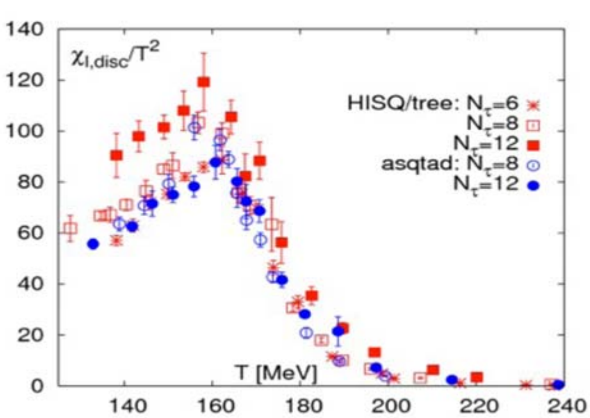
At finite temperature, the vacuum excitation
At finite density, the vacuum condensation



QCD phase transitions and symmetries:

Deconfinement:	***Z(3) symmetry***
Chiral restoration:	***SU(3) chiral symmetry***
Color superconductivity	***SU(3) color symmetry***
Pion superfluidity:	***SU(2) isospin symmetry***

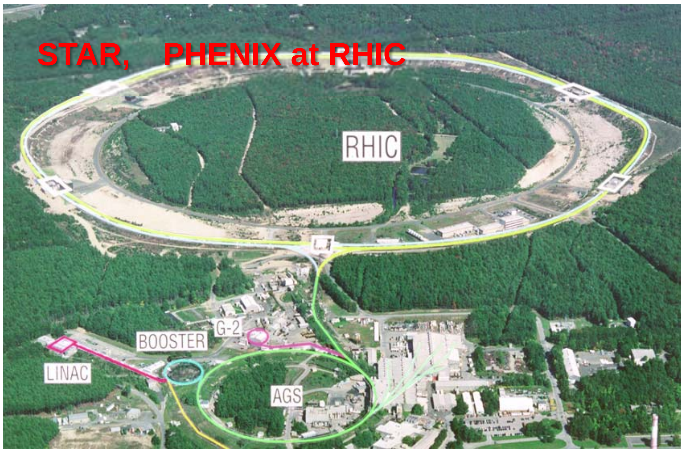
The critical temperature is T_c =154(9) MeV from lattice simulations *(A.Bazavov et al.[HotQCD Collaboration], Phys. Rev. D85 (2012) 054503),* ***but the density effect is still not clear.***



How to realize the QCD phase transitions?

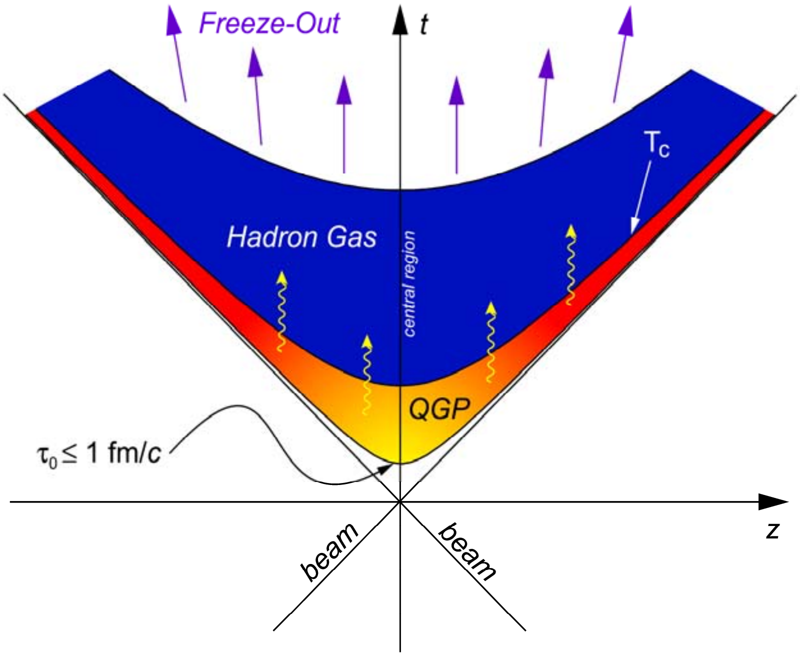
High temperature limit is probably the case in the beginning of the Big Bang
High density limit may correspond to the compact stars
The wide region between the two limits is through nuclear collisions

High energy heavy ion accelerators in the world

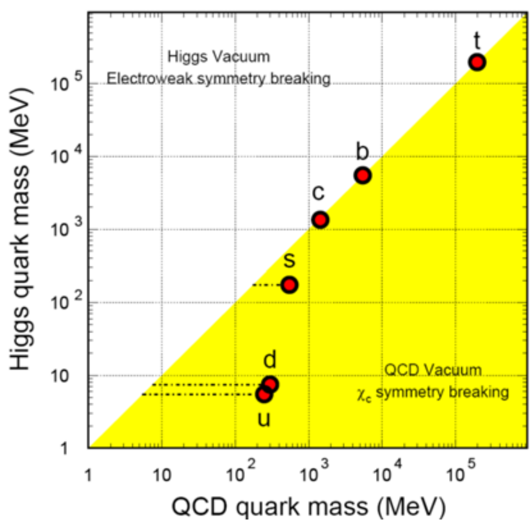


1.2 Heavy Flavor as a Probe of QGP

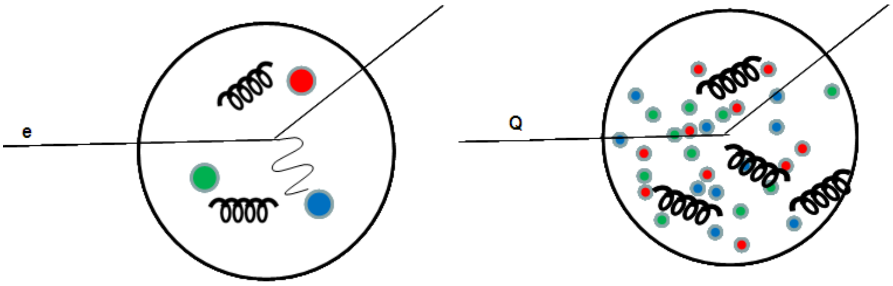
QGP can exist only as an intermediate state
We cannot directly observe the QGP in the final state
We need sensitive signatures



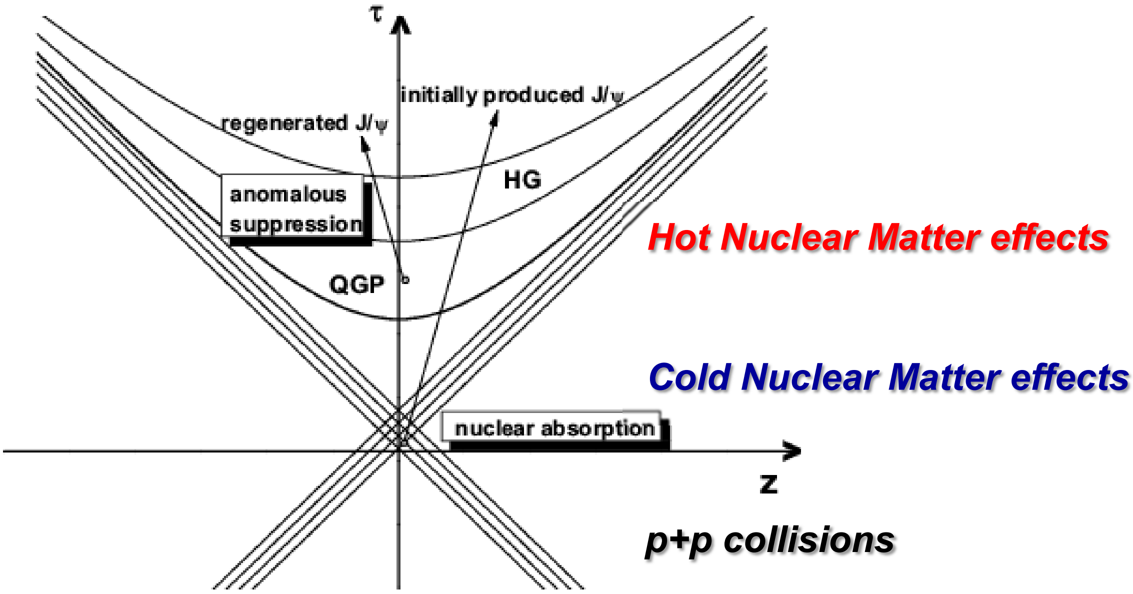
Light quarks become light in hot medium and largely produced in the medium
Heavy quarks are still heavy in hot medium and created mainly in the initial impact of the collisions, the production process is controlled by pQCD.



Similar to electrons which are usually used to probe the electro-magnetic structure of nucleons, heavy quarks can be used to signal the fireball structure produced in heavy ion collisions (*T.Matsui and H.Satz, Phys. Lett. B178, 416(1986)*).



The produced D (B) mesons and quarkonia suffer from cold and hot nuclear matter effects, and we need their ***vacuum*** *properties as the baseline of the medium effects.*



2. Heavy Flavor in Vacuum

2.1 Heavy Flavor Production in p+p Collisions

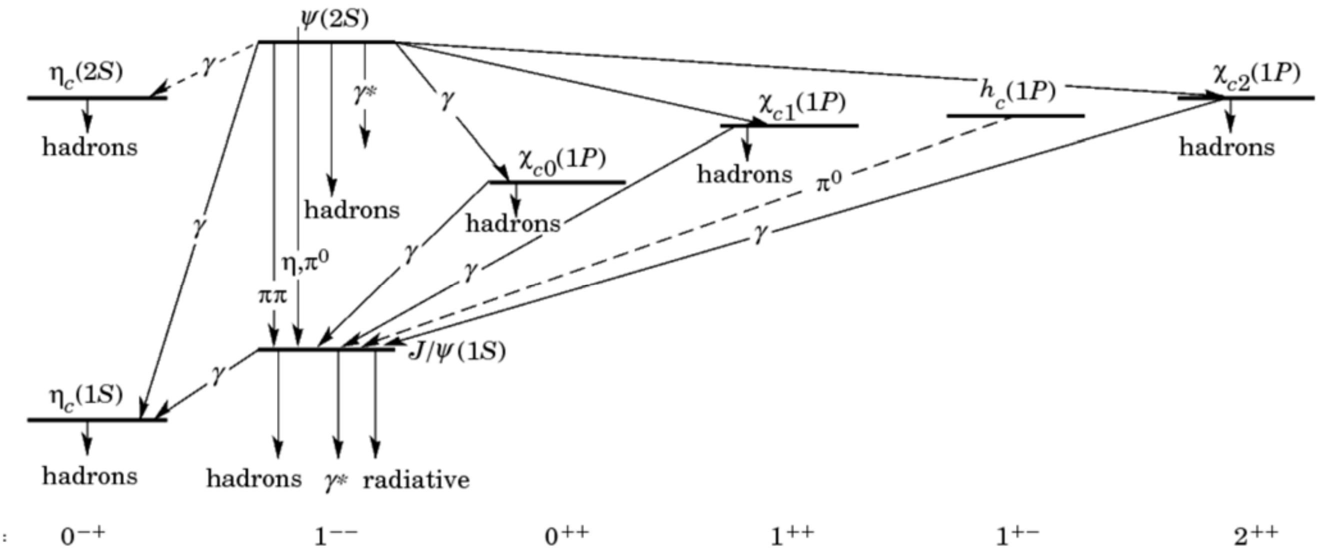
Quarkonium states $n^{2S+1}L_J$

J/Ψ (1^3S_1)***, the charmonium ground state observed in 1974***
mass and size parameters

State	J/ψ (1S)	χ_c (1P)	ψ' (2S)
m (GeV/c^2)	3.10	3.53	3.68
r_0 (fm)	0.50	0.72	0.90

State	Υ (1S)	χ_b (1P)	Υ' (2S)	χ_b' (2P)	Υ'' (3S)
m (GeV/c^2)	9.46	9.99	10.02	10.26	10.36
r_0 (fm)	0.28	0.44	0.56	0.68	0.78

decay mode:
hadron channel ~88%, dilepton channel ~6% for di-electrons and ~6% for di-muons.



feed back from the excited states

feed-back from the B-hadron decay which is mainly in the high pt region and becomes important at LHC energy.

Contribution to the observed ground state $\Upsilon(1S)$

$\Upsilon(1S)$	$\Upsilon(1P)$	$\Upsilon(2S)$	$\Upsilon(2P)$	$\Upsilon(3S)$
51%	27%	11%	10%	1%

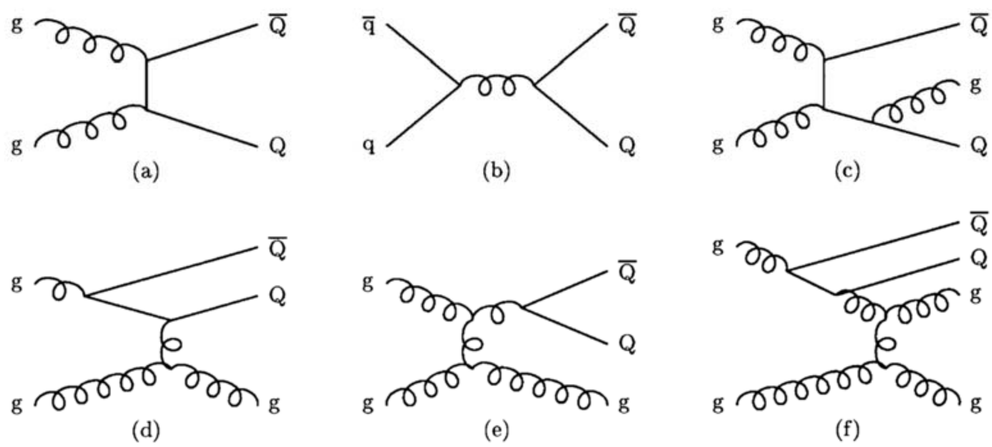
Contribution to the observed ground state J/ψ

J/ψ	χ_c	ψ'
60%	30%	10%

quarkonium production in p+p collisions

c and b quarks are heavy in comparison with the typical QCD scale (Λ_{QCD} ~ 0.2 GeV), the coupling constant is small (α_s <<1), the heavy quark pair production can be precisely calculated through perturbative QCD (pQCD).

the primary source of heavy quark production at RHIC and LHC energies is gluon fusion.



(a) gluon fusion, (b) quark-antiquark annihilation, (c) pair creation with gluon emission, (d) flavor excitation, (e) gluon splitting, (f) together gluon splitting and flavor excitation.

the subsequent soft interactions required to form quarkonium are still theoretically not well understood, and we need various mechanisms to describe the quarkonium production in p+p collisions.

(1) Color-singlet model *(C-H.Chang, Nucl. Phys. B172, 425(1980); EL.Berger, D.Jones, Phys. Rev. D23, 1521(1981); R.Baier, R.Rueckl, Phys. Lett. B102, 364(1981))*.

$$\sigma_{\mathrm{CS}}(pp \to J/\psi X, x_F, p_T; s) = |R_{J/\psi}(0)|^2 \int dx_1\, dx_2$$
$$\times \int d^2 p_T'\, d^2 p_T'' \delta(x_1 + x_2 - x_F) g(x_1, p_T') g(x_2, p_T'')$$
$$\times G_3\big(gg \to [c\bar{c}]_{J/\psi} + g;\, M_{J/\psi}^2, x_F, p_T; \hat{s}, p_T', p_T''\big).$$

The elementary 3-gluon process leads to the creation of a $c\bar{c}$ in the color-singlet state with the quantum numbers and the mass of J/Ψ. The radial wave function $R_{J/\psi}(0)$ determines the probability that this $c\bar{c}$ pair is a J/Ψ.

(2)Color-octet model *(GT Bodwin, et al., Phys. Rev. D46, 3703(1992); D51, 1125(1995))*

$$\sigma_{\mathrm{CO}}(pp \to J/\psi; s) = \sum_n \langle O_n^{J/\psi} \rangle \int dx_1\, dx_2 g(x_1) g(x_2)$$
$$\times G_3(gg \to [c\bar{c}]_n + X; \hat{s}),$$

$c\bar{c}$ pair is created with the quantum numbers labeled by n (color, angular momentum, and spin) and $\langle O^n_{J/\psi} \rangle$ is the probability of finding the pointlike $c\bar{c}$ in the wave function of J/Ψ.

(3)Color-evaporation model *(H.Fritzsch, Phys. Lett. B67, 217(1977); V.Barger et al., Z. Phys. C6, 169(1980), Phys. Lett. B91, 253(1980))*

$$\sigma_{\mathrm{CE}}(pp \to J/\psi X, x_F; s) = f_{J/\psi} \int_{4m_c^2}^{4M_D^2} d\mu^2 \int dx_1\, dx_2 \delta(x_F - x_1 - x_2)$$
$$\times g(x_1) g(x_2) G_2(gg \to [c\bar{c}](\mu^2); \hat{s}).$$

$c\bar{c}$ pair with mass μ but unspecified quantum numbers. The colored $c\bar{c}$ pair evolves—via an unspecified mechanism called color evaporation—to a bound charmonium state if the mass μ satisfies $4m_c^2 < \mu^2 < 4m_D^2$.

2.2 Potential Model

Taking the one-gluon exchange in the limit of short range,

$$\int d^3k e^{-i\vec{k}\vec{r}} \frac{g_s^2}{k^2} = -\frac{4}{3}\frac{\alpha_s}{r}, \qquad \alpha_s = \frac{g_s^2}{4\pi}$$

and the linear part for the confinement,

$$V(r) = -\frac{\alpha_c}{r} + \sigma r$$

The Cornel potential is in agreement with the lattice QCD simulation *(see GS Bali, Physics Report 343, 1(2001)).*

$$\left[-\frac{1}{2m_c}\left(\vec{\nabla}_1^2 + \vec{\nabla}_2^2\right) + V(\vec{r})\right]\psi(\vec{r}_1,\vec{r}_2) = E\psi(\vec{r}_1,\vec{r}_2), \qquad \vec{r} = \vec{r}_1 - \vec{r}_2$$

radial equation in the rest frame of the bound state

$$\left[\frac{1}{m_c}\left(-\frac{1}{r}\frac{d^2}{dr^2}r + \frac{l(l+1)}{r^2}\right) + \left(V(r) - \varepsilon_{nl}\right)\right]R_{nl}(r) = 0$$

with $\boldsymbol{\varepsilon_{nl}}$ ***the binding energy.***

with the boundary conditions

$$R(0) < \infty, \quad R(\infty) = 0$$

and the three parameters

$$\alpha_c = 0.29, \quad \sigma = (0.18\ \text{GeV})^2, \quad m_c = 1.84\ \text{GeV}$$

fixed by the quarkonium mass parameters

$$M_1 = M_{J/\psi}, \quad M_2 = M_{\psi'}, \quad M_3 \qquad\qquad M_n = 2m_c + \varepsilon_n$$

one obtains

$$\boldsymbol{\varepsilon_{nl}}, \quad \boldsymbol{R_{nl}(r)}, \quad \boldsymbol{\langle r\rangle_\psi}$$

2.3 Relativistic Corrections

qualitative estimation:

$$H = \sqrt{\mu^2 + p^2} - \mu + V(r) \simeq \frac{p^2}{2\mu} + V_{eff}$$

with a deeper potential

$$V_{eff} = V - \frac{p^4}{8\mu^3},$$

$$V_{eff} < V,$$

The quarkonium becomes a more deeply bound state (and the temperature needed to dissociate the quarkonium should be higher).

The two-body Dirac equation (***TBDE***, see *H.W.Crater et al., Phys. Rev.D46, 5117(1992); D70, 034026(2004); D79, 034011(2009); D37, 1982(1988))* ***of constrained dynamics was successfully applied to the relativistic description of light and heavy mesons.***

The group of covariant relativistic Schrodinger equations for the spin triplet $(\boldsymbol{u_1^0, u_1^+, u_1^-})$ and spin singlet $(\boldsymbol{u_0})$,

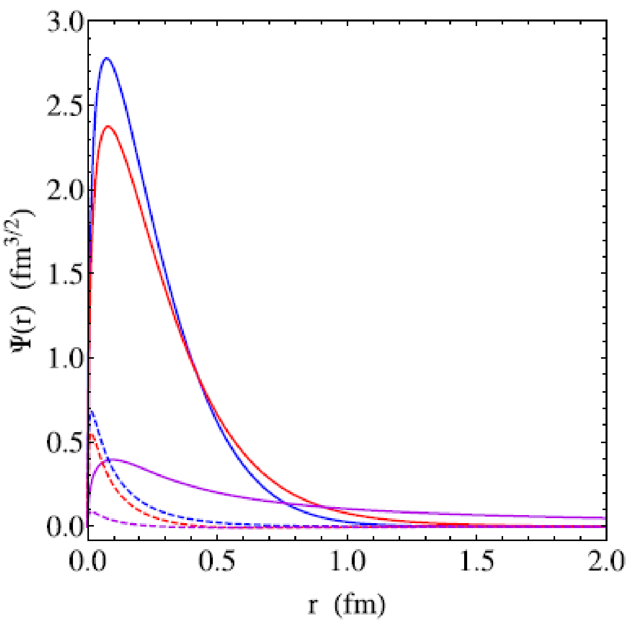
$$\left[-\frac{d^2}{dr^2}+\frac{J(J+1)}{r^2}+2m_wB+B^2-A^2+2\epsilon_wA+\Phi_D \right.$$
$$\left. -2\Phi_{SO}+\Phi_{SS}+2\Phi_T-2\Phi_{SOT}\right]u_1^0=b^2u_1^0,$$

$$\left[-\frac{d^2}{dr^2}+\frac{J(J-1)}{r^2}+2m_wB+B^2-A^2+2\epsilon_wA+\Phi_D \right.$$
$$\left. +2(J-1)\Phi_{SO}+\Phi_{SS}+\frac{2(J-1)}{2J+1}(\Phi_{SOT}-\Phi_T)\right]u_1^+$$
$$+\frac{2\sqrt{J(J+1)}}{2J+1}\big(3\Phi_T-2(J+2)\Phi_{SOT}\big)u_1^-=b^2u_1^+,$$

$$\left[-\frac{d^2}{dr^2}+\frac{(J+1)(J+2)}{r^2}+2m_wB+B^2-A^2+2\epsilon_wA+\Phi_D \right.$$
$$\left. -2(J+2)\Phi_{SO}+\Phi_{SS}+\frac{2(J+2)}{2J+1}(\Phi_{SOT}-\Phi_T)\right]u_1^-$$
$$+\frac{2\sqrt{J(J+1)}}{2J+1}\big(3\Phi_T+2(J-1)\Phi_{SOT}\big)u_1^+=b^2u_1^-$$

where V(r)=A(r)+B(r) is the Cornel potential with A being the Coulomb part and B the confinement part, and $\boldsymbol{\Phi}$ represent the Darwin and spin dependent potentials.

The components u_1^+ (S wave) with J = L+1 and u_1^- (D wave) with J = L−1 are coupled to each other.



3. Cold Nuclear Matter Effects

While we focus on the hot nuclear matter effects which are the necessary condition to produce QGP, the cold nuclear matter effects characterize the initial condition of the hot and dense fireball. The baseline for quarkonium production and suppression in heavy ion collisions should be determined from studies of cold nuclear matter effects.

There are several cold nuclear matter effects:

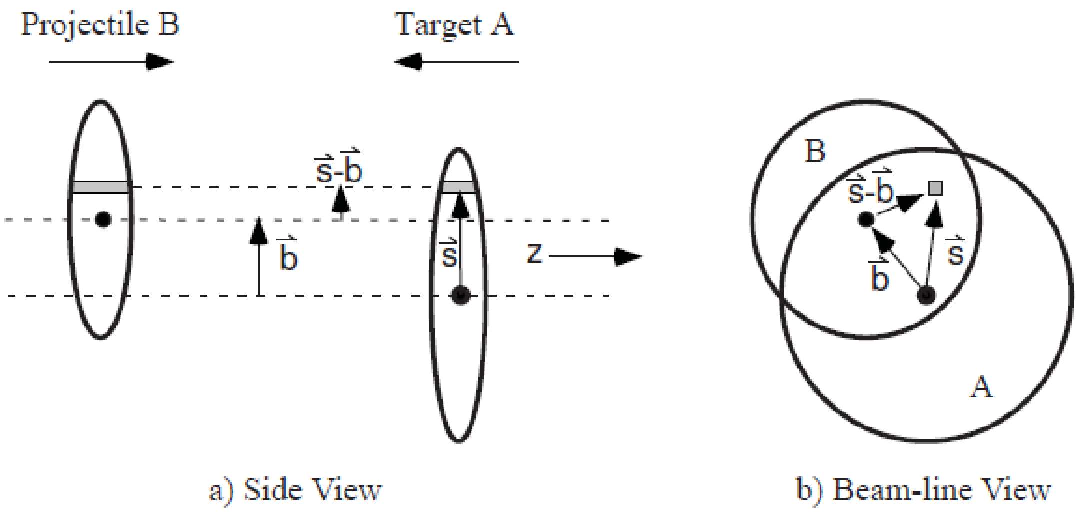
1)Modifications of the parton distribution functions in the nucleus, relative to the nucleons (shadowing),

2)The parton multi-scattering in the nucleus before the $Q\overline{Q}$ pair formation (Cronin effect),

3)Absorption of the quarkonium state as it passes through the nucleus (nuclear absorption).

3.1 Nuclear Geometry

the number of participant nucleons N_{part} and the number of nucleon-nucleon collisions N_{coll} (***Glauber model:*** *R.J.Glauber, in Lectures in Theoretical Physics, edited by W.E.Brittin and L.G.Dunham (N.Y., 1959), Vol. 1, p.315)*)



a) Side View b) Beam-line View

The assumption in the Glauber model is that the two nucleons in A and B can collide only when they have the same transverse coordinate.

Taking the Woods-Saxon distribution

$$\rho(\mathbf{x}_T, z) = \frac{\rho_0}{1 + e^{\frac{\sqrt{\mathbf{x}_T^2 + z^2} - R}{a}}},$$

The probability to find a nucleon in the tube located at the transverse position x_T in A

$$T_A(\mathbf{x}_T) = \int dz \hat{\rho}_A(\mathbf{x}_T, z)$$

The probability for any such pair of nucleons to collide

$$N'_{coll}(b) = \sigma_{inel}^{NN} T_{AB}(b) = \sigma_{inel}^{NN} \int T_A(\mathbf{x}_T) T_B(\mathbf{x}_T - \mathbf{b}) d\mathbf{x}_T,$$

The number of nucleon-nucleon collisions in a collision at impact parameter b

$$N_{coll}(b) = ABN'_{coll}(b) = ABT_{AB}(b)\sigma_{inel}^{NN}.$$

The number of participant nucleons at impact parameter b,

$$\begin{aligned} N_{part}(b) &= AP_{part}^A(b) + BP_{part}^B(b) \\ &= A \int T_A(\mathbf{x}_T) 1 - [1 - T_B(\mathbf{x}_T - \mathbf{b})\sigma_{inel}^{NN}]^B d\mathbf{x}_T \\ &\quad + B \int T_B(\mathbf{x}_T) 1 - [1 - T_A(\mathbf{x}_T - \mathbf{b})\sigma_{inel}^{NN}]^A d\mathbf{x}_T, \end{aligned}$$

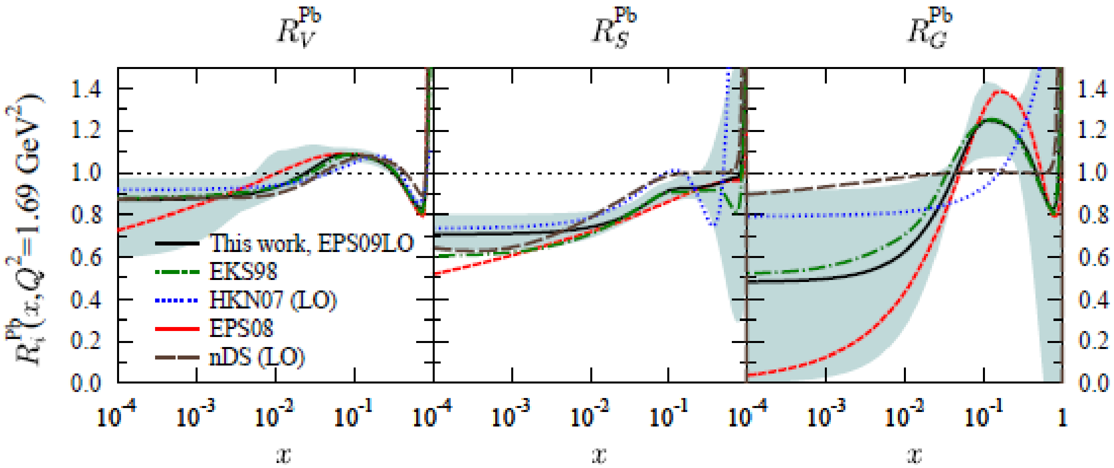
3.2 Shadowing Effect

The distribution function f_i^A for parton i in a nucleus differs from a simple superposition of the distribution function f_i in a free nucleon. The modification factor

$$R_i^A(x,\mu_F) = \frac{f_i^A(x,\mu_F)}{A f_i(x,\mu_F)}, i = q, \bar{q}, g.$$

where x and μ_F describe the parton longitudinal and transverse momentua.

There are different models to parameterize the nuclear shadowing function R_i^A.



The HKN07 (M.Hirai, S.Kumano and T.H.Nagai, Phys. Rev. C76, 065207(2007)) and nDS (D.de Florian and R.Sassot, Phys. Rev. D69, 074028(2004)) indicate small shadowing, the EKS98 (K.Eskola, V.Kolhinen and C.Salgado, Eur. Phys. J. C9, 61(1999)) and EPS09 suggest moderate shadowing, while the EPS08 (K.Eskola, H.Paukkunen and C.Salgado, JHEP0807, 102(2008)) gives large shadowing.

The nuclear effect depends strongly on the parton momentum fraction x.

small x $(x < 0.025)$: $R_i^A < 1$, shadowing effect,
intermediate x $(0.025 < x < 0.3)$: $R_i^A >$, anti-shadowing effect
large x $(0.3 < x < 0.8)$: $R_i^A < 1$, EMC effect *(P.Norton, Rept. Prog. Phys. 66, 1253(2003))*
$x > 0.8$: $R_i^A > 1$, Fermi motion *(A.Bodek, E.Iancu, J.jalilian-Martin and R.Venugopalan, Ann. Rev. Nucl. Part. Sci. 60, 46392010))*

At RHIC and LHC energies, the gluon fusion $g + g \to (Q\bar{Q}) + g$ is the main source to create a $Q\bar{Q}$ pair. Assuming that the emitted gluon in the process is soft in comparison with the initial gluons and the produced quarkonium,

$$x_{1,2} = \frac{\sqrt{m_\Psi^2 + p_T^2}}{\sqrt{s_{NN}}} e^{\pm y},$$

In central rapidity region around y=0, the two gluons have the same $x = x_1 = x_2$. For charmonia in the transverse momentum region $0 < p_T < 5$ GeV/c, one has

$0.18 < x < 0.34$ at SPS energy $\sqrt{s_{NN}} = 17.3$ GeV, anti-shadowing

$0.016 < x < 0.029$ at RHIC energy $\sqrt{s_{NN}} = 200$ GeV, weak shadowing

$0.0011 < x < 0.0021$ at LHC energy $\sqrt{s_{NN}} = 2.76$ TeV, strong shadowing

To account for the spatial dependence of the shadowing in a finite nucleus, one assumes that the ***inhomogeneous shadowing is proportional to the parton path length through the nucleus*** *(S.R.Klein and R.Vogt, Phys. Rev. Lett. 91, 142301(2003)),*

$$\mathcal{R}_i = 1 + A(R_i - 1)T_A(\mathbf{x}_T)/T_{AB}(0),$$

with x_T $T_{AB}(b) = \int d^2x_T T_A(x_T) T_B(x_T - b)$ determined by the nuclear geometry.

Replacing the gluon distribution f_g in the free p+p process

$$\frac{d\sigma_\Psi^{pp}}{dp_T dy} = \int dy_g x_1 x_2 f_g(x_1, \mu_F) f_g(x_2, \mu_F) \frac{d\sigma_{gg\to\Psi g}}{d\hat{t}},$$

by the modified distribution $\bar{f}_g = A f_g \mathcal{R}_g$, we get the shadowing effect on the quarkonium distribution in A+B collisions,

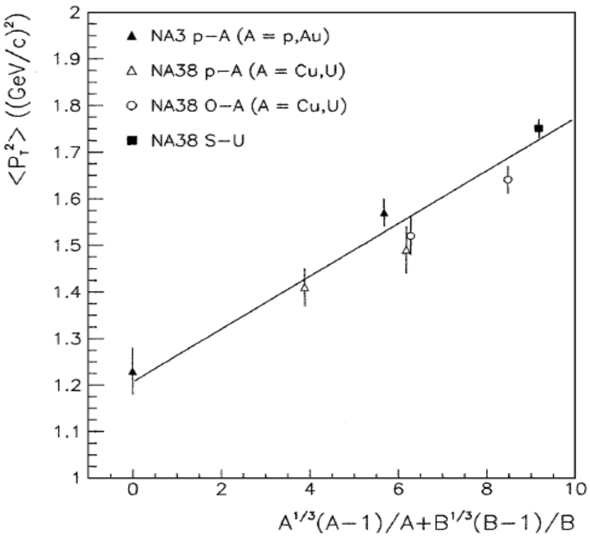
$$\begin{aligned} f_\Psi(\mathbf{x}, \mathbf{p}, \tau_0|\mathbf{b}) = \frac{(2\pi)^3}{E_T \tau_0} \int & dz_A dz_B \rho_A(\mathbf{x}_T, z_A) \rho_B(\mathbf{x}_T, z_B) \\ & \times \mathcal{R}_g(x_1, \mu_F, \mathbf{x}_T) \mathcal{R}_g(x_2, \mu_F, \mathbf{x}_T - \mathbf{b}) \\ & \times \overline{f}_\Psi^{pp}(\mathbf{x}, \mathbf{p}, z_A, z_B|\mathbf{b}), \qquad (11) \end{aligned}$$

3.3 Cronin Effect

Parton multi-scattering before the $Q\bar{Q}$ formation

Before two gluons fuse into a quarkonium, they acquire additional transverse momentum via multi-scattering with the surrounding nucleons, and this extra momentum would be inherited by the produced quarkonium. *Inspired from a random-walk picture, one obtains (C.Gerschel and J.Huefner, Ann. Rev. Nucl. Part. Sci. 49, 255(1999))*

$$\langle p_T^2\rangle_{J/\psi}^{pA} = \langle p_T^2\rangle_{J/\psi}^{pp} + \sigma_{gN}\langle p_T^2\rangle_{gN}\rho_0 L_i,$$



The measured slope can be used to obtain the value for the parameter

$$\sigma_{gN}\langle p_T^2\rangle_{gN} = (4.5 \pm .4)\ \mathrm{mb}(\mathrm{GeV}/c)^2.$$

With considering the shadowing and Cronin effects, the effective momentum distribution in p+p collision can be written as

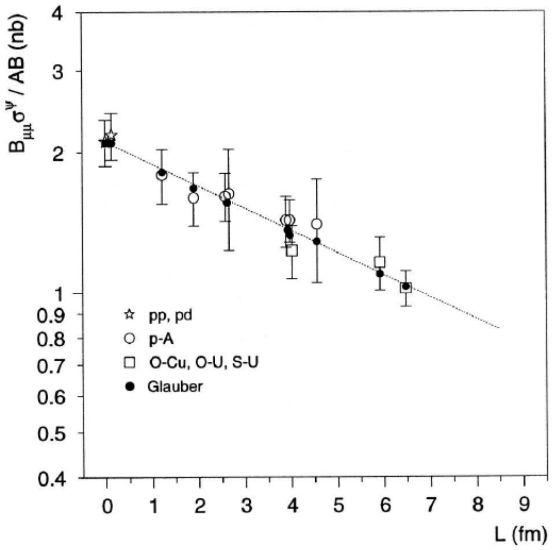
$$\tilde{f}_\psi^{pp} = \frac{1}{\pi\sigma_{gN}\langle p_T^2\rangle_{gN}} \int d^2p'_T e^{\frac{-p_T'^2}{\sigma_{gN}\langle p_T^2\rangle_{gN} l}} \bar{f}_\psi^{pp}(|p_T - p'_T|, p_z)$$

the Cronin effect is reflected in the Gauss distribution ($l(x, z_A, z_B|b)$ is the path length of the two gluons in nuclei before their fusion into a quarkonium), and the shadowing is in included in the distribution $\bar{f}_\psi^{pp}$.

The modified distribution function, including shadowing and Cronin effects, will be used as initial input of the quarkonium motion in A+A collisions.

3.4 Nuclear Absorption

Quarkonium suppression is observed in p+A and light nuclear collisions at SPS energy where QGP formation is not expected.



This follows from the nuclear absorption. When a quarkonium is instantaneously produced in the nuclear environment, on its way out, it has inelastic interaction with the surrounding nucleons and suffers from a suppression.

$$S^A_{J/\psi} = \frac{1}{A}\int d^2b\, dz\ \rho(b,z)\exp\left(-\int_z^{\infty} dz' \sigma_{\rm abs}(J/\psi)\rho(b,z')\right).$$

$$S^A = \frac{1}{\sigma_{\rm abs}}\int d^2b(1-e^{-\sigma_{\rm abs}T(b)}),$$

From the comparison with the data *(M.C.Abreuet al. [NA38 Collaboration], Phys. Lett. B466, 408(1999))*, ***the average nuclear absorption cross section at SPS energy is extracted at $\sigma_{abs} = 6.5 \pm 1.0$ mb, similar for both J/ψ and ψ'.***

Considering a nonzero quarkonium formation time τ_f, the absorption cross section σ_{abs} in nuclear collisions is for a pre-meson.

The time scale for a $Q\bar{Q}$ pair production $1/2m_Q$ is very small, ***the quarkonium formation time is just the time from a $Q\bar{Q}$ pair to a full developed quarkonium.***

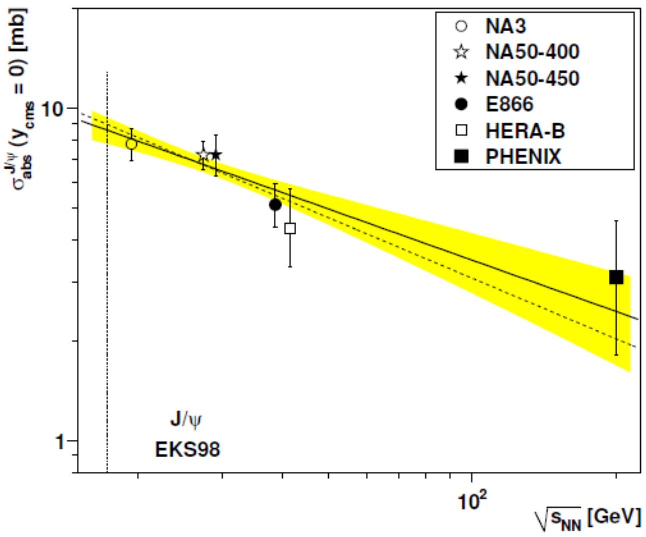
If the pair is produced as a small color-singlet, the absorption cross section immediately after its production should be small and increase with proper time until, at the formation time, it reaches its final state size. From the kinematics, one has

$$\tau_f = \left(\frac{\langle r_T^2\rangle_\psi}{\langle v_T^2\rangle_\psi}\right)^{1/2} \sim 0.5\, fm$$

and the time dependence of the cross section

$$\sigma_{abs}(\tau) \sim \langle r_T^2\rangle \sim \left(\frac{\tau}{\tau_f}\right)^2 .$$

1) At high colliding energies, the collision time for the two colliding nuclei to pass through to each other is very short, the color-singlet quarkonium states will experience negligible nuclear absorption effects, since they will be formed well outside the nuclei. The J/ψ absorption cross section at central rapidity *(C.Lourenco, R.Vogt and H.K.Woehri, JHEP 0902, 014(2009))* looks to decrease with energy.



2) The absorption cross section for excited states should be larger than that for the ground state.

The recent analysis of NA50 data shows $\sigma_{abs} = 4.1 \pm 0.5$ mb and 8.2 ± 1.0 mb for J/ψ and ψ', respectively.

If the pair is an octet state, it immediately interact with a large cross section since it is a colored object.

1)The ground and excited states will interact with the same cross section. From the comparison with the SPS data. The average nuclear absorption cross section at SPS energy is extracted at $\sigma_{abs} = 6.5 \pm 1.0$ mb, similar for both J/ψ and ψ'.

Notes:

1)The cold nuclear matter effects (shadowing, Cronin, absorption) depend differently on the quarkonium kinematic variables and the collision energy, it is then unsatisfactory to combine all these mechanisms into an effective absorption cross section.

2)Simply taking the σ_{abs} ***obtained from the analysis of the p+A data and then using it to define the A+A baseline may not be sufficient.***