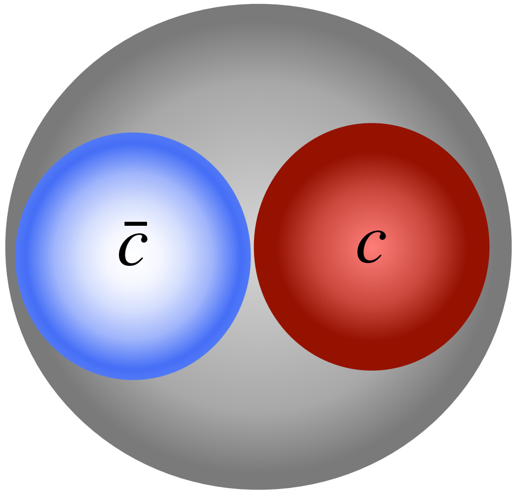
EMMI Rapid Reaction Task Force (RRTF) - Part 2

Quarkonium production and evolution in heavy ion collisions



Jiaxing Zhao (jzhao@subatech.in2p3.fr)

On behalf of the Tsinghua Group

12. Dec. 2022

Outline

Tsinghua model

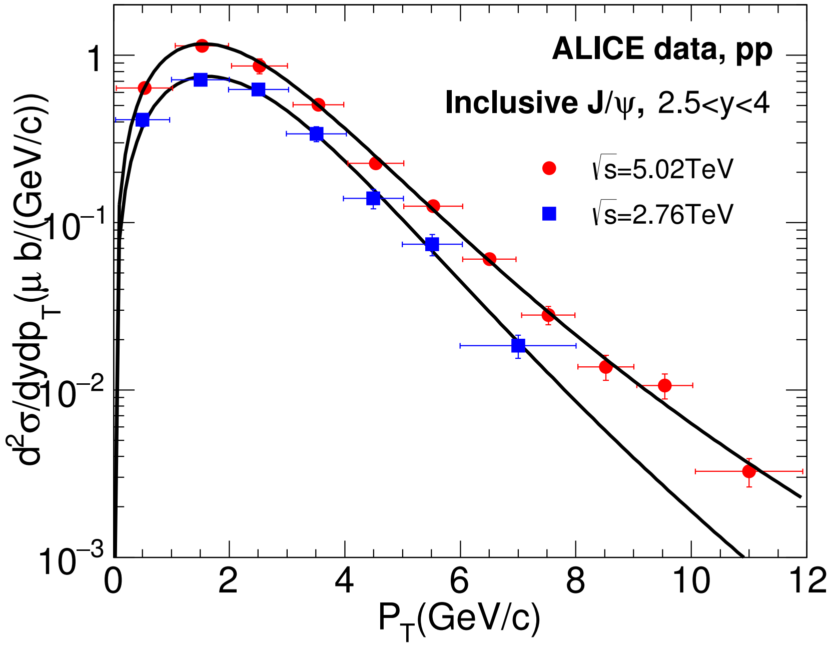
- *Initial state*
- *Cold nuclear effects*
  - *Nuclear absorption*
  - *Corin effect*
  - *Shadowing effect*
- *QGP evolution*
- *Quarkonium evolution*
  - *Quarkonium dissociation*
  - *Quarkonium regeneration*
- *Quarkonium in hadronic phase*

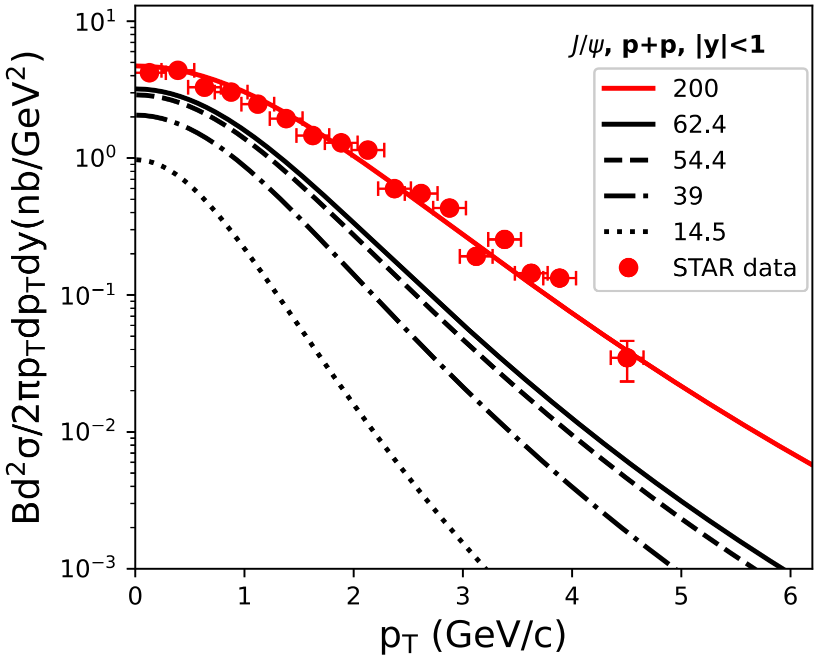
Initial state

The initial quarkonium distribution is constructed by a superposition of that in p+p collisions with considering the cold nuclear matter effects. The quarkonia are produced at (t=z=0; or τ=z=0) and free streaming in the pre-hydro stage (τ_0).

$$f_\psi(\mathbf{p},\mathbf{x},\tau_0) = \frac{(2\pi)^3}{E\tau_0}\int dz_A dz_B \rho_A(\mathbf{x}_T+\frac{\mathbf{b}}{2},z_A)\rho_B(\mathbf{x}_T-\frac{\mathbf{b}}{2},z_B)$$

$$\times S_{abs}\mathcal{R}_g(x_1,\mu_F,\mathbf{x}_T+\frac{\mathbf{b}}{2})\mathcal{R}_g(x_2,\mu_F,\mathbf{x}_T-\frac{\mathbf{b}}{2})\bar{f}^{pp}_\psi(\mathbf{p},\mathbf{x},z_A,z_B)$$





$$\frac{d^2\sigma^{J/\psi}_{\rm pp}}{2\pi p_T dp_T dy} = f^{\rm Norm}_{J/\psi}(p_T|y)\cdot\frac{d\sigma^{J/\psi}_{\rm pp}}{dy}$$

$$f^{\rm Norm}_{J/\psi}(p_T|y) = \frac{(n-1)}{\pi(n-2)\langle p_T^2\rangle_{pp}}[1+\frac{p_T^2}{(n-2)\langle p_T^2\rangle_{pp}}]^{-n}$$

Initial state

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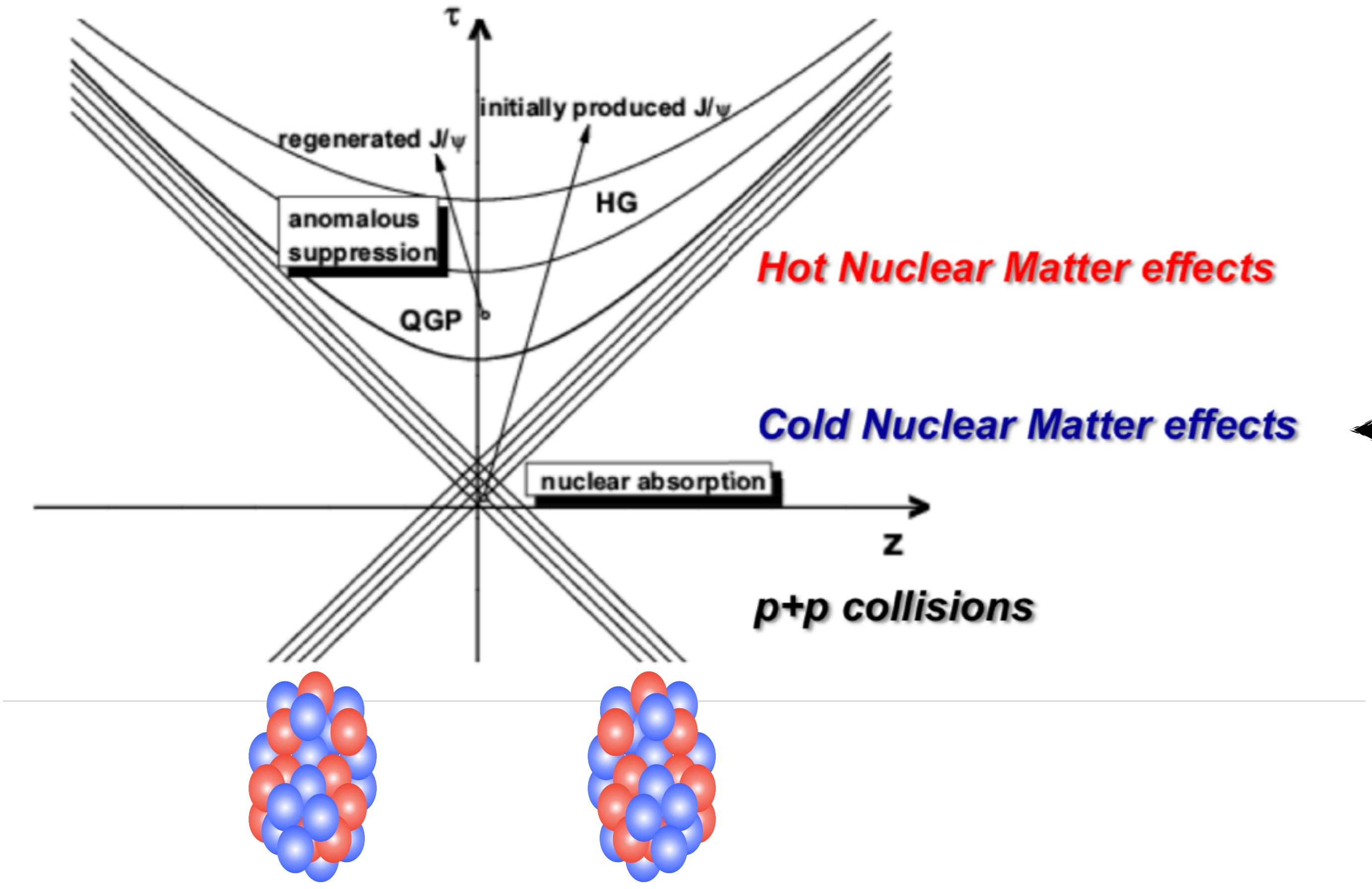


Shadowing effect
Corin effect
Nuclear absorption

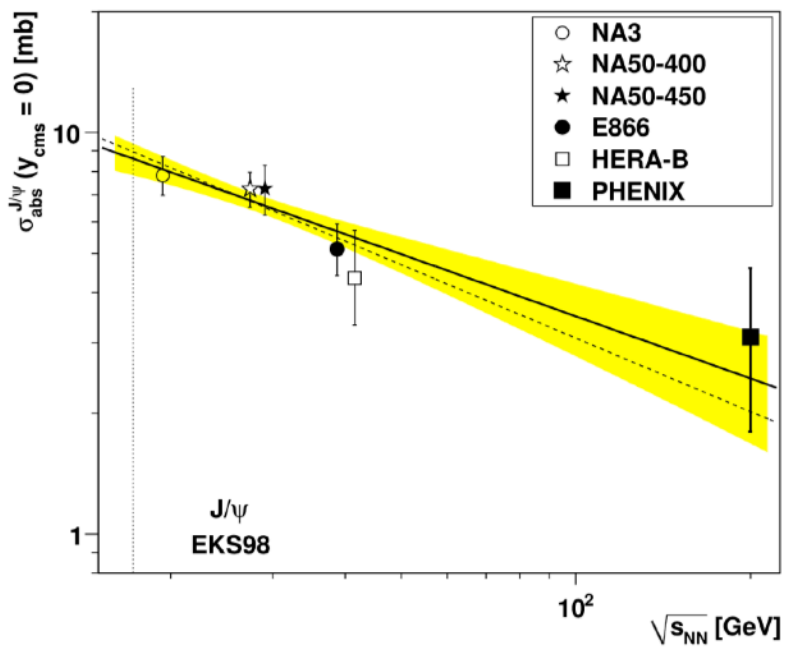
$$f_\psi(\mathbf{p},\mathbf{x},\tau_0) = \frac{(2\pi)^3}{E\tau_0}\int dz_A dz_B \rho_A(\mathbf{x}_T+\frac{\mathbf{b}}{2},z_A)\rho_B(\mathbf{x}_T-\frac{\mathbf{b}}{2},z_B)$$

$$\times S_{abs}\mathcal{R}_g(x_1,\mu_F,\mathbf{x}_T+\frac{\mathbf{b}}{2})\mathcal{R}_g(x_2,\mu_F,\mathbf{x}_T-\frac{\mathbf{b}}{2})\bar{f}^{pp}_\psi(\mathbf{p},\mathbf{x},z_A,z_B)$$

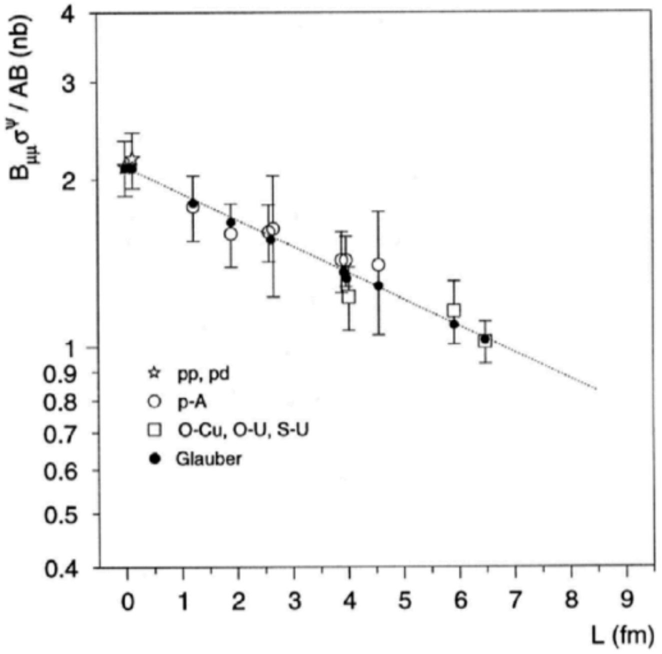
Cold nuclear effects

1. Nuclear absorption : quarkonium has inelastic interaction with the surrounding nucleons and suffers from a suppression

$$S_{AB} = \frac{1}{AB}\int d^2\mathbf{s}dz_A dz_B \rho_A(\mathbf{b}, z_A)\rho_B(\mathbf{s}-\mathbf{b}, z_B) \times \exp\left[-\sigma_{abs}\left(\int_{z_A}^{\infty} dz'\rho_A(\mathbf{b}, z') + \int_{-\infty}^{z_B} dz'\rho_B(\mathbf{s}-\mathbf{b}, z')\right)\right],$$



N. Brambilla, et al., Eur. Phys. J. C 71 (2011) 1534.



M.C. Abreu, et al., Phys. Lett. B 466 (1999) 408.

$\sqrt{s_{NN}}$(GeV)	14.5	39	54.4	62.4	200	2760	5020
$\sigma^{J/\psi}_{abs}$(mb)	8.9	5.2	5.0	4.8	1.5	-	-

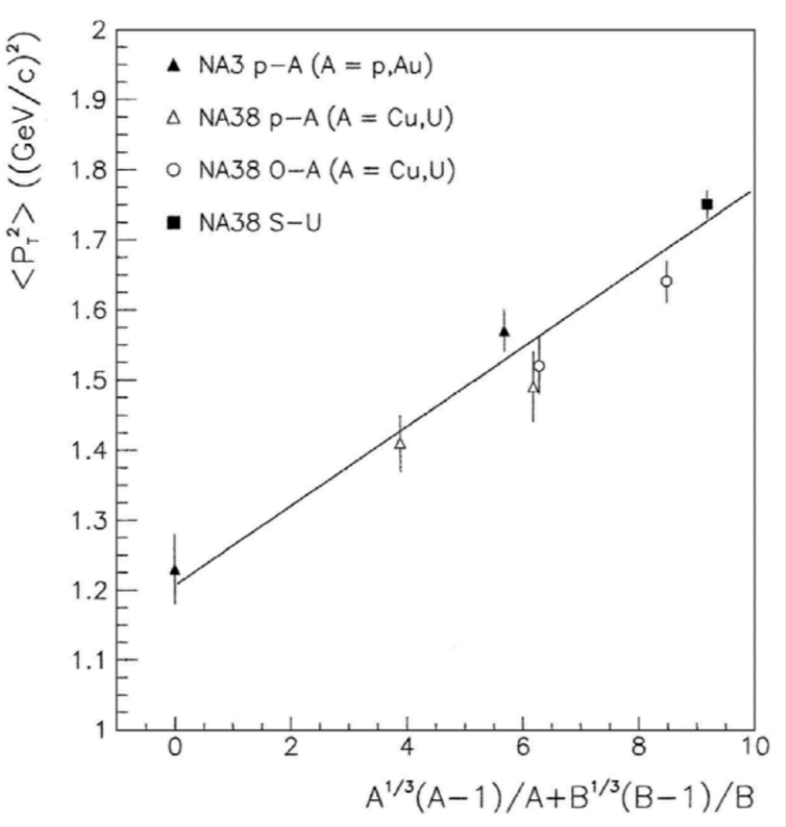
Neglected at LHC energies!

Cold nuclear effects

2. Corin effect : 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

$$\langle p_T^2 \rangle_{AB} = \langle p_T^2 \rangle_{pp} + a_{gN}\, l,$$

$$\overline{f}_{\Psi}^{pp} = \frac{1}{\pi a_{gN} l} \int d^2\mathbf{p}'_T e^{\frac{-\mathbf{p}'^2_T}{a_{gN} l}} f_{\Psi}^{pp}(|\mathbf{p}_T - \mathbf{p}'_T|, p_z),$$



C. Gerschel, J. Hufner, Ann. Rev. Nucl. Part. Sci. 49 (1999) 255.

We take a Gaussian smearing for the modified transverse momentum distribution.

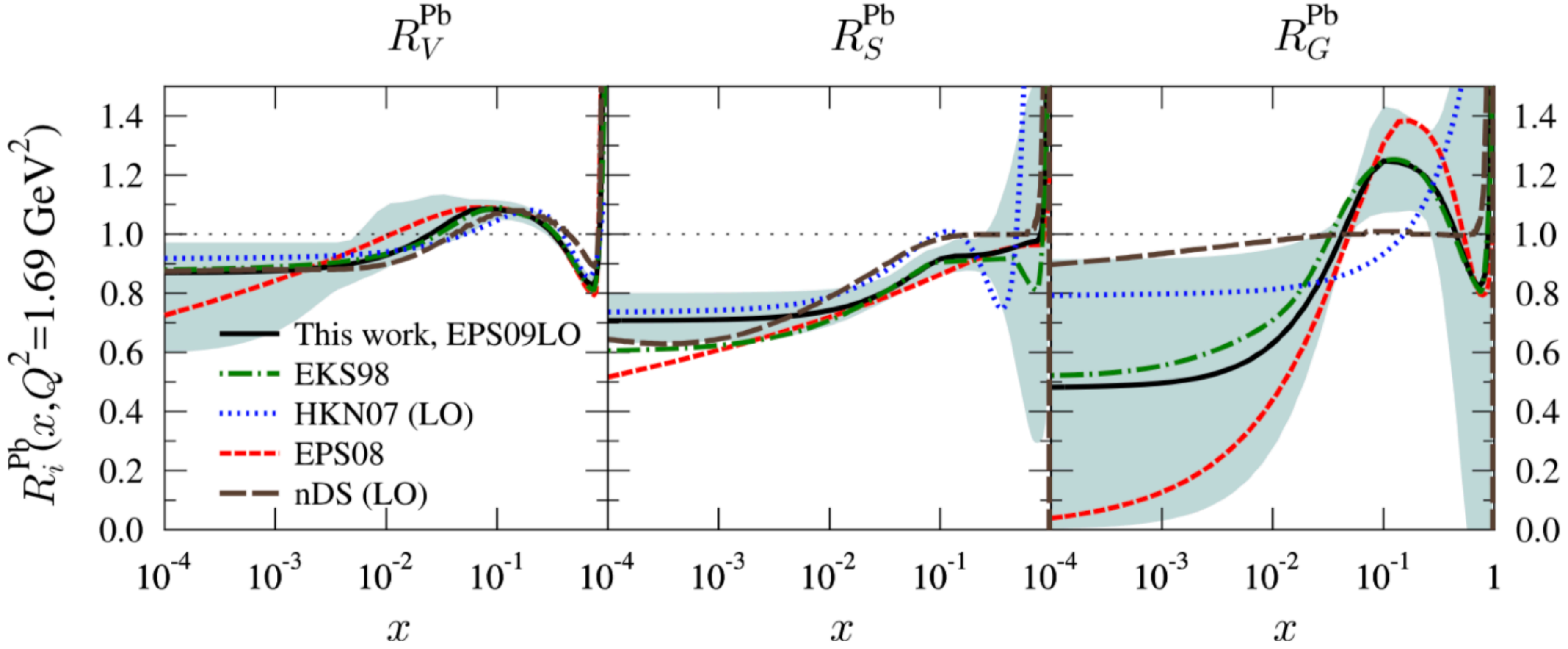
$\sqrt{s_{NN}}$(GeV)	14.5	39	54.4	62.4	200	2760	5020
a_{gN}(GeV^2/fm)	0.077	0.080	0.085	0.085	0.100	0.150	0.150

Cold nuclear effects

3. Shadowing effect: The distribution function for parton in a nucleus differs from a simple superposition of the distribution in a free nucleon

$$R_i^A(x,Q^2)=\frac{f_i^A(x,Q^2)}{Af_i(x,Q^2)},\qquad i=q,\bar{q},g \qquad \mathcal{R}=1+A(R_i-1)T_A(\mathbf{x}_T)/T_{AB}(0),$$

EPS09, EKS08, KHN07, NNPDF,…. Many model. Extracted from eA, pA,,,data



K.J. Eskola, H. Paukkunen, C.A. Salgado, JHEP 0904 (2009) 065.

To produce a charmonium state: $x_{1,2}=\frac{\sqrt{m_\psi^2+p_T^2}}{\sqrt{s_{NN}}}e^{\pm y},$

We read directly the shadowing effect from the EPS09 model

QGP evolution

Hydrodynamic :

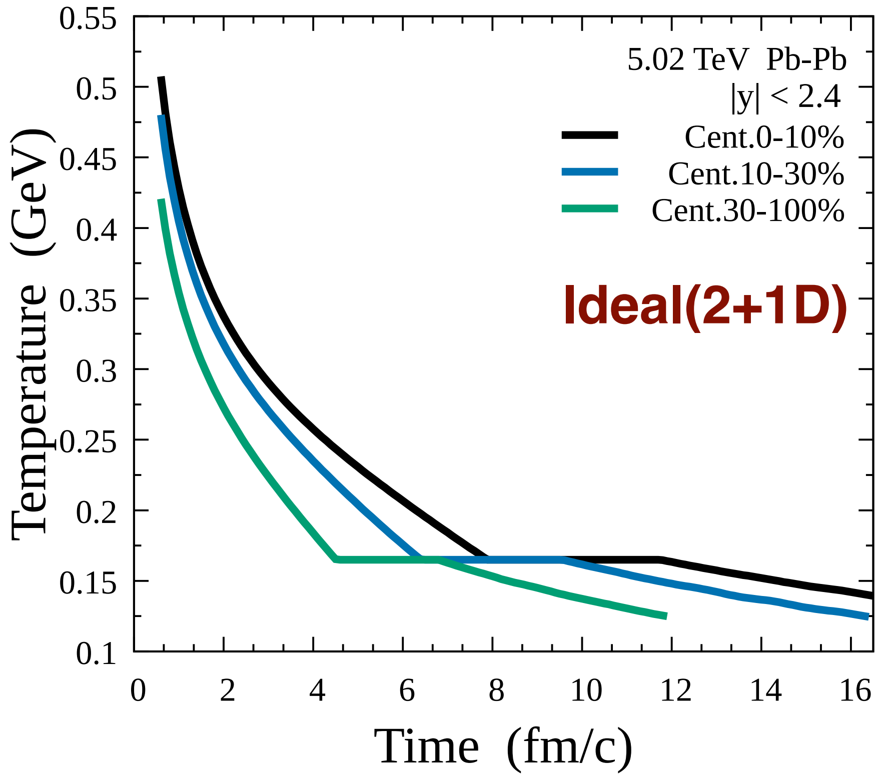
- *2+1D ideal hydro*

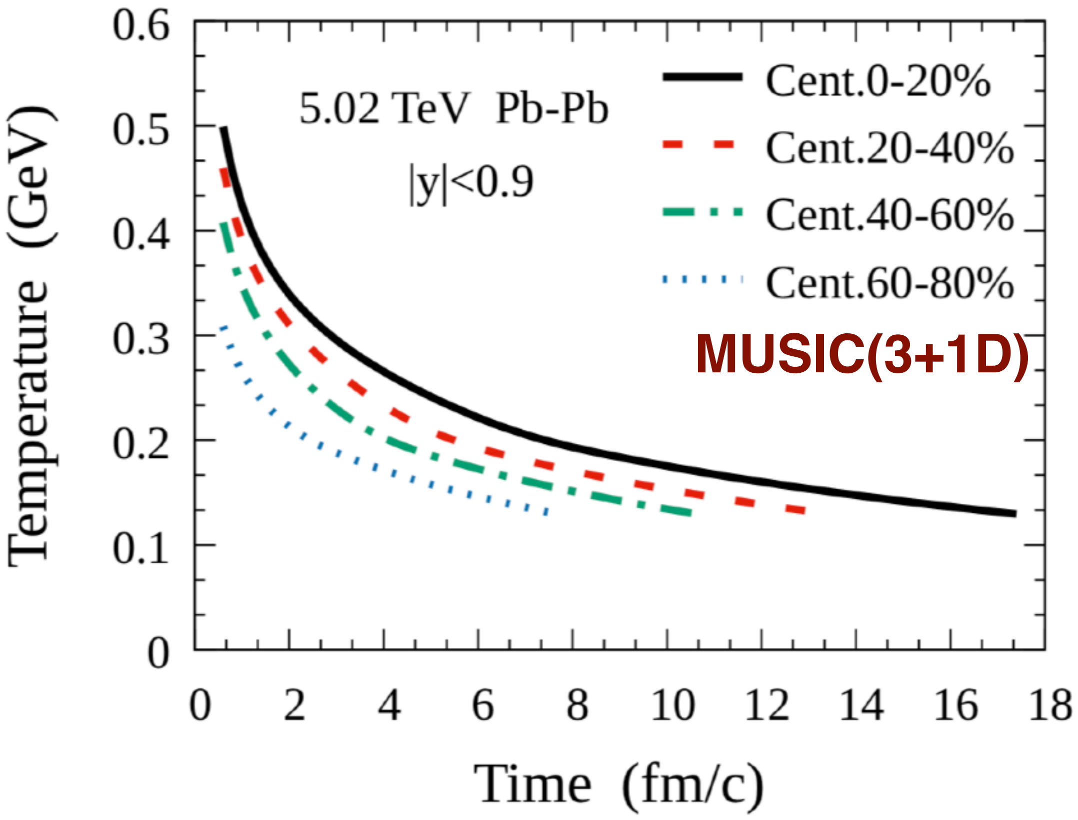
  Optical Glauber + first order phase transition

- *3+1D viscous hydro (MUSIC package) with fine-tuned parameters*

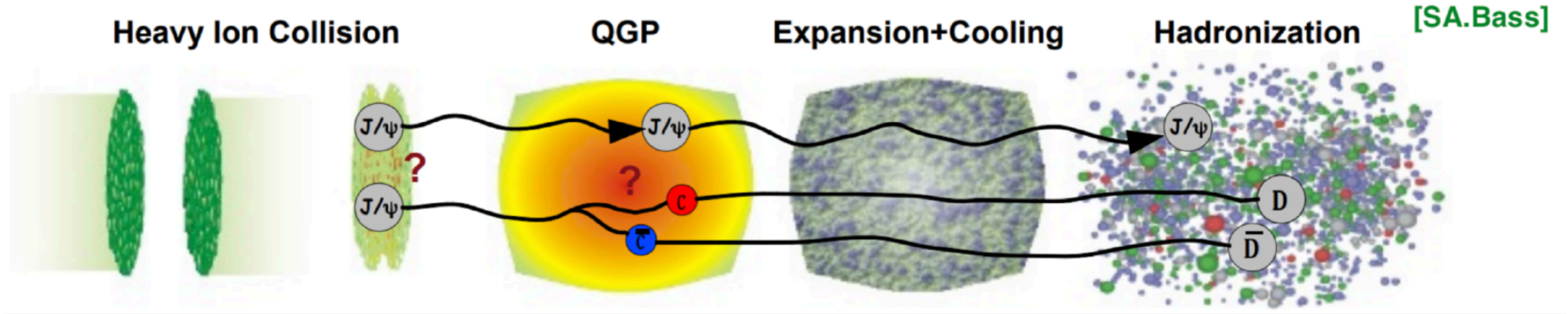
  http://www.physics.mcgill.ca/music/

  Optical Glauber + "s95p-v1" EOS (lattice QCD+ hadron resonance gas) + $\eta/s = 0.08$





Quarkonium evolution



[SA.Bass]

Transport description (Boltzmann equation)

X. Zhu, L. Yan, Y. Liu, K. Zhou, B. Chen, J. Zhao
PF. Zhuang. Tsinghua Model

$$p^{\mu}\partial_{\mu}f_{\psi} = -\alpha E f_{\psi} + \beta E$$

$$\alpha = \frac{1}{2E_T}\int \frac{d^3\mathbf{p}_g}{(2\pi)^3 2E_g} W_{g\psi}^{c\bar{c}}(s) f_g(p_g, x)$$

$$\beta = \frac{1}{2E_T}\int \frac{d^3\mathbf{p}_g}{(2\pi)^3 2E_g}\frac{d^3\mathbf{p}_c}{(2\pi)^3 2E_c}\frac{d^3\mathbf{p}_{\bar{c}}}{(2\pi)^3 2E_{\bar{c}}} W_{c\bar{c}}^{g\psi}(s) f_c(p_c, x) f_{\bar{c}}(p_{\bar{c}}, x)(2\pi)^4\delta^{(4)}(p + p_g - p_c - p_{\bar{c}})$$

Dissociation and regeneration are related to each other via the detailed balance.

$$\begin{aligned} f(\mathbf{p}_T, y, \mathbf{x}_T, \eta, \tau) &= f(\mathbf{p}_T, y, \mathbf{X}(\tau_0), H(\tau_0), \tau_0) e^{-\int_{\tau_0}^{\tau} d\tau' \alpha(\mathbf{p}_T, y, \mathbf{X}(\tau'), H(\tau'), \tau')/\Delta(\tau')} \\ &+ \int_{\tau_0}^{\tau} d\tau' \beta(\mathbf{p}_T, y, \mathbf{X}(\tau'), H(\tau'), \tau')/\Delta(\tau') e^{-\int_{\tau'}^{\tau} d\tau'' \alpha(\mathbf{p}_T, y, \mathbf{X}(\tau''), H(\tau''), \tau'')/\Delta(\tau'')} \end{aligned}$$

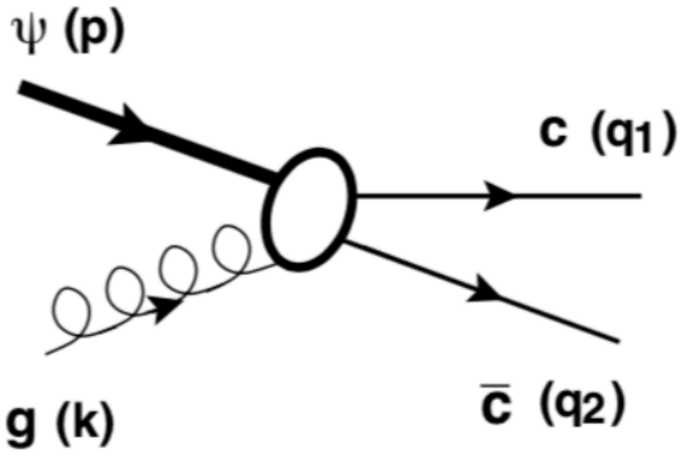
Cooper-Frye : $$E\frac{dN}{d^3p} = \frac{g}{(2\pi)^3}\int d\Sigma_{\mu}(x) p^{\mu} f(\mathbf{p}_T, y, \mathbf{x}_T, \eta, \tau).$$

Quarkonium dissociation

$$\alpha = \frac{1}{2E_T}\int \frac{d^3\mathbf{p}_g}{(2\pi)^3 2E_g} W^{c\bar{c}}_{g\psi}(s) f_g(p_g, x)$$

Only gluo-dissociation process in Tsinghua model

f_g *is thermal distribution function.*
$W^{c\bar{c}}_{g\psi} = 4F_{g\psi}(s)\sigma^{c\bar{c}}_{g\psi}$ *is related to the dissociation cross section*

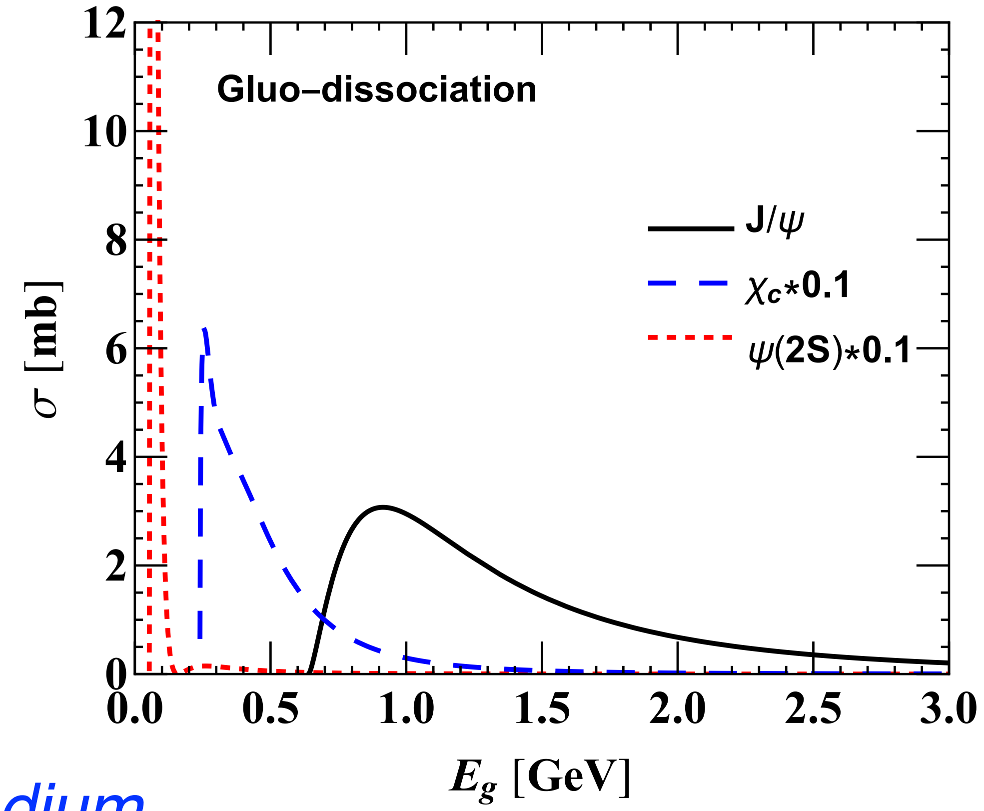


Gluon dissociation: $\psi + g \rightarrow Q + \bar{Q}$

Operator Production Expansion method (OPE)
Bhanot and Peskin.

$$\begin{aligned}
\sigma_{1S}(\omega) &= A_0(r-1)^{3/2}/r^5, \\
\sigma_{1P}(\omega) &= 4A_0(r-1)^{1/2}(9r^2-20r+12)/r^7, \\
\sigma_{1D}(\omega) &= 32A_0(r-1)^{3/2}(21r^2-48r+32)/r^9, \\
\sigma_{2S}(\omega) &= 16A_0(r-1)^{3/2}(r-3)^2/r^7,
\end{aligned}$$

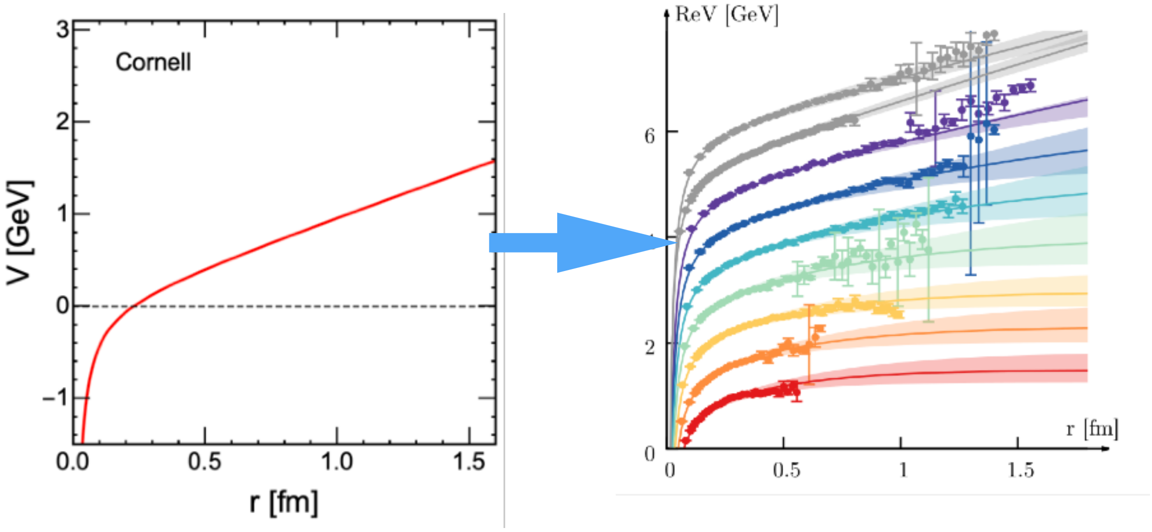
$r = \omega/\epsilon$ *and the coefficient* $A_0 = 2^{11}\pi/(27\sqrt{(2\mu)^3\epsilon})$ *with the binding energy* ϵ *of the quarkonium.* μ *is the reduced mass.*



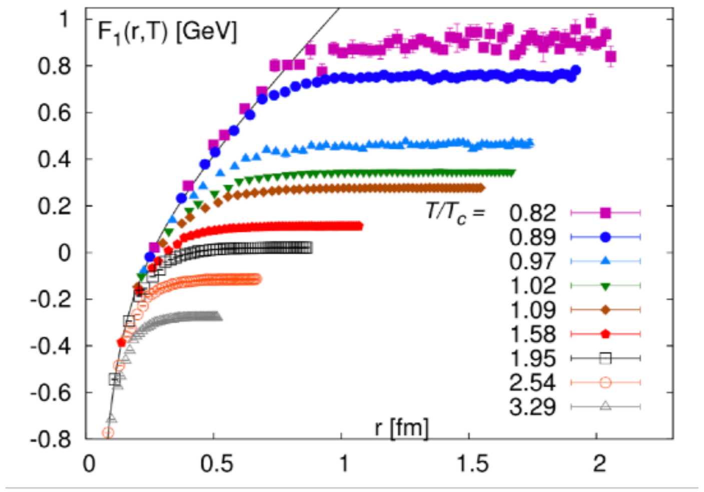
The binding energy ϵ *of quarkonium in the hot medium.*

Quarkonium dissociation

Color screening



Burnier Y, Kaczmarek O, Rothkopf A. JHEP, 2015, 12:101.



S. Digal et al., Eur. Phys. J. C 43 (2005) 71.

However, the volume of the produced fire-ball in relativistic heavy ion collisions is relatively small and expands rapidly, implying rather fast temperature changes and short fireball lifetimes. In this case, the conclusion from the static Debye screening effect may deviate from the real system. In particular, the quarkonia can be destroyed below Td and survivable above Td.

Choose an effective binding energy for ground state. And the decay width of excited states can be obtained via the scale:

$$\Gamma_\psi = \Gamma_{GS}\frac{\langle r_\psi^2\rangle}{\langle r_{GS}^2\rangle}$$

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

H. Satz, J. Phys. G 32, R25 (2006)

Quarkonium regeneration

$$\beta = \frac{1}{2E_T}\int \frac{d^3\mathbf{p}_g}{(2\pi)^3 2E_g}\frac{d^3\mathbf{p}_c}{(2\pi)^3 2E_c}\frac{d^3\mathbf{p}_{\bar{c}}}{(2\pi)^3 2E_{\bar{c}}} W_{c\bar{c}}^{g\psi}(s) f_c(p_c,x) f_{\bar{c}}(p_{\bar{c}},x)(2\pi)^4\delta^{(4)}(p+p_g-p_c-p_{\bar{c}})$$

- *The experimentally observed large charmed meson flow in high energy RHIC and LHC energies indicates charm quarks seem thermalized at low pT regions. We take, as a first approximation, a kinetically equilibrated distribution for charm (anti-charm) quarks*

$$f_c(p,x) = \frac{\rho_c(x)N(x)}{e^{p\cdot u/T}+1}$$

N(x) is the normalization factor
ρ_c *is the density in coordinate space and controlled by the charm conservation equation* $\partial_\mu(\rho_c u^\mu) = 0$ *. With the initial distribution:*

$$\rho_c(x,\tau_0) = \frac{T_A(\mathbf{x}_T + \frac{\mathbf{b}}{2})T_B(\mathbf{x}_T - \frac{\mathbf{b}}{2})\cosh\eta}{\tau_0}\frac{d\sigma_{pp}^{c\bar{c}}}{dy}$$

- *For bottom quark, we use firstly the non-thermal distribution in Bc production recently.*

arXiv: 2209.13475

- *No regeneration for bottomonium !*

Quarkonium in hadronic phase

At SPS energy, we consider the charmonium dissociation in hadronic phase via
$J/\psi + \pi \to D + \bar{D}* \;\; or \; \bar{D} + D*; J/\psi + \rho \to D* + \bar{D}* \;\; or \; \bar{D} + D$

B. Chen, P. Zhuang and Z. Xu, Phys. Rev. C 93, no. 4, 044917 (2016).

We didn't consider the evolution (dissociation and regeneration) of charmonium in the hadronic phase at high energy RHIC and LHC energies.

Thank you!

Other points

For the group assignments, please nominate a speaker to represent your group.

The talks shall be very compact, within a 15 min. slot each, addressing (as applicable) the following model ingredients:
-In-medium binding/potential
-Vacuum limit of potential/spectroscopy
-Reaction rates (3-momentum dependence): gluo-diss vs. quasi-free, medium model
-Equilibrium limits in transport
-Medium evolution model
~~-Quantum features~~
-Regeneration, impact of open HF distributions/transport
-Cold Nuclear Matter Effects (nuclear absorption, nPDF,…)
-Hadronic-Phase Transport
-~~Constraints from lattice QCD~~
-~~Constraints from p/dA collisio~~ns

During the mornings of Tue-Thu we will be working in subgroups, as follows: