Rare particles (J/$\psi, \Upsilon, B_c,$ Ω_{ccc}, $cc\bar{c}\bar{c}$, $\mu^+\mu^-$)

Rare Particle Enhancement in HIC

In comparison with pp collisions,

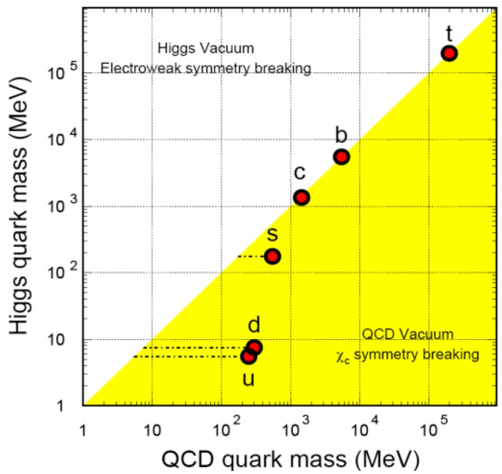
1) *the off-diagonal interaction among heavy quarks in QGP leads to a strong enhancement of multi-charmed hadrons ($J/\psi, \Upsilon$, B_c, Ω_{ccc}, $c\bar{c}c\bar{c}$,…),*

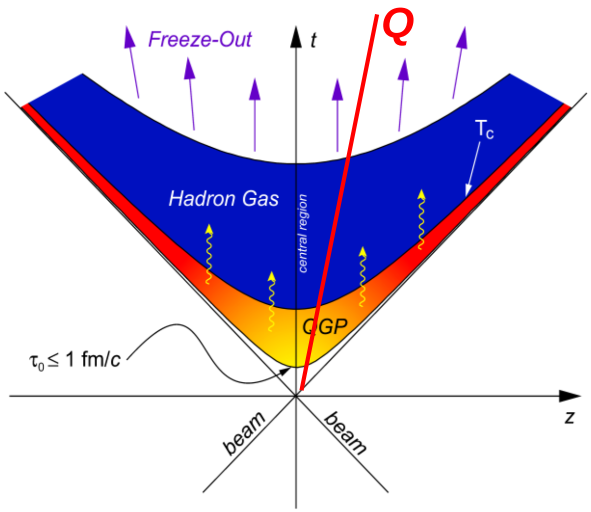
2) *and the production of dileptons in QGP results in a significant enhancement of true muonium $(\mu^+\mu^-)$!*

Why Heavy Flavors?

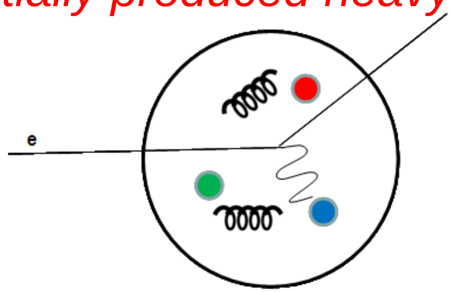
- *QCD → NRQCD → pNRQCD, a relatively solid calculation*

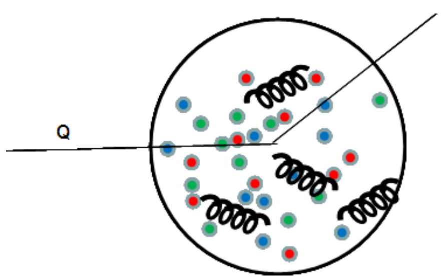
- *Medium-independent heavy-quark mass*





→ Initially produced heavy quarks pass through the QGP and carry its information.





electrons as a probe of nucleon structure — *heavy quarks as a probe of QGP structure*

J/Ψ Suppression or Enhancement ?

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

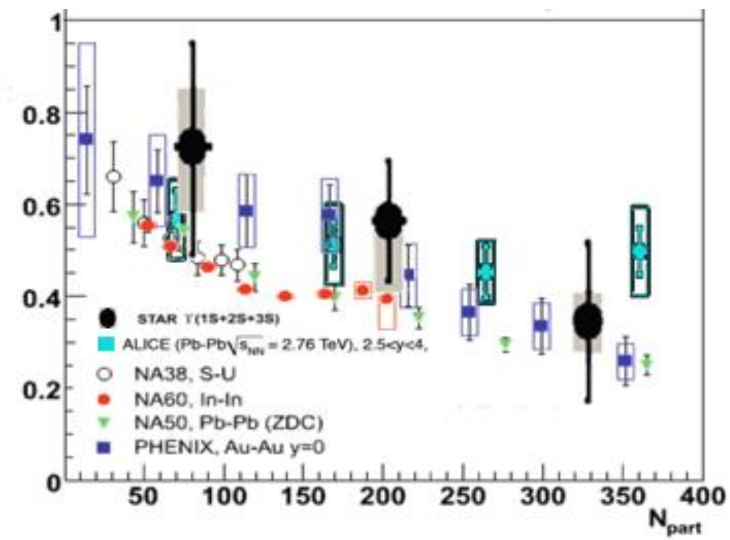
T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

PLB178,416(1986), citation 3323!

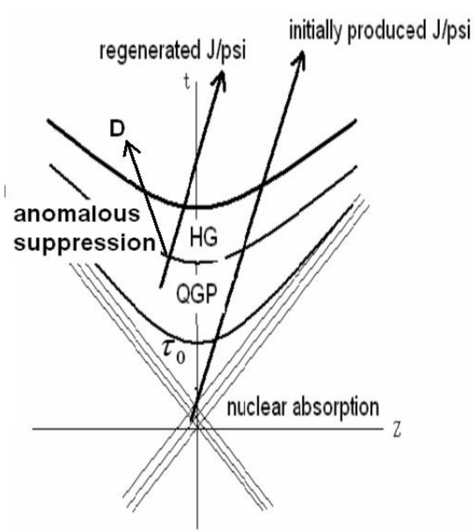


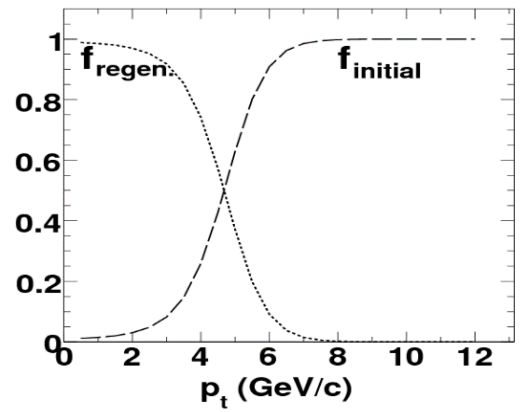
The data show almost the same yield R_{AA} at SPS, RHIC and LHC !

→ We need sensitive probes!

P_t Distributions

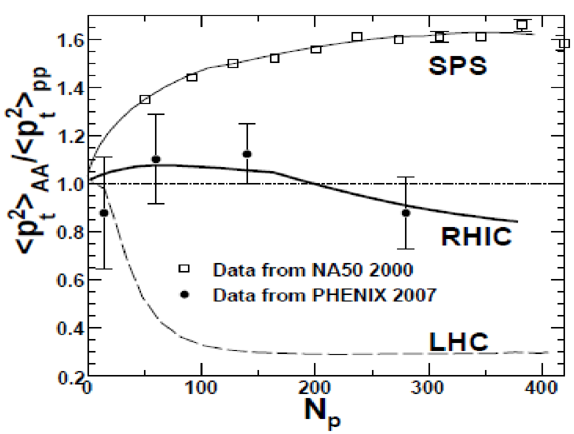
【Tsinghua Group, since 2006】

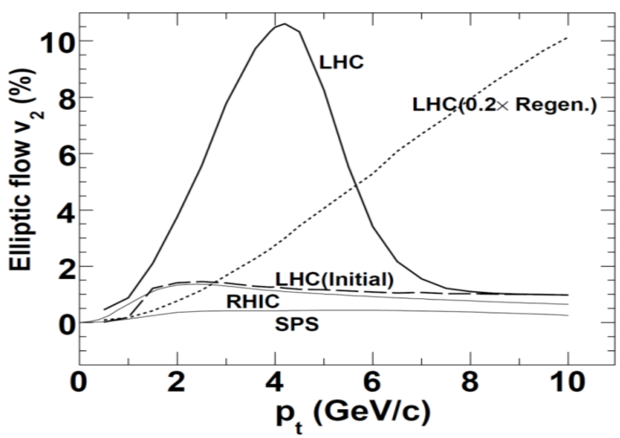




$$r_{AA} = \frac{\langle p_t^2 \rangle_{AA}}{\langle p_t^2 \rangle_{pp}} \begin{cases} >1 & SPS \\ \approx 1 & RHIC \\ <1 & LHC \end{cases}$$

- P_t distribution should be more sensitive to the QGP properties!





A Transport Approach

We need a transport approach to control J/ψ motion in medium, including self-consistently the competition between suppression and regeneration

Yan, Xu, Zhuang, PRL97, 232301(2006), PRC89, 054911(2014)

- *Transport equation for quarkonia:*

$$\partial f_\Psi/\partial\tau + \mathbf{v}_\Psi\cdot\nabla f_\Psi = -\alpha_\Psi f_\Psi + \beta_\Psi.$$

$$\alpha_\Psi(\mathbf{p}_t,\mathbf{x}_t,\tau|\mathbf{b}) = \frac{1}{2E_\Psi}\int\frac{d^3\mathbf{p}_g}{(2\pi)^3 2E_g}W_{g\Psi}^{c\bar{c}}(s)f_g(\mathbf{p}_g,\mathbf{x}_t,\tau)\Theta\left(T(\mathbf{x}_t,\tau|\mathbf{b})-T_c\right),$$

suppression: g+J/ψ → $c+\bar{c}$

$$\beta_\Psi(\mathbf{p}_t,\mathbf{x}_t,\tau|\mathbf{b}) = \frac{1}{2E_\Psi}\int\frac{d^3\mathbf{p}_g}{(2\pi)^3 2E_g}\frac{d^3\mathbf{p}_c}{(2\pi)^3 2E_c}\frac{d^3\mathbf{p}_{\bar{c}}}{(2\pi)^3 2E_{\bar{c}}}W_{c\bar{c}}^{g\Psi}(s)f_c(\mathbf{p}_c,\mathbf{x}_t,\tau|\mathbf{b})f_{\bar{c}}(\mathbf{p}_{\bar{c}},\mathbf{x}_t,\tau|\mathbf{b}) \times(2\pi)^4\delta^{(4)}(p+p_g-p_c-p_{\bar{c}})\Theta\left(T(\mathbf{x}_t,\tau|\mathbf{b})-T_c\right),$$

regeneration: c+$\bar{c}$ →g+J/ψ

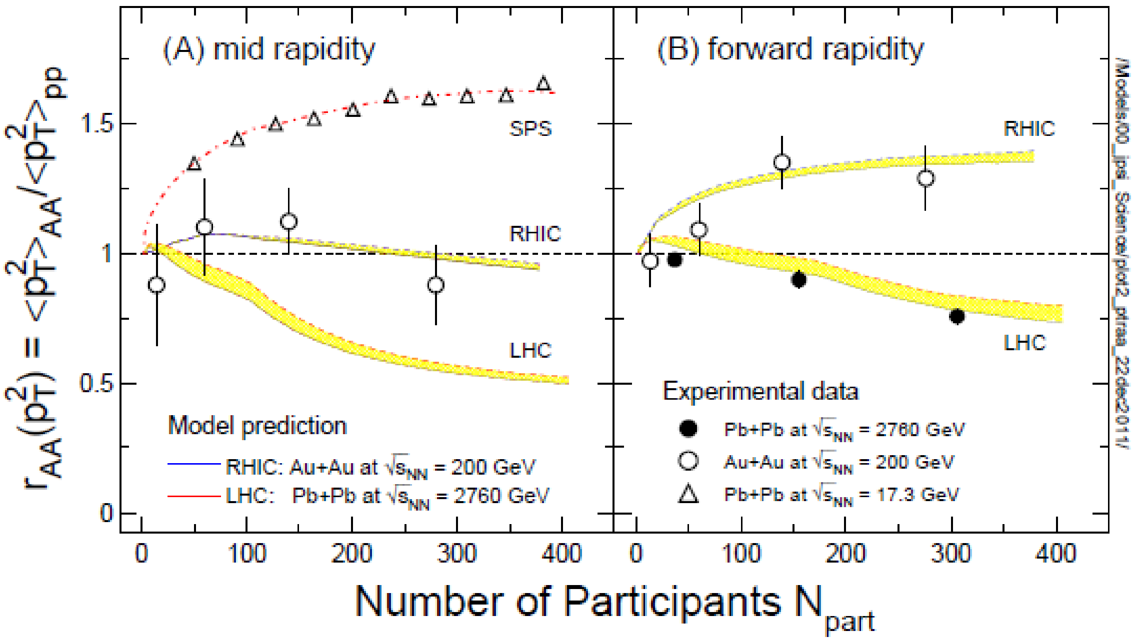
$$f_\Psi(\mathbf{p}_t,\mathbf{x}_t,\tau|\mathbf{b}) = f_\Psi(\mathbf{p}_t,\mathbf{x}_t-\mathbf{v}_\Psi(\tau-\tau_0),\tau_0|\mathbf{b})e^{-\int_{\tau_0}^{\tau}d\tau'\alpha_\Psi(\mathbf{p}_t,\mathbf{x}_t-\mathbf{v}_\Psi(\tau-\tau'),\tau'|\mathbf{b})} + \int_{\tau_0}^{\tau}d\tau'\beta_\Psi(\mathbf{p}_t,\mathbf{x}_t-\mathbf{v}_\Psi(\tau-\tau'),\tau'|\mathbf{b})e^{-\int_{\tau'}^{\tau}d\tau''\alpha_\Psi(\mathbf{p}_t,\mathbf{x}_t-\mathbf{v}_\Psi(\tau-\tau''),\tau''|\mathbf{b})}.$$

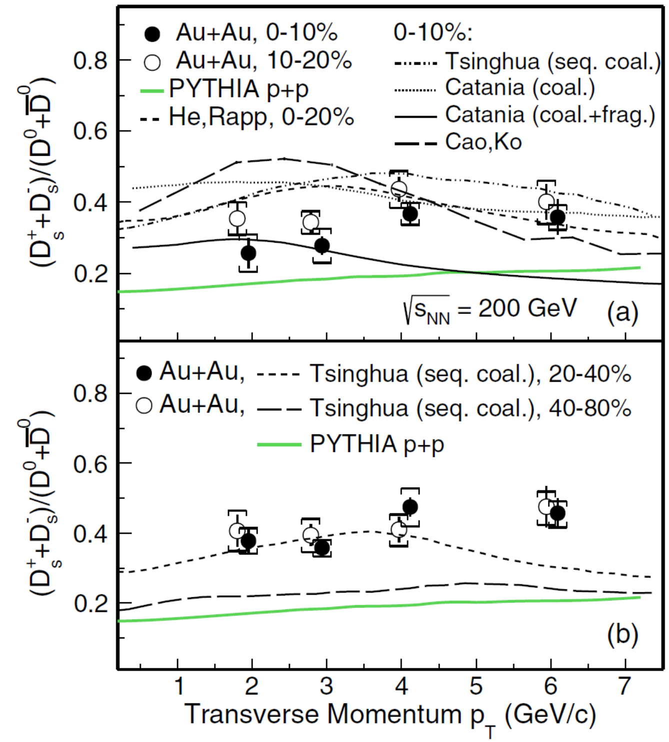
- *Hydrodynamic equations for QGP:*

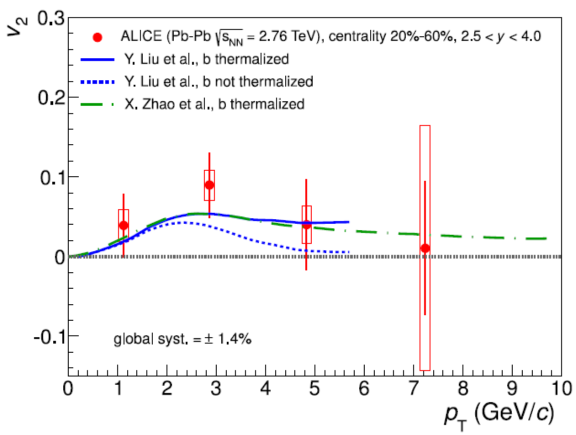
$$\partial_\mu T^{\mu\nu}=0,\qquad \partial_\mu n^\mu=0$$

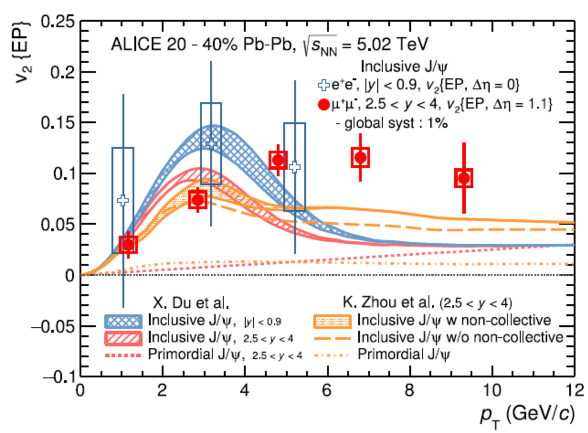
- *QCD equation of state*
- *Initial distribution from p+p data.*
- *Cold nuclear matter effects:* *shadowing effect, Cronin effect, nuclear absorption.*

r_{AA} and v_2


(A) mid rapidity
(B) forward rapidity
SPS
RHIC
LHC
Model prediction
RHIC: Au+Au at √sNN = 200 GeV
LHC: Pb+Pb at √sNN = 2760 GeV
Experimental data
Pb+Pb at √sNN = 2760 GeV
Au+Au at √sNN = 200 GeV
Pb+Pb at √sNN = 17.3 GeV
rAA(pT2) = <pT2>AA/<pT2>pp
Number of Participants Npart


Au+Au, 0-10%
Au+Au, 10-20%
PYTHIA p+p
He,Rapp, 0-20%
0-10%:
Tsinghua (seq. coal.)
Catania (coal.)
Catania (coal.+frag.)
Cao,Ko
√sNN = 200 GeV
(a)
Au+Au,
Au+Au,
Tsinghua (seq. coal.), 20-40%
Tsinghua (seq. coal.), 40-80%
PYTHIA p+p
(b)
(Ds+ + Ds-)/(D0 + D̄0)
Transverse Momentum pT (GeV/c)

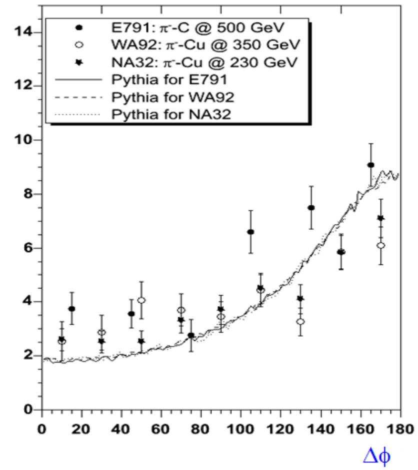

ALICE (Pb-Pb √sNN = 2.76 TeV), centrality 20%-60%, 2.5 < y < 4.0
Y. Liu et al., b thermalized
Y. Liu et al., b not thermalized
X. Zhao et al., b thermalized
global syst. = ± 1.4%
v2
pT (GeV/c)


ALICE 20 - 40% Pb-Pb, √sNN = 5.02 TeV
Inclusive J/ψ
e+e-, |y| < 0.9, v2{EP, Δη = 0}
μ+μ-, 2.5 < y < 4, v2{EP, Δη = 1.1}
- global syst : 1%
X. Du et al.
Inclusive J/ψ, |y| < 0.9
Inclusive J/ψ, 2.5 < y < 4
Primordial J/ψ, 2.5 < y < 4
K. Zhou et al. (2.5 < y < 4)
Inclusive J/ψ w non-collective
Inclusive J/ψ w/o non-collective
Primordial J/ψ
v2 {EP}
pT (GeV/c)

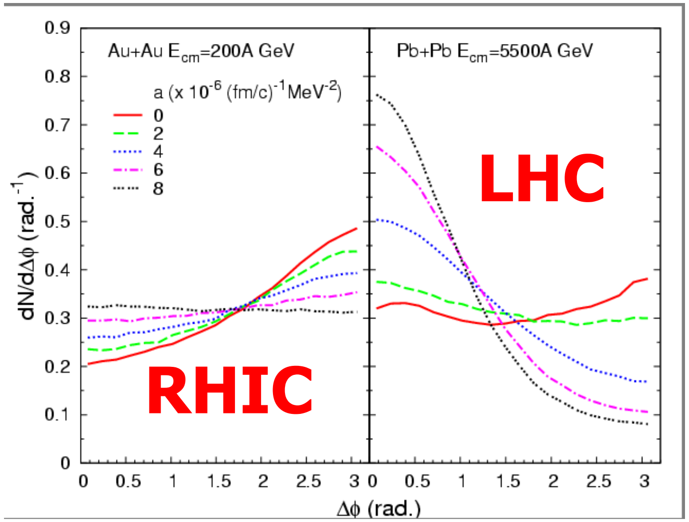
Partonic Wind

Zhu, Xu, Zhuang, PRL97, 232301(2008)

- *Strong $c\bar{c}$ $(D\bar{D})$ back-to-back correlation in p+p collisions!*



- *How does the QGP modify the angular correlation?*



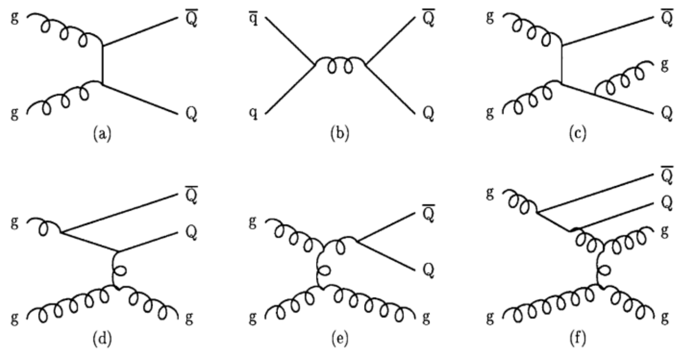
- *at RHIC, the back-to-back correlation is washed away by partonic collectivity.*

- *At LHC, larger partonic density, higher temperature, and stronger collective expansion lead to a near side correlation!*

Heavy Quark Production in QGP at FCC

Zhou, Chen, Greiner, Zhuang, PLB758, 434(2016)

Charm production in QGP

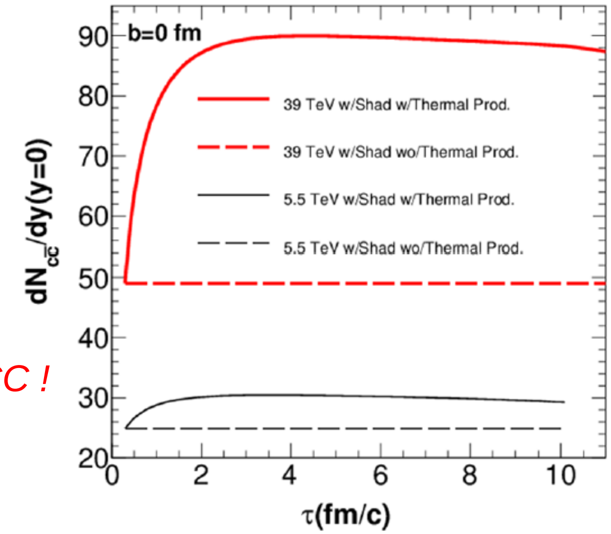


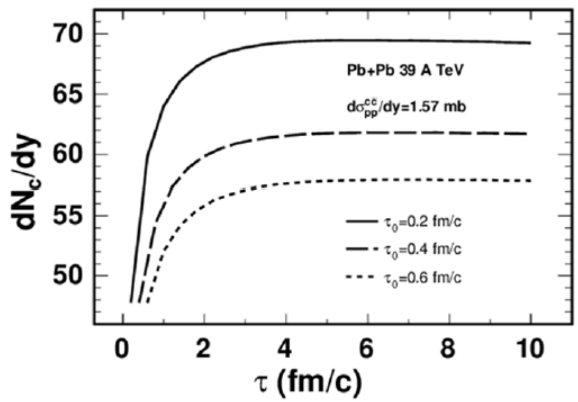
Levai, Muller, Wang, PRC51, 3326(1995);
Kaempfer, Pavlenko, PLB391, 185(1997);
Uphoff, Fochler, Xu, Greiner, PRC82, 044906(2010);
Zhang, Ko, Liu, PRC77, 024901(2008),……

FCC physics opportunities, [FCC collaboration], EPJC79, 474(2019)

Fig. 16.4 Time-evolution of the $c\bar{c}$ yield (per unit of rapidity at midrapidity) for central Pb–Pb collisions at $\sqrt{s_{NN}} = 39$ TeV [395,396]

80% enhancement at FCC !

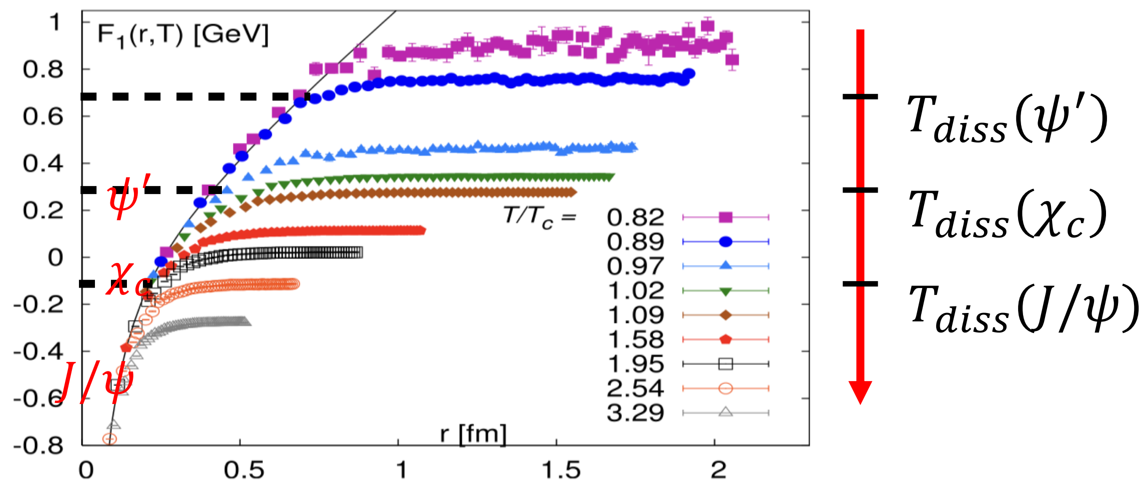




Dominant Mechanism for Quarkonium Dissociation

- *Mechanism I: color screening*

P. Petreczky, J. Phys. G 37 (2010) 094009.



- *Mechanism II: scattering*

Singlet-octet thermal break up → gluon-dissociation

Landau damping → inelastic scattering (quasi-free limit)

N. Brambilla, M. Escobedo, J. Ghiglieri, M. Laine, O. Philipsen, P. Romatschke, M. Tassler, P. Petreczky, et al, JHEP 03, 054 (2007). PRD 78, 014017 (2008). JHEP 09, 038 (2010). JHEP 1112 (2011) 116…

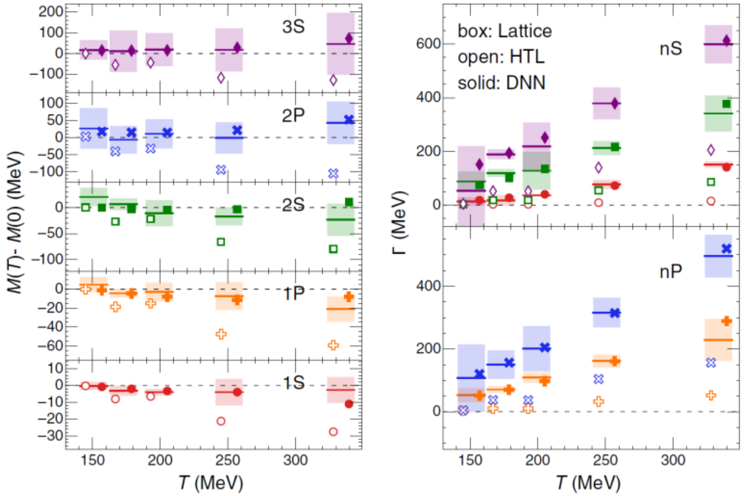
Which mechanism is the dominant one ?

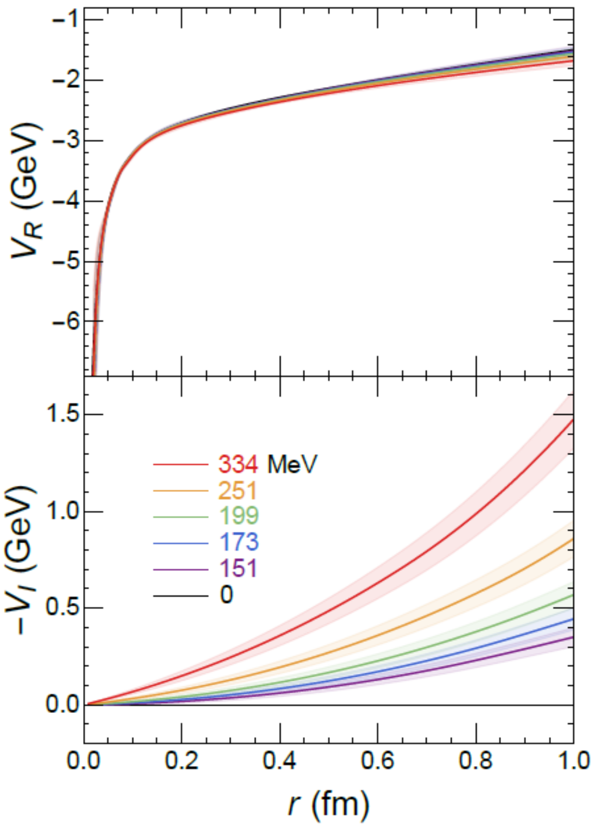
Machine Learning Meets LQCD

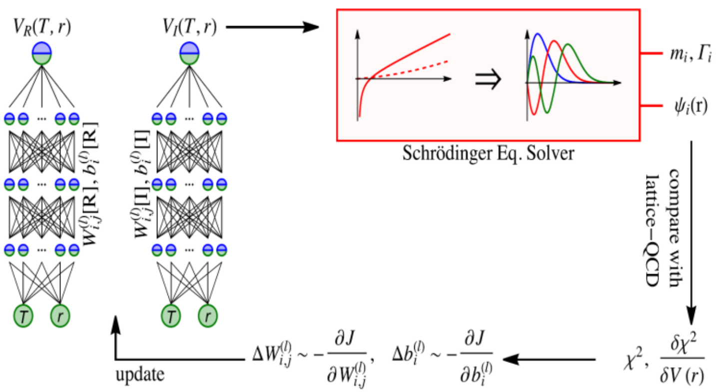
S.Shi, K.Zhou, J.Zhao, S.Mukherjee and PZ, PRD105, 014017(2021)

Inversely solving the Schroedinger equation

$$m(T),\ \ \Gamma(T) \rightarrow\ \ V(r,T) = Re\, V(r,T) + i\, Im\, V(r,T)$$





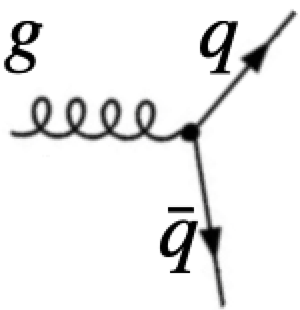


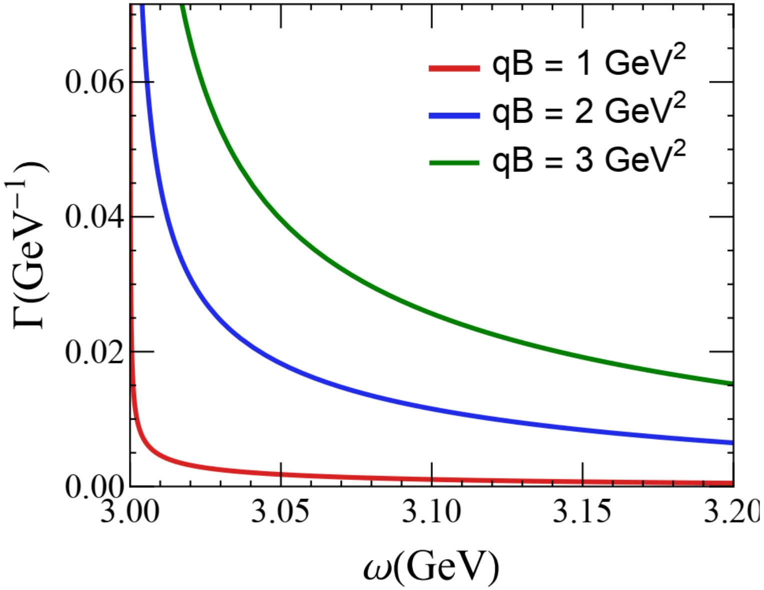
Strong T-dependent imaginary part but very small screening effect!

Gluon Decay into a Heavy Quark Pair in Magnetic Field

Chen, Zhao and Zhuang, arXiv: 2407.03586

The decay cannot happen in vacuum, due to the constraint of energy and momentum conservation. However, it can happen in magnetic field due to the breaking down of momentum conservation.



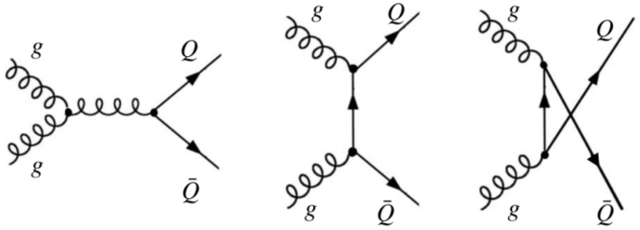


Heavy Quark Production in Magnetic Field

Chen, Zhao and Zhuang, arXiv: 2401.17559

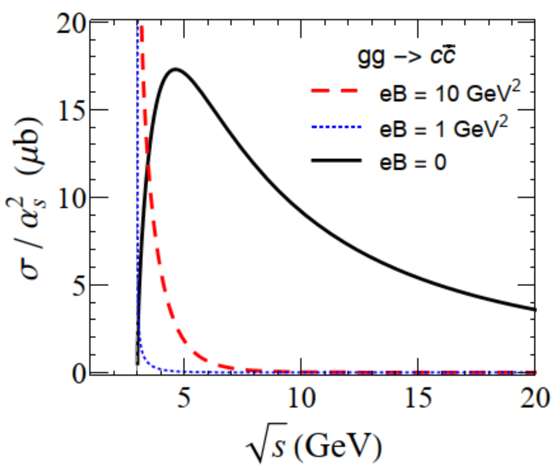
Heavy quarks are produced in the initial stage and therefore sensitive to the strong magnetic field.

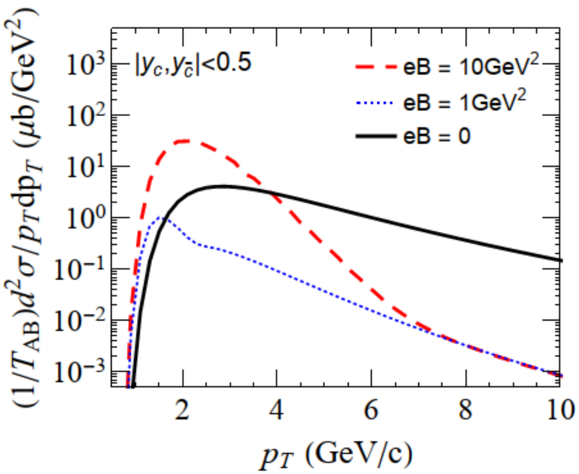
$$gg \to Q\bar{Q}$$



Only quarks are affected by the magnetic field.

Due to the dimension reduction of heavy quark phase space, the production is concentrated in a narrow region above the threshold.

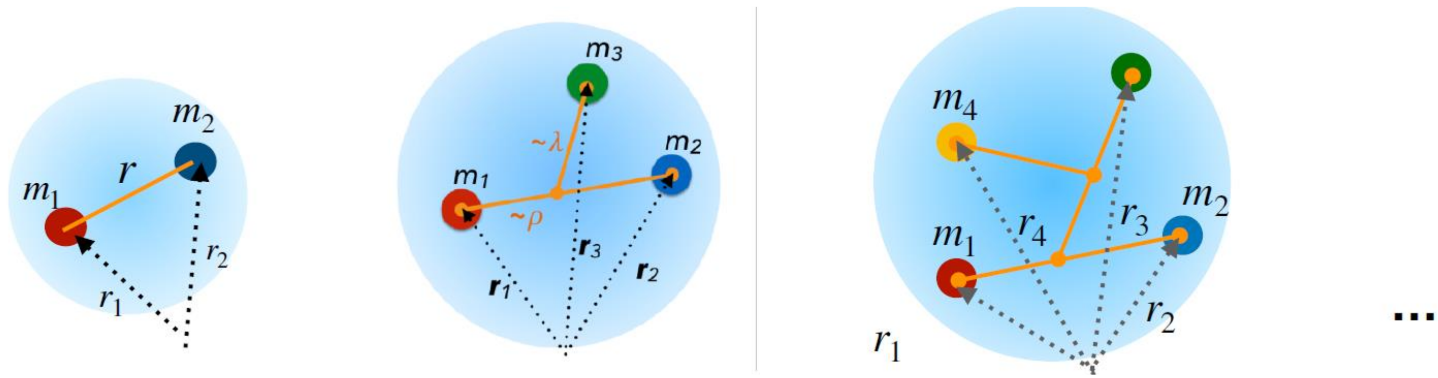




low p_t enhancement & high p_t suppression in heavy ion collisions.

N-body Potential Model for Fully Heavy-flavor Hadrons

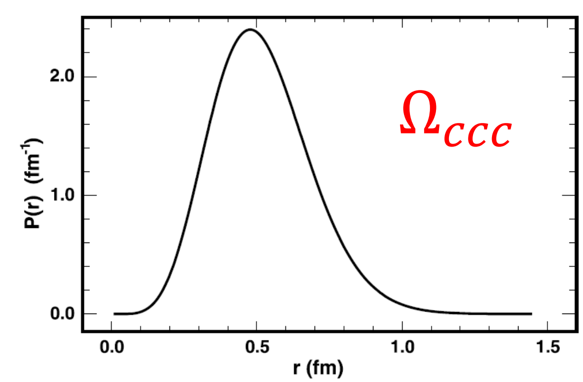
J.Zhao, S.Shi and PZ, PRD102, 114001 (2020)



$$\left[\sum_{i=1}^{N}\left(-\frac{\vec{\nabla}_i^2}{2m_i}\right)+V(\vec{r}_1,\dots\dots\vec{r}_N,T)\right]\Psi(\vec{r}_1,\dots\dots\vec{r}_N)=E_N\Psi(\vec{r}_1,\dots\dots\vec{r}_N)$$

$$V(\vec{r}_1,\dots\dots\vec{r}_N,T)=\sum_{i\neq j}^{N}\left[V_{ij}^{c}(|\vec{r}_{ij}|,T)+V_{ij}^{s}(|\vec{r}_{ij}|)\right]$$

$V_{ij}^{c}(|\vec{r}_{ij}|,T)$ *from Lattice QCD*, $\quad V_{ij}^{s}(|\vec{r}_{ij}|)=\beta e^{-\gamma|\vec{r}_{ij}|}\vec{s}_i\cdot\vec{s}_j$



- (Center−of−mass motion) · (relative motion)

$$\Psi(\vec{r}_1,\dots\dots\vec{r}_N)=\Theta(\vec{R})\Phi(\vec{x}_1,\dots\dots\vec{x}_{N-1})$$

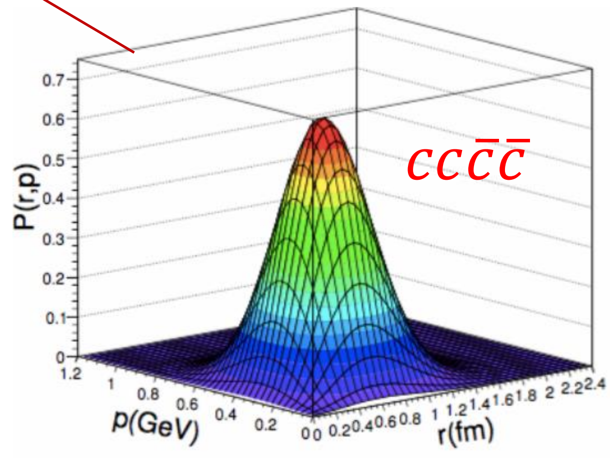
Heavy Quark Coalescence Mechanism

$$\frac{dn}{d^3\vec{p}} = C\int_{\Sigma} \frac{p^{\mu}d\sigma_{\mu}}{(2\pi)^3}\int \frac{d^{N-1}\vec{x}d^{N-1}\vec{y}}{(2\pi)^9} W(\vec{x},\vec{p})\, f_1(\vec{x}_1,\vec{p}_1) \ldots \ldots f_N(\vec{x}_N,\vec{p}_N)$$

eigenvalue of Schroedinger Eq.

eigenfunction of Schroedinger Eq.

heavy quark distribution



- *Hadronization hypersurface is the production surface*

$$\Sigma(\vec{x},t):\ \ T(\vec{x},t) = T_D\ \ (> T_c)$$

Temperature $T(\vec{x},t)$ can be calculated by hydrodynamics

$$\partial^{\mu}T_{\mu\nu} = 0$$

- *$f_i(\vec{x}_i,\vec{p}_i)$ is controlled by heavy quark transport. If thermalized with QGP, Fermi-Dirac distribution*

$$f_i(\vec{x}_i,\vec{p}_i) = \frac{1}{e^{p_i^{\mu}u_{\mu}/T(\vec{x}_i)}+1}$$

Hanting the new particle Ω_{ccc} at LHC

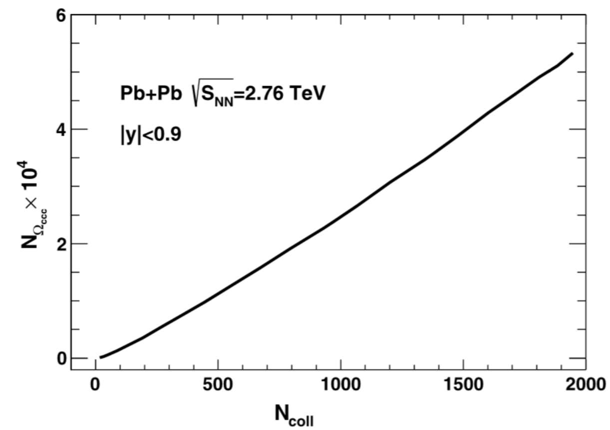
题目:	Experimental test of quark deconfinement - hadrons with charm quarks
报告人:	Johanna Stachel (Heidelberg University)
时间:	2023年9月14日 (周四) 10:00
地点:	理科楼 C302

dependence of Ωccc production yields on syst
for a run time of 10^6 s

arXiv: 2211.02491	O-O	Ar-Ar	Kr-Kr	Xe-Xe	Pb-Pb
$\sigma_{\rm inel}(10\%)$ mb	140	260	420	580	800
$T_{\rm AA}(0-10\%)\,{\rm mb}^{-1}$	0.63	2.36	6.80	13.0	24.3
$\mathcal{L}({\rm cm}^{-2}{\rm s}^{-1})$	$4.5\cdot10^{31}$	$2.4\cdot10^{30}$	$1.7\cdot10^{29}$	$3.0\cdot10^{28}$	$3.8\cdot10^{27}$
	$d\sigma_{c\bar{c}}/dy = 0.53$ mb				
$dN_{\Omega_{ccc}}/dy$	$8.38\cdot10^{-8}$	$1.29\cdot10^{-6}$	$1.23\cdot10^{-5}$	$4.17\cdot10^{-5}$	$1.25\cdot10^{-4}$
Ω_{ccc} Yield	$5.3\cdot10^{5}$	$8.05\cdot10^{5}$	$8.78\cdot10^{5}$	$7.26\cdot10^{5}$	$3.80\cdot10^{5}$
	$d\sigma_{c\bar{c}}/dy = 0.63$ mb				
$dN_{\Omega_{ccc}}/dy$	$1.44\cdot10^{-7}$	$2.33\cdot10^{-6}$	$2.14\cdot10^{-5}$	$7.03\cdot10^{-5}$	$2.07\cdot10^{-4}$
Ω_{ccc} Yield	$9.2\cdot10^{5}$	$1.45\cdot10^{6}$	$1.53\cdot10^{6}$	$1.22\cdot10^{6}$	$6.29\cdot10^{5}$

current estimates for luminosities for LHC for lighter nuclei somewhat less optimisti
→ optimum for Xe-Xe with 3.9-6.5 10^5 Ωccc per year

Coalescence prediction via solving 3-body Schrodinger equation:

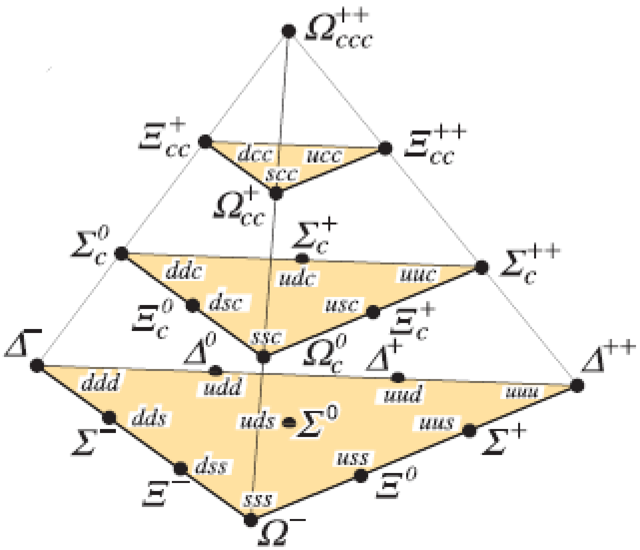


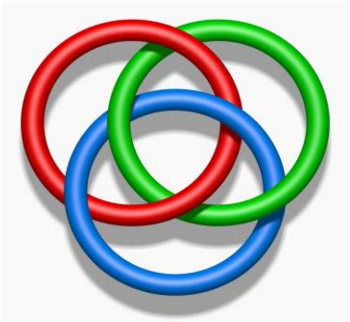
Theory Prediction:

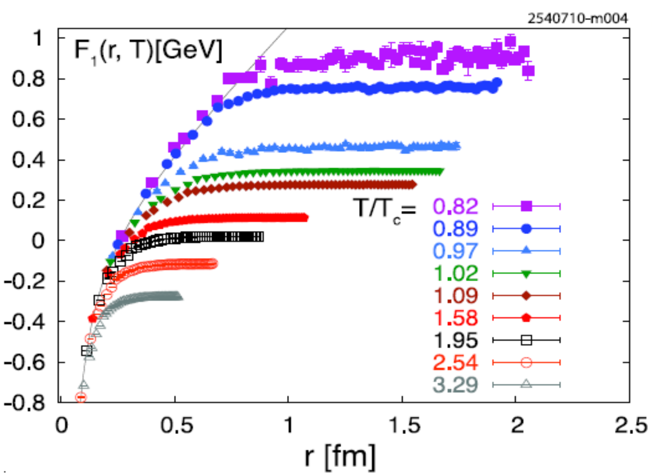
Ωccc production in high energy nuclear collisions, H.He, Y.Liu and PZ, PLB746, 59(2015);
Searching for Ξcc in Relativistic Heavy Ion Collisions, J.Zhao, H.He and PZ, PLB771, 349(2017);
Exotic Quantum States for Charmed Baryons at Finite Temperature, J.Zhao and P.Zhuang, PLB775, 84(2017);

Ω_{ccc} as a Borromean Ring and an Efimov State

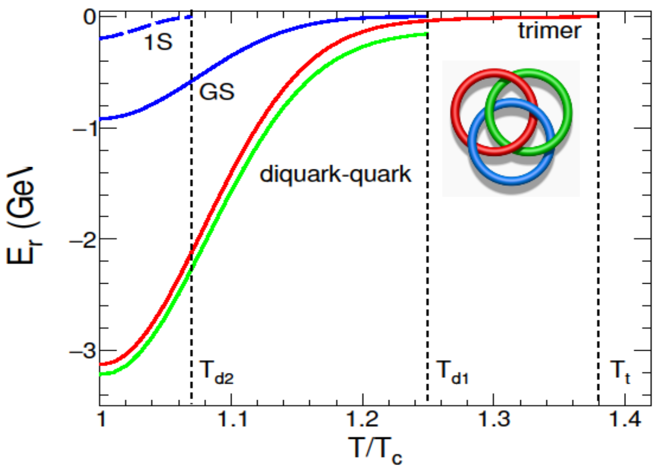
J.Zhao and PZ, PLB775,84(2017)

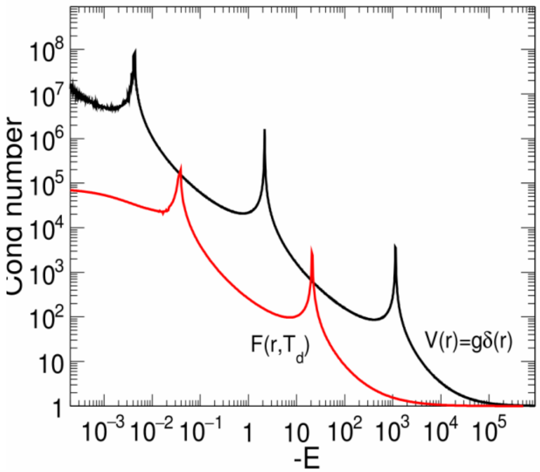






short range potential at high T !





$$\frac{E_n}{E_{n+1}} = e^{2\pi/s_0} = 515,$$ *Efimov state !*

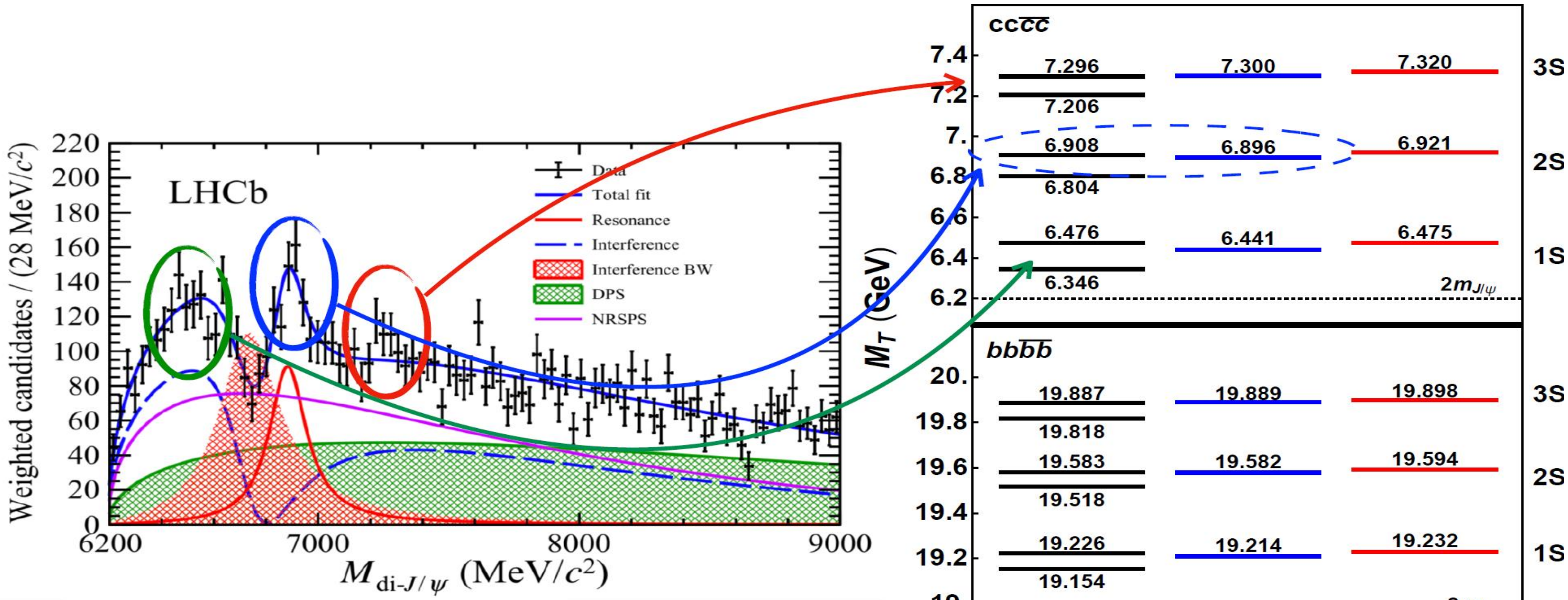
A challenge to experimentalists:

Discovery of Ω_{ccc} and its Borromean state in A+A !

Exotic Hadrons

J.Zhao, S.Shi and PZ, PRD102, 114001 (2020)

- 2022： ATLAS, CMS and LHCb announced the discovery of fully-heavy tetraquarks in p+p!
- HIC: Plenty of charm quarks and coalescence → exotic hadron enhancement in A+A!



$m[X(6900)] = 6905 \pm 11 \pm 7\ \text{MeV}/c^2$

$\Gamma[X(6900)] = 80 \pm 19 \pm 33\ \text{MeV}$

$$\left(\frac{d\sigma}{N_c dy}\right)_{AA} \sim 770\, pb \gg \left(\frac{d\sigma}{dy}\right)_{pp} \sim 78\, pb$$

A challenge to experimentalists: Discovery of exotic hadrons and their structure !

关于重味的综述文章

Eur. Phys. J. C (2016) 76:107
DOI 10.1140/epjc/s10052-015-3819-5

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Review

Heavy-flavour and quarkonium production in the LHC era: from proton–proton to heavy-ion collisions

A. Andronic[1], F. Arleo[2,3], R. Arnaldi[4], A. Beraudo[4], E. Bruna[4], D. Caffarri[5], Z. Conesa del Valle[6], J. G. Contreras[7], T. Dahms[8], A. Dainese[9], M. Djordjevic[10], E. G. Ferreiro[11], H. Fujii[12], P.-B. Gossiaux[13], R. Granier de Cassagnac[2], C. Hadjidakis[6], M. He[14], H. van Hees[15], W. A. Horowitz[16], R. Kolevatov[13,17], B. Z. Kopeliovich[18], J.-P. Lansberg[6], M. P. Lombardo[19], C. Lourenço[5], G. Martinez-Garcia[13], L. Massacrier[6,13,20,a], C. Mironov[2], A. Mischke[21,22], M. Nahrgang[23], M. Nguyen[2], J. Nystrand[24], S. Peigné[13], S. Porteboeuf-Houssais[25], I. K. Potashnikova[18], A. Rakotozafindrabe[26], R. Rapp[27], P. Robbe[20], M. Rosati[28], P. Rosnet[25], H. Satz[29], R. Schicker[30], I. Schienbein[31], I. Schmidt[18], E. Scomparin[4], R. Sharma[32], J. Stachel[30], D. Stocco[13], M. Strickland[33], R. Tieulent[34], B. A. Trzeciak[7], J. Uphoff[35], I. Vitev[36], R. Vogt[37,38], K. Watanabe[39,40], H. Woehri[5], P. Zhuang[41]

Progress in Particle and Nuclear Physics 114 (2020) 103801

ELSEVIER

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

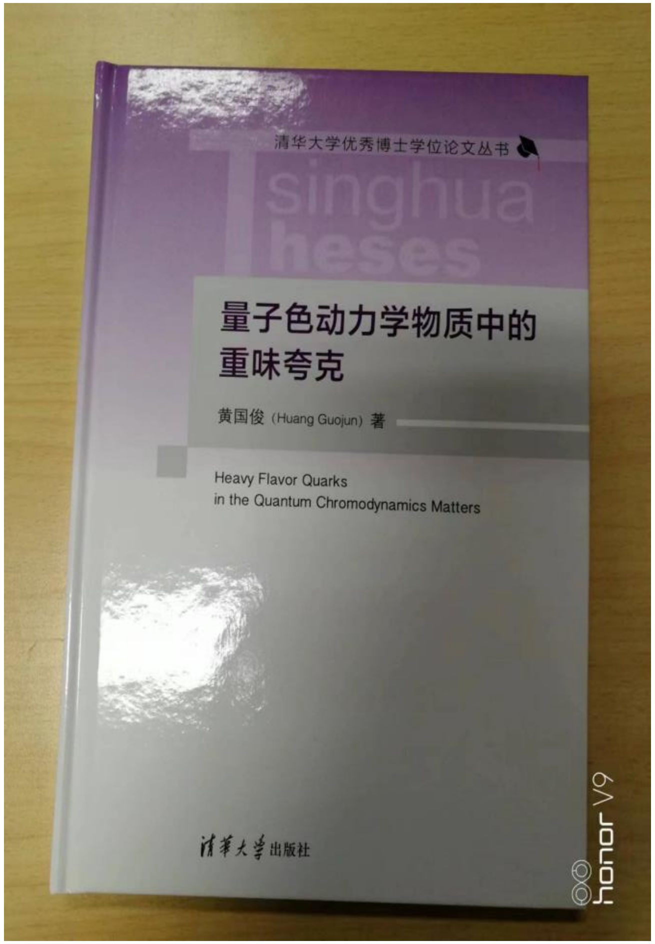
Review

Heavy flavors under extreme conditions in high energy nuclear collisions

Check for updates

Jiaxing Zhao[a], Kai Zhou[b], Shile Chen[a], Pengfei Zhuang[a,*]

[a] Physics Department, Tsinghua University, Beijing 100084, China
[b] Frankfurt Institute for Advanced Studies, Ruth-Moufang-Str. 1, 60438 Frankfurt am Main, Germany



$(\mu^+\mu^-)$ *in Vacuum*

- *A pure QED system*
- *Lifetime:* $\mathcal{O}(1)$ ps, *6 decades smaller than the life time of* μ
- *Decay channel:* $(\mu^+\mu^-) \rightarrow e^+e^-$, 98%
- *Binding energy:* $\varepsilon_n \sim -1.4/n^2$ KeV
- *Mass:* $m_n \sim 2m_\mu = 211$ MeV
- *Mean radius:* $r_n \sim \left(m_\mu \varepsilon_n\right)^{1/2} = 512\, n$ fm
- *Formation time:* $\tau_n \sim r_n = 1.72 \times 10^{-21}$s

$(\mu^+\mu^-)$ *in QGP*

■ *QGP temperature:* T_{QGP}~*hundreds of* MeV

■ *QGP lifetime:* $\tau_{QGP} \sim 10$ *fm* $\sim \mathcal{O}(10^{-23})$ s $\ll \tau_n$

■ *QGP radius:* $r_{QGP} \sim 10$ fm $\ll r_n$

■ *The interaction between* μ^+ *and* μ^- *is Coulomb-like outside the QGP and Yukawa-like with photon screening radius* $r_D \sim 2.11/T$ *inside the QGP.*

■ *QGP serves as a source of* μ^+ *and* μ^-*,while not interfering with the formation and decay of the bound state* $(\mu^+\mu^-)$*.*

Parton Mass and Coupling in QGP

Extracted from Lattice QCD:

$$m_g^2(T) = \frac{g^2(T)}{6}\left(N_c + \frac{1}{2}N_f\right)T^2,$$

$$m_q^2(T) = \frac{N_c^2-1}{8N_c}g^2(T)T^2,$$

$$m_s(T) = m_q(T) + 0.045\ \text{GeV},$$

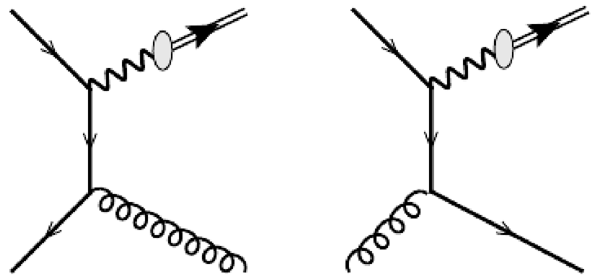
$$g^2(T) = \begin{cases} \frac{48\pi^2}{(11N_c-2N_f)\log\left[\lambda^2\left(\frac{T}{T_c}-0.56\right)^2\right]}, & T \geq T^*, \\ g^2(T^*)\left(\frac{T^*}{T}\right)^{3.1}, & T < T^*, \end{cases}$$

where $T_c = 158$ MeV, $T^* = 1.19\,T_c$ and $\lambda = 2.42$.

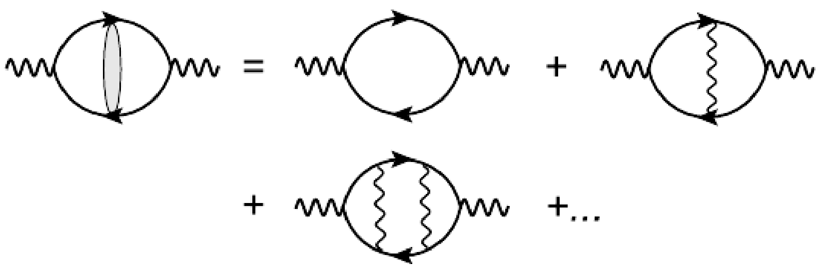
The process $(\mu^+\mu^-) \rightarrow q\bar{q}$ is kinematically forbidden due to the thermal quark mass.

$(\mu^+\mu^-)$ Production Process

- *LO:* $q\bar{q} \to (\mu^+\mu^-)$ *is kinematically forbidden.*
- *NLO:* $q\bar{q} \to (\mu^+\mu^-)g$ and $qg \to (\mu^+\mu^-)q$



- *Coulomb resummation*



- *Photon-*$(\mu^+\mu^-)$ *vertex*

$$iZ_n = i\frac{\alpha^2}{4\pi}\sqrt{\frac{m_\mu^3 m_n}{n^3}}$$

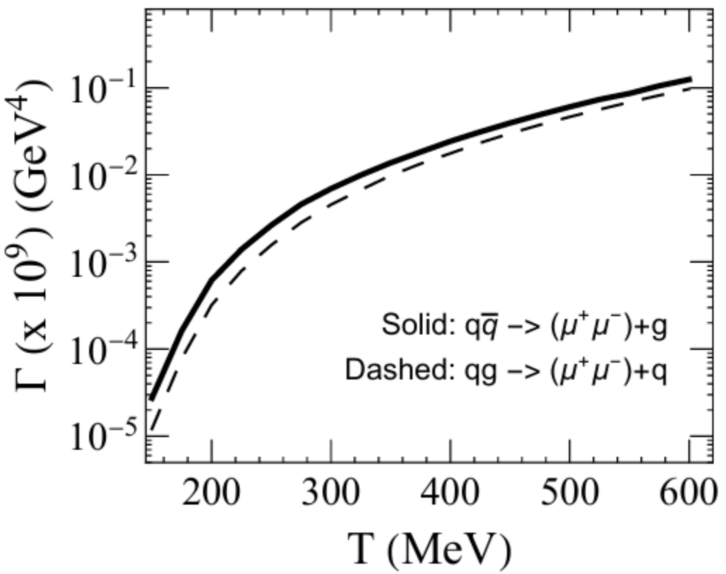
- $(\mu^+\mu^-)$*is not thermalized with the QGP.*
- *Neglecting the dissociation in QGP, the Boltzmann equation*

$$\left(\frac{\partial}{\partial t}+\frac{\mathbf{p}}{E}\frac{\partial}{\partial \mathbf{r}}\right)f(k_1)=\sum_{i=1,2}C_{\mathrm{NLO},i}[f(k_1)]$$

$$\begin{aligned} C_{\mathrm{NLO},1} &= \frac{1}{E_{k_1}}\sum_{f,n}\int\frac{d^3p_1}{(2\pi)^3 2E_{p_1}}\frac{d^3p_2}{(2\pi)^3 2E_{p_2}}\frac{d^3k_2}{(2\pi)^3 2E_{k_2}} \\ &\times \sum_{s,s',\lambda,i}|\mathcal{M}_1|^2 f_q(p_1)f_{\bar{q}}(p_2)\left(1+f_g(k_2)\right) \\ &\times (2\pi)^4\delta^{(4)}(p_1+p_2-k_1-k_2), \end{aligned}$$

- *Production rate*

$$\Gamma \equiv \int C_{\mathrm{NLO}}d\mathbf{k}_1/(2\pi)^3$$



Yield

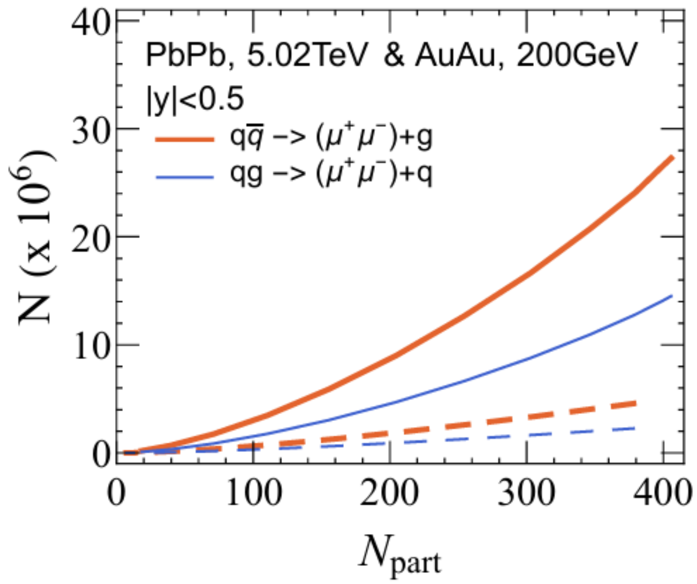
■ $(\mu^+\mu^-)$ distribution

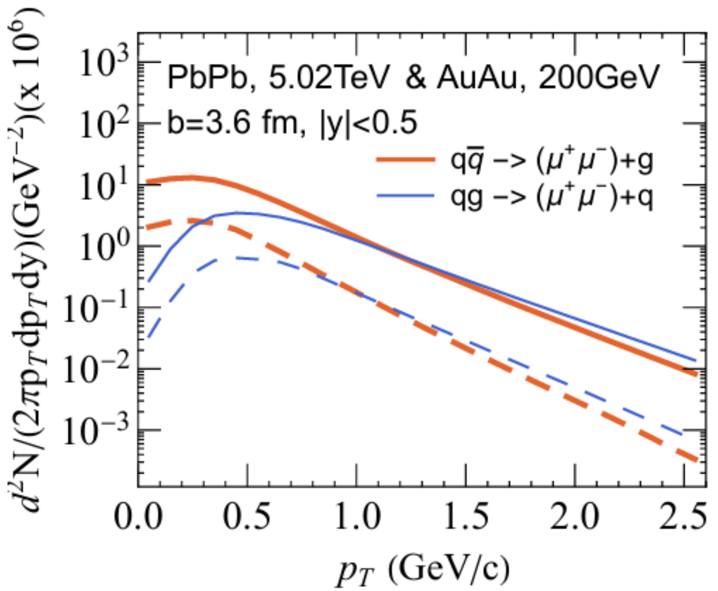
$$f(\mathbf{p}_T, y, \mathbf{x}_T, \eta, \tau) = \int_{\tau_0}^{\tau} d\tau' \frac{C_{\rm NLO}[f(\mathbf{p}_T, y, \mathbf{X}_T, H, \tau')]}{\cosh(\Delta(y-\eta))} \times \Theta(T(\mathbf{X}_T, H, \tau') - T_c), \quad (7)$$

■ Yield

$$N(\tau) = \frac{1}{(2\pi)^3} \int d^2\mathbf{p}_T d^2\mathbf{x}_T dy d\eta \tau E_T \cosh(y-\eta) \times f(\mathbf{p}_T, y, \mathbf{x}_T, \eta, \tau).$$

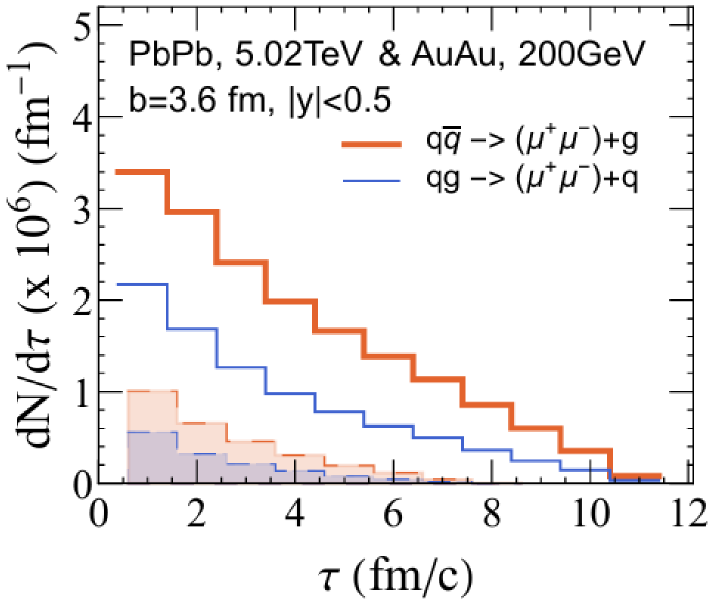
In a billion central Pb+Pb collisions, there are approximately 10^4 and 10^5 $(\mu^+\mu^-)$ at RHIC and LHC energy !





Time Dependence

■ *Like e^+e^- production which is usually used to measure the medium temperature, $(\mu^+\mu^-)$ is sensitive to the initial condition of the QGP: it is produced mainly in the initial stage.*

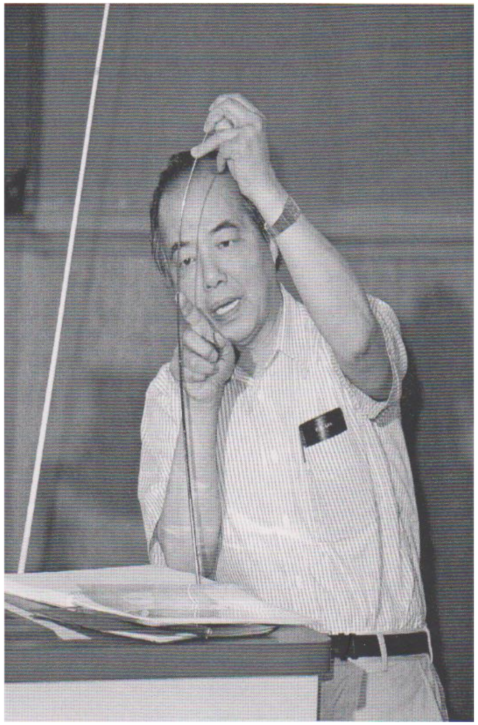


总结

用量子色动力学（QCD）研究自然界最微（夸克胶子等离子体）最热（$T\sim500$ MeV）最密（$n_B\sim3n_0$）最磁（$eB\sim10m_\pi^2$）最旋（$\omega\sim10$ MeV）最流（$\eta/s\sim1/(4\pi)$）的火球。

要想认识最小的，需要知道最大的

李政道, 1996



Large things are made of small
And even smaller.
To know the smallest
We need also the largest

All lie in vacuum
Everywhen and everywhere.
How can the micro
Be separate from the macro?

Let vacuum be a condensate
Violating harmony
We can then penetrate
Through asymmetry into symmetry

大事物由小事物组成
甚至是更小的。
要想认识最小的
我们也需要知道最大的。
一切都取决于真空
无论何时何地。
微观的事物怎能
与宏观相分离？
真空其实是一种凝聚
破坏了和谐。
如此我们方可洞穿
不对称中的对称。

【杨振伟翻译】