Hot and Dense Matter Physics: Theory

Pengfei Zhuang
Physics Department, Tsinghua University

- *Phases of QCD*

  Lattice QCD, Critical Point, CME and CVE

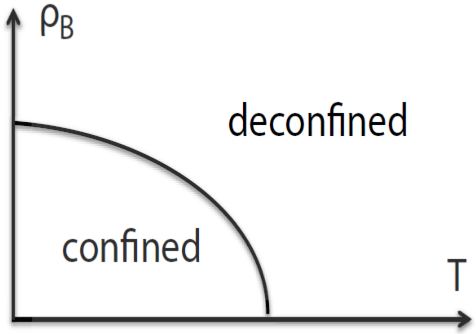
- *Probes of QGP*

  Jet Quenching, Quarkonia and Multi-charmed Baryons

QCD Phase Diagrams

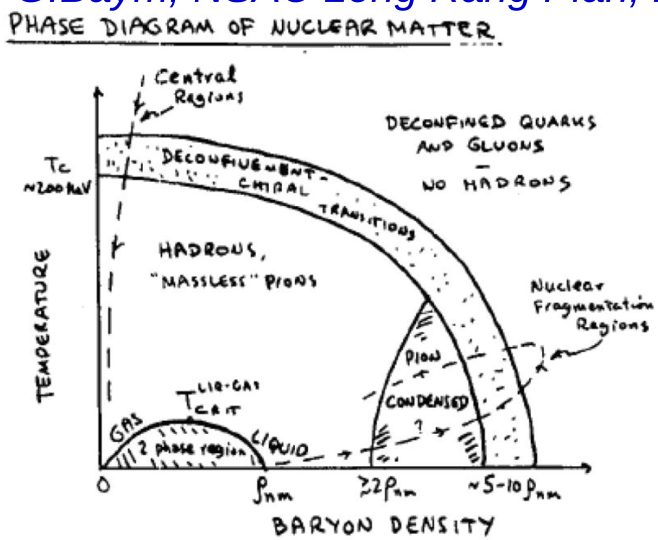
Deconfinement

N.Cabbibo and G.Parisi, PLB59, 67(1975)

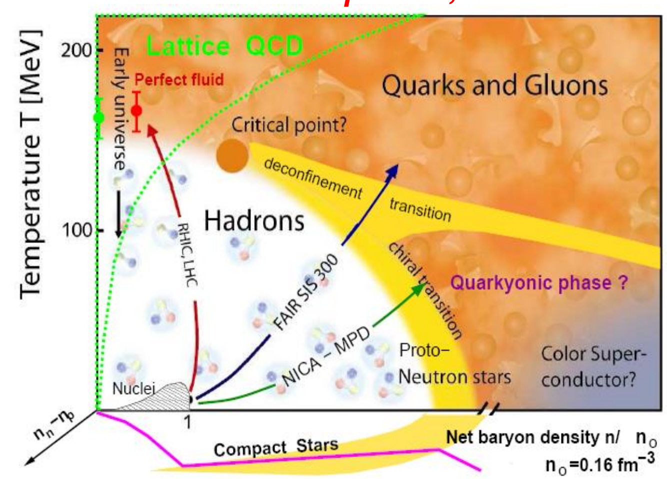


+ Chiral restoration

G.Baym, NSAC Long Rang Plan, 1983



+ CSC, Quarkonic phase and Critical point, ……



Theoretical Methods:

Lattice QCD

Functional RG

Resumed pQCD

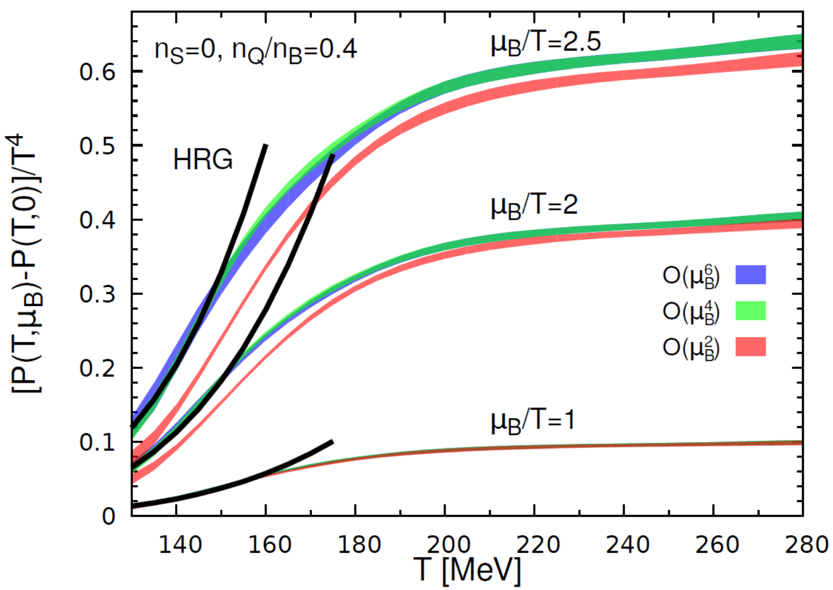
Dyson-Schwinger equation

AdS/CFT

Effective models

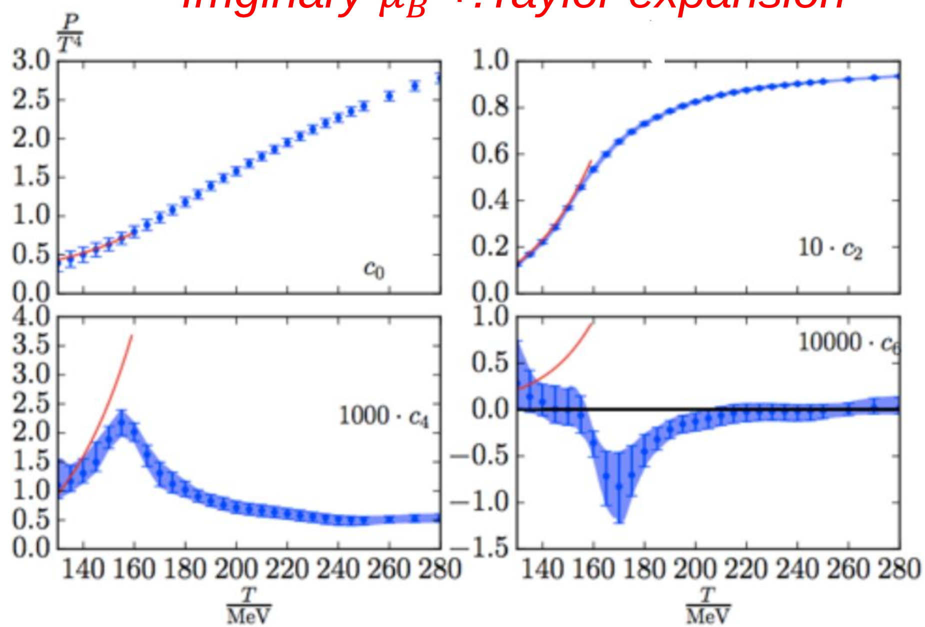
Lattice QCD: Equation of State at Nonzero μ_B

Taylor expansion $$\frac{P}{T^4} = \sum_n c_n \left(\frac{\mu_B}{T}\right)^n$$



Bielefeld-BNL-CCNU, Phys.Rev. D95 (2017) no.5, 05450

Imginary μ_B +.Taylor expansion



Wuppertal-Budapest-Houston:
EPJ Web Conf. 137 (2017) 07008

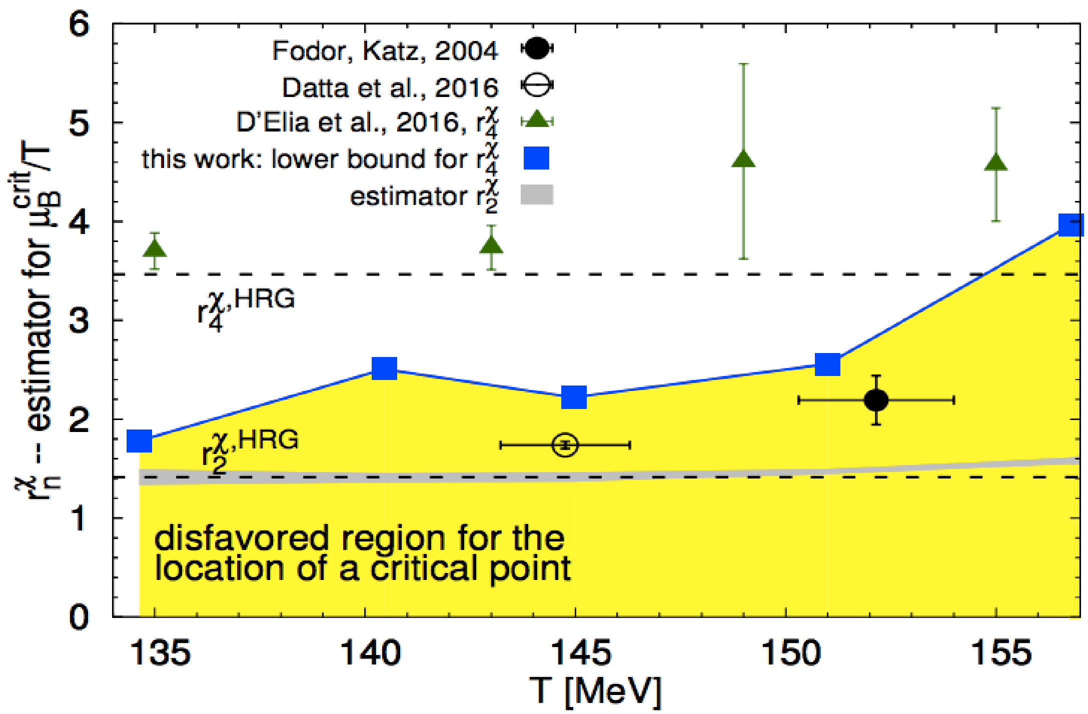
The EoS is well under control at $\mu_B/T \lesssim 2$ or $\sqrt{s_{NN}} \gtrsim 12$ GeV

Tsinghua University

Lattice QCD: Critical Point is Disfavored at $\mu_B/T \lesssim 2$

Critical point is a singularity of EoS,

Calculating the radius of convergence of EoS to 6th order at high T



Bielefeld-BNL-CCNU, PRD 95 (2017) no.5, 054504
D'Elia et al., PRD 95 (2017) 094503
Datta et al., PRD 95 (2017) 054512
Fodor and Katz, JHEP 0404 (2004) 050

Critical point is not excluded in this region ！

Tsinghua University

Dynamical Fluctuations around Critical Point

- Correlation length $\xi \to \infty$ at a critical point
- Order parameter field $\sigma(x)$

  fluctuation distribution $P[\sigma] \sim e^{-\Omega(\sigma)/T}$

  Cumulants:

$$C_2 = \langle \sigma_V^2 \rangle \sim \xi^2, \qquad C_3 = \langle \sigma_V^3 \rangle \sim \xi^6, \qquad \ldots\ldots$$

  High order cumulants are more sensitive to ξ and cab be used to sensitively probe the critical point.

  M.Stephanov, PRL102, 032301(2009)

  M.Asakava, S.Ejiri, M.Kitazawa, PRL103, 262301(2009)

- The sign of C_4 (C_4/C_2) depends on which side of the critical point we are.

  M.Stephanov, PRL107, 052301(2011)

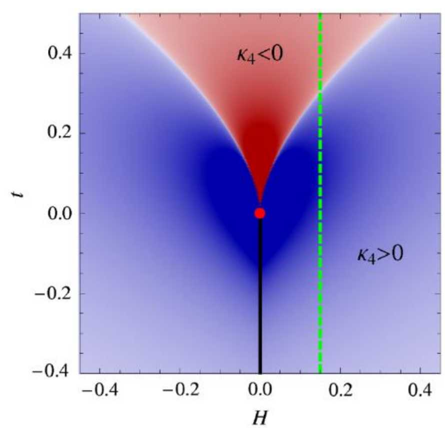
Far from CP: $C_4 = 0$

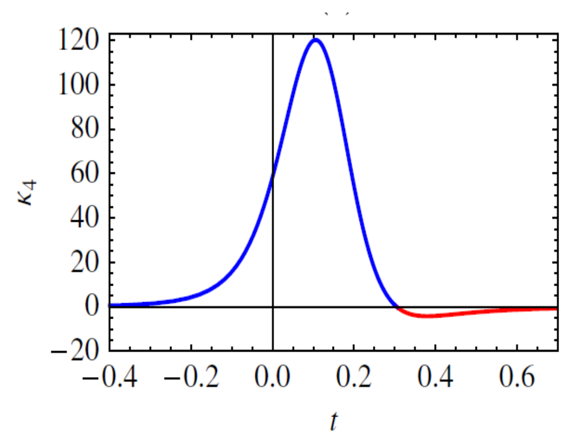
Crossover side: $C_4 < 0$

First order side: $C_4 > 0$

$$t = \frac{T - T_c}{T_c}$$

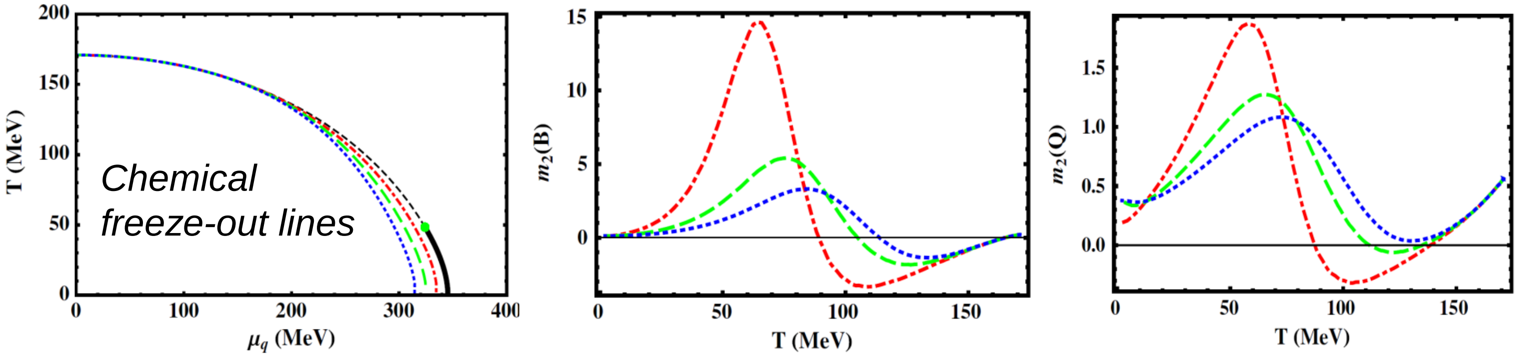
H: magnetic field





Baryon Number Moments in HIC

● NJL model — *Chen, Deng, Kohyama, Labum, PRD93, 034037 (2016)*



$m_2 \sim \chi^4$

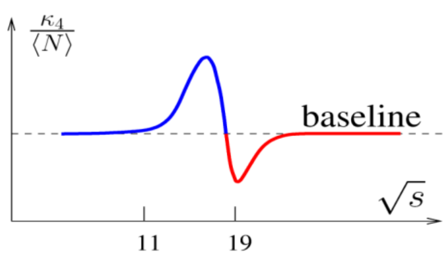
1) The shape depends on the location of the freeze-out with respect to the location of CP.
2) Baryon number moments are more sensitive to the correlation length than electronic charge moments.

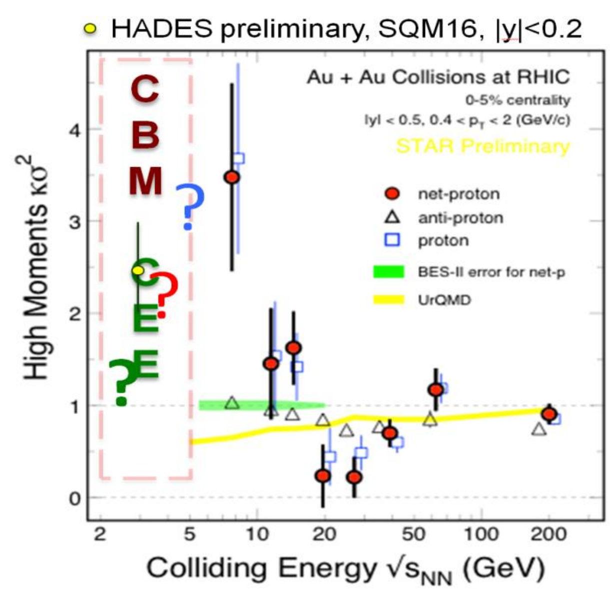
Similar results in PQM (Schaefer, Wanger, PRD85,034027(2012), V.Skokov, QM12), VDW (Vovchenko et al., PRC92, 054901(2015)), and considering Memory and Non-equilibrium effects (Swagato et al., PRC92, 034912(2015)).

● *Experimental data*

Challenges:

- ♣ *finite size*
- ♣ *non-equilibrium (Yin, Song,……)*
- ♣ *background*
- ♣ *data at lower energies*

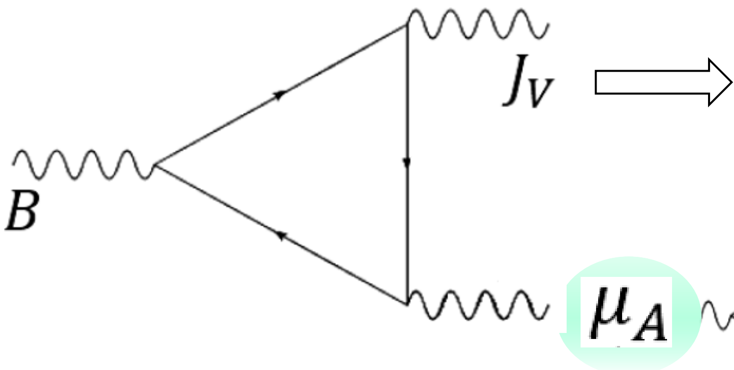




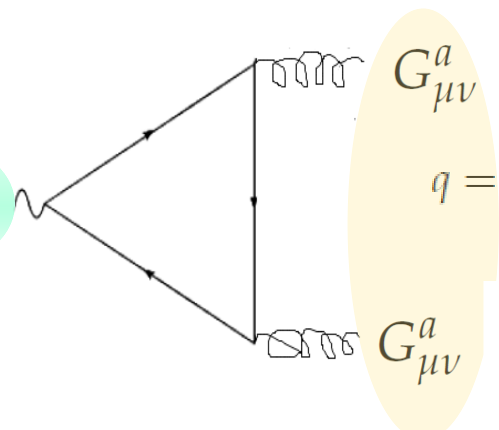
Chiral Magnetic Effect

A chirality imbalance induced electric current in external magnetic field, a probe of nontrivial topology of QCD.

QED VVA triangle anomaly

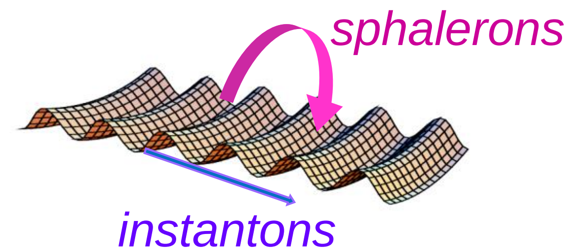


CME: $\mathbf{J}_V = \frac{N_c e}{2\pi^2}\mu_A \mathbf{B}$



$$q = \frac{g^2}{32\pi^2}\int d^4x G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

QCD VVA triangle anomaly

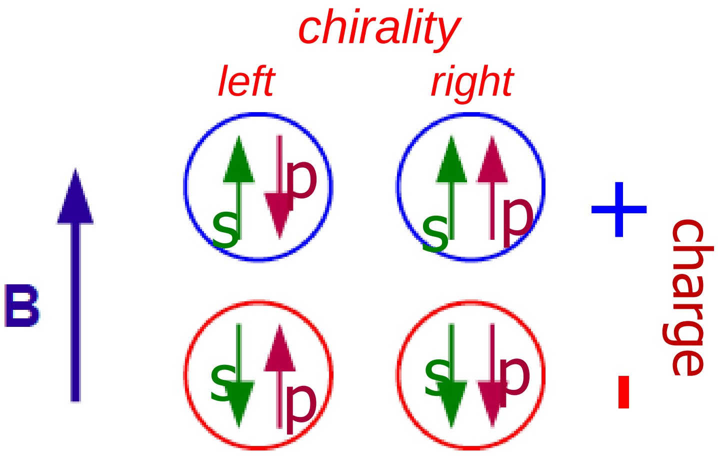


Topological transitions have never been observed directly.
An observation of the local strong parity violation could be a clear proof for the existence of such physics.

QCD vacuum transition:
- *nonzero topological charge*
- *chirality imbalance (local parity violation)*

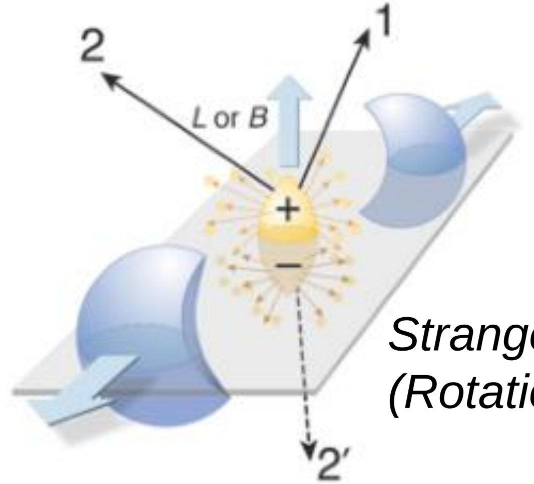
Kharzeev, 2004
Kharzeev, Warringa, McLarren, Fukushima, 2008
Kharzeev, Liao, Voloshin, Wang, Prog. Part. Nucl. Phys., 2016, 88: 1
Huang, Rep. Prog. Phys., 2016, 79: 076302,……

Charge Separation in HIC



negative goes up
positive goes down

positive goes up
negative goes down



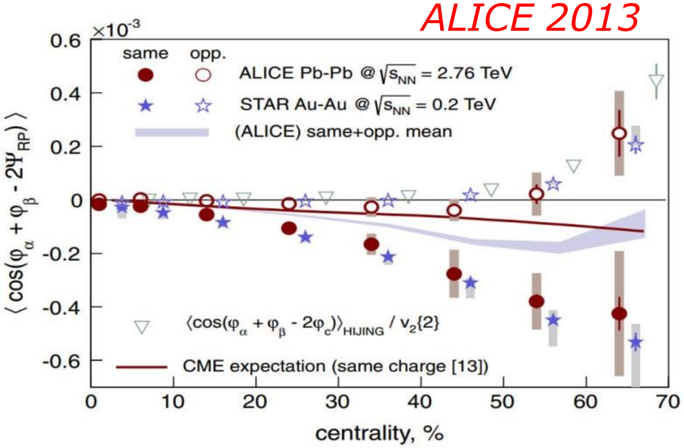
Strangest magnetic field (Rotation) in nature !

An excess of right or left handed quarks should lead to a current flow along the magnetic field !

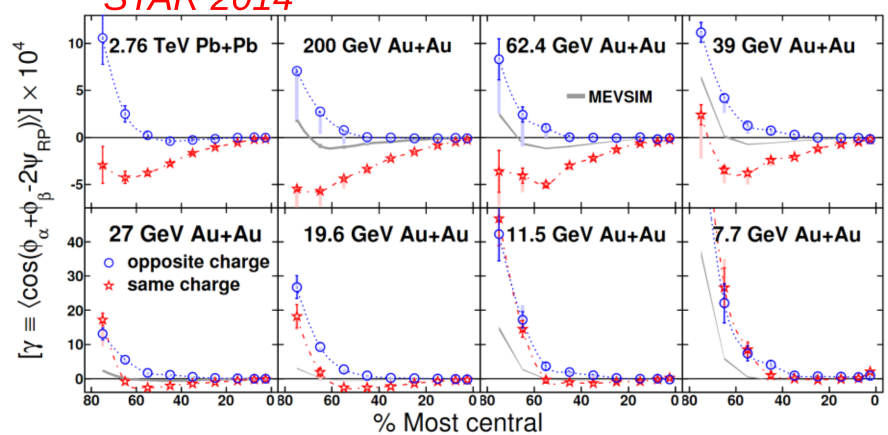
The observable: The gamma correlator (Voloshin 2004)

$$\gamma = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \rangle$$

ALICE 2013

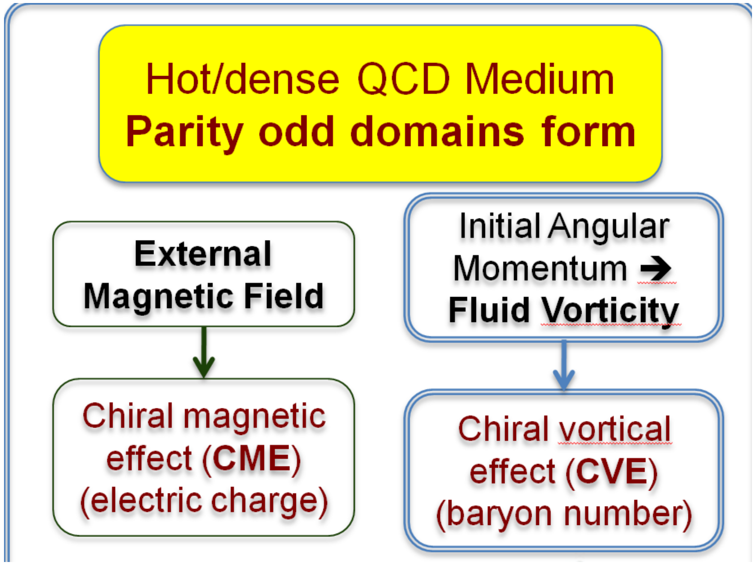


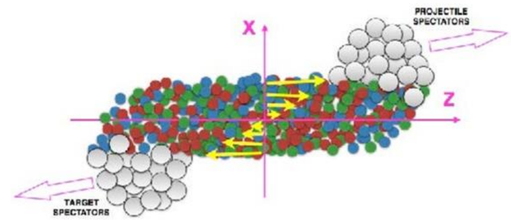
STAR 2014



Main challenge: how to separate the background effects?

Chiral Vortical Effect in HIC



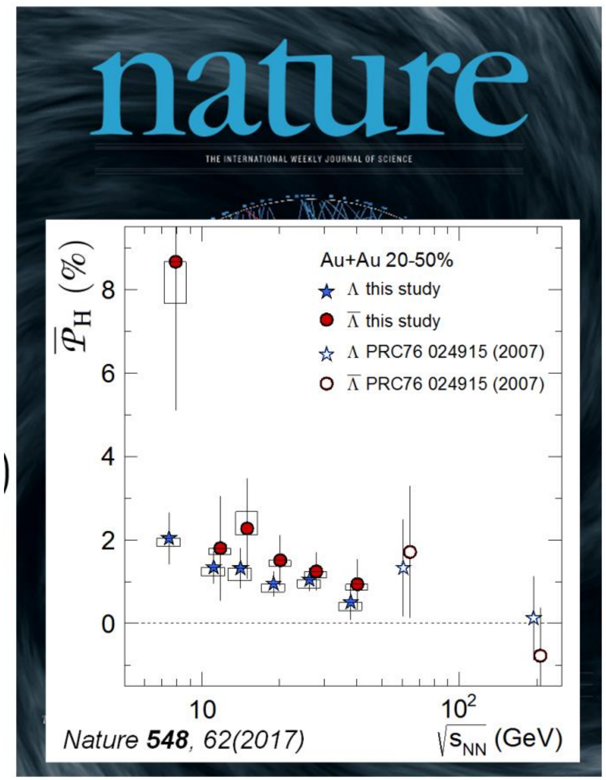


Global collision angular momentum generates QGP vorticity

$$P_{\pm} \sim \exp\left[\pm\frac{\frac{1}{2}\hbar\omega + \mu B}{T}\right] \qquad (\mu_{\Lambda} = -\mu_{\bar{\Lambda}})$$

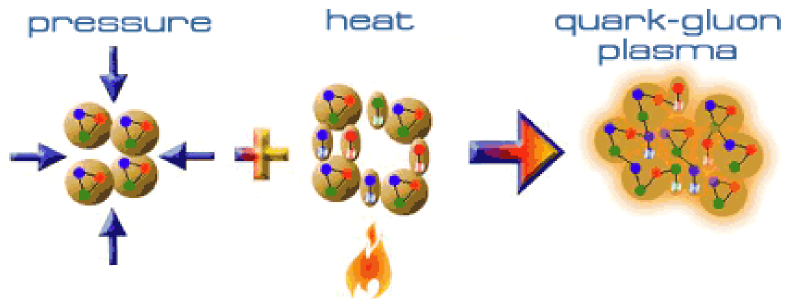
The signal is consistent with vorticity ***ω = (9 ± 1)x10²¹/s****, greater than previously observed in any system.*

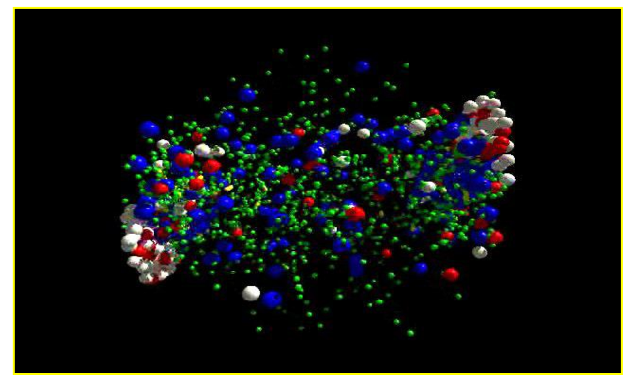
Liang & Wang, PRL (2005)
Betz, Gyulassy, Torrieri, PRC (2007)
Becattini, Piccinini, Rizzo, PRC (2008)
Becattini, Karpenko, Lisa, Upsal, Voloshin, PRC (2017)

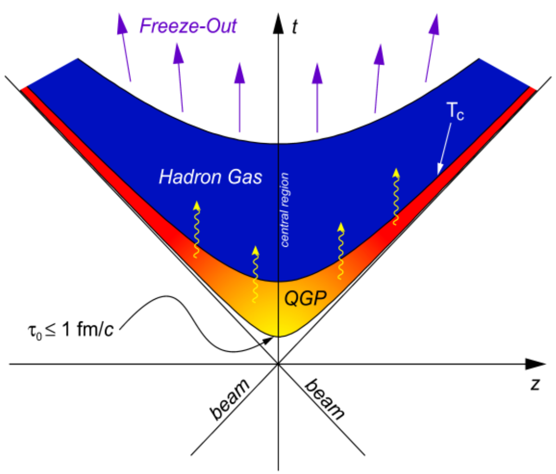


Nature ***548****, 62(2017)*

Probing QGP in HIC







Signatures of QGP:

Collective flow

Strangeness enhancement

Jet quenching

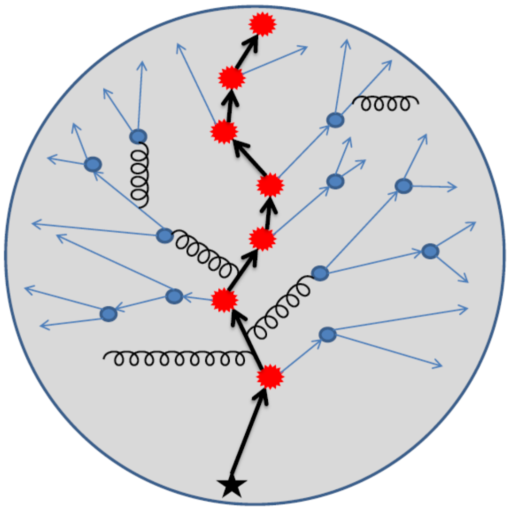
Quarkonium supression/enhancement

Global polarization ……

Coupled Linear Boltzmann Jet Transport and Hydrodynamics

S S Cao, W Chen, Y He, T Luo, L Pang, E Wang, X Wang, 2017

A comprehensive treatment of soft physics (medium) and hard physics (jet)

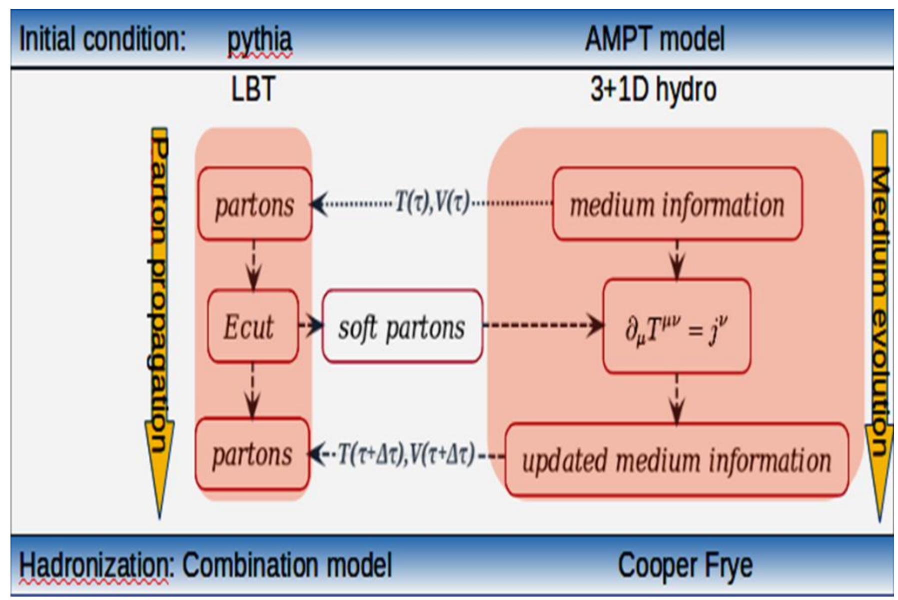


$$
\begin{aligned}
p_1 \cdot \partial f_1(p_1) &= -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) |M_{12\to 34}|^2 \\
&\times \quad (2\pi)^4 \delta^4 (P_1 + P_2 - P_3 - P_4)
\end{aligned}
$$

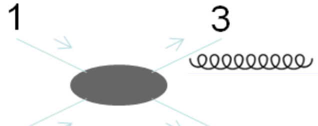
$$dp_i \equiv \frac{d^3 p_i}{2E_i (2\pi)^3},$$

$$f_i = 1/(e_i^{p.u/T} \pm 1)(i = 2,4), f_i = (2\pi)^3 \delta^3 (\vec{p} - \vec{p}_i) \delta^3 (\vec{x} - \vec{x}_i)(i = 1,3)$$

Jet energy loss and medium excitation



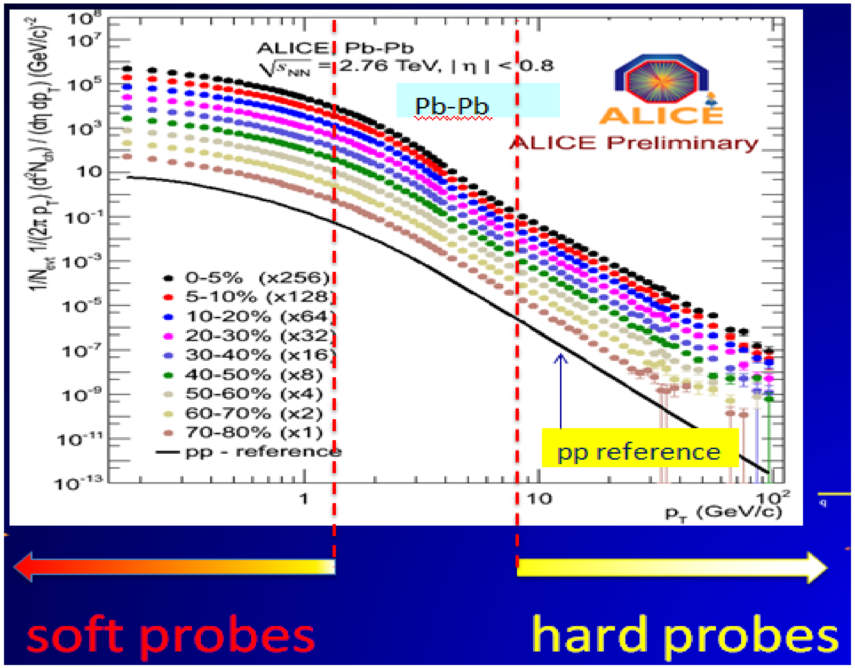
complete set of 2-2 processes
+ radiation:



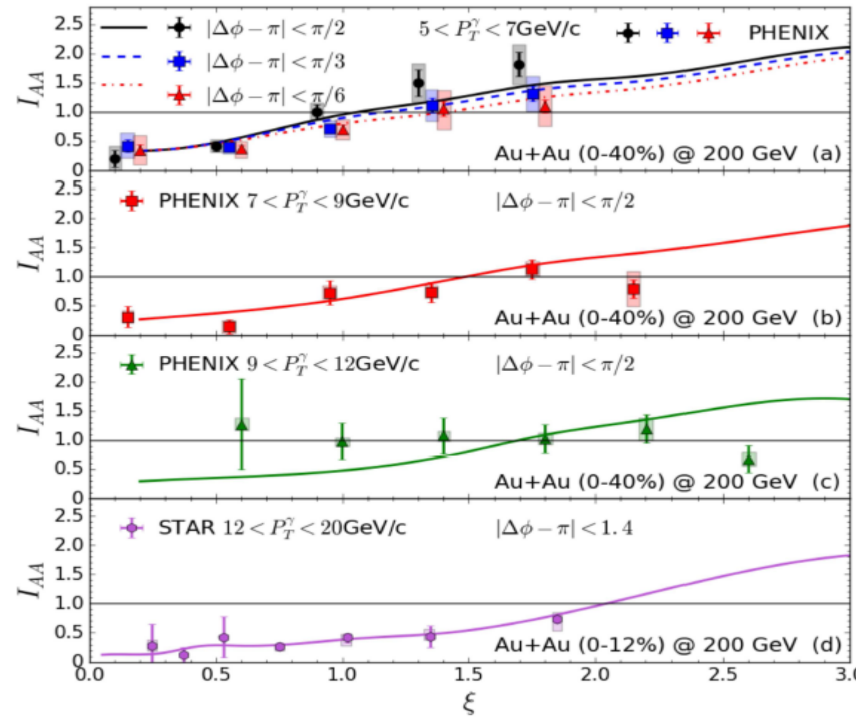
Results with CoLBT-Hydro Model

W Chen, S Cao, T Luo, L G Pang, X Wang, arXiv:1704.03648

Charged hadron p_t distribution



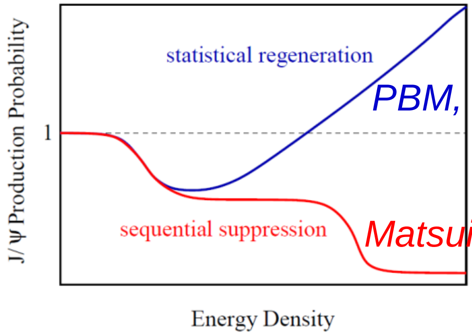
Photon+ hadron with CoLBT-hydro

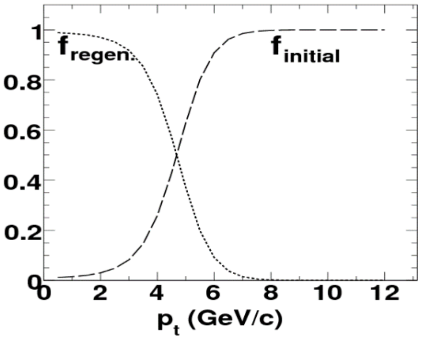


$z = p_T^h / p_T^\gamma \qquad D(z) = \frac{dN_h}{dz} \qquad I_{AA} = D_{AA}(z)/D_{pp}(z) \qquad \xi = \log(1/z)$

Strong suppression of high p_t leading hadrons due to jet energy loss and significant enhancement of low p_t hadrons due to jet-induced medium excitation.

Quarkonium p_t Distribution





- *Cancellation between suppression and regeneration !*
- *How to increase the sensitivity of the thermometer ?*

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

$$f(p_t) = f_{ini}(p_t) + f_{reg}(p_t)$$

- *initial production: p_t broadening due to Cronin effect and leakage effect.*
- *regeneration: p_t suppression due to coalescence at later stage.*

Transport equations for quarkonia and hydrodynamic equation for QGP:

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

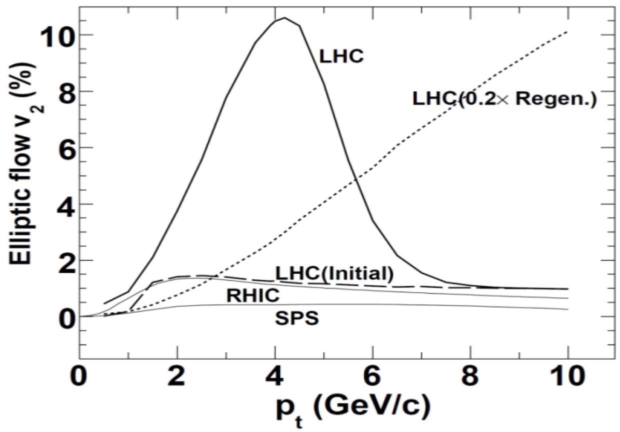
$$\alpha_\Psi(\mathbf{p}_t, \mathbf{x}_t, \tau|\mathbf{b}) = \frac{1}{2E_\Psi}\int \frac{d^3\mathbf{p}_g}{(2\pi)^3 2E_g} W_{g\Psi}^{c\bar{c}}(s) f_g(\mathbf{p}_g, \mathbf{x}_t, \tau)\Theta\left(T(\mathbf{x}_t, \tau|\mathbf{b}) - T_c\right),$$

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

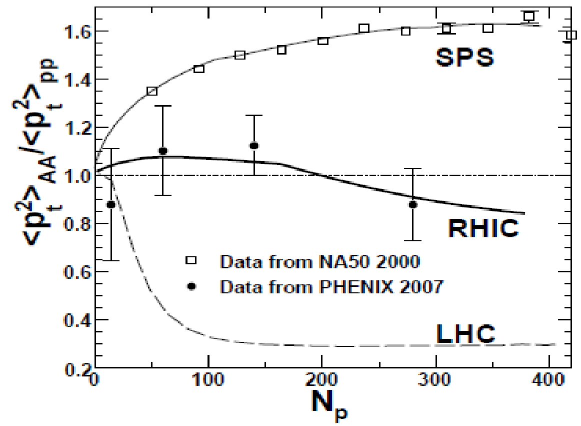
$\partial_\mu T^{\mu\nu} = 0, \quad \partial_\mu n^\mu = 0$ *+ QCD equation of state*

Quarkonia in p+A and A+A

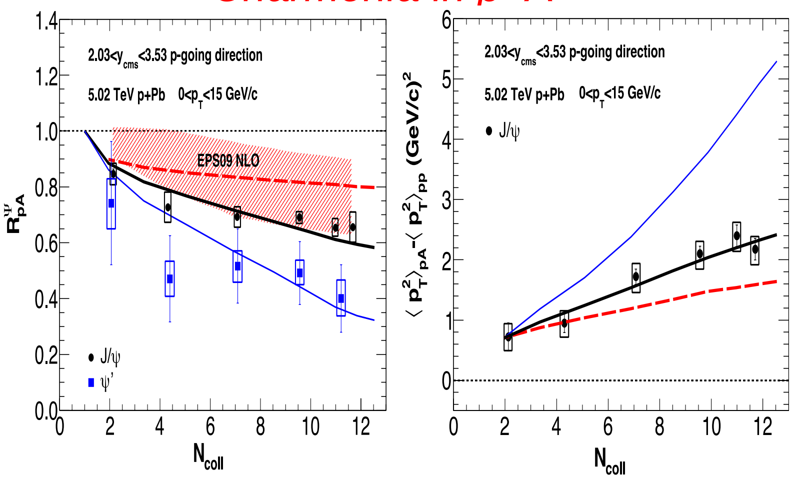
Quarkonium V_2 in A+A



Quarkonium $r_{AA} = \frac{\langle p_t^2 \rangle_{AA}}{\langle p_t^2 \rangle_{pp}}$ in A+A



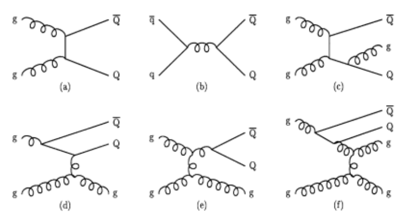
Charmonia in p+A



Chen, Guo, Liu, Zhuang, PLB765, 323(2017)

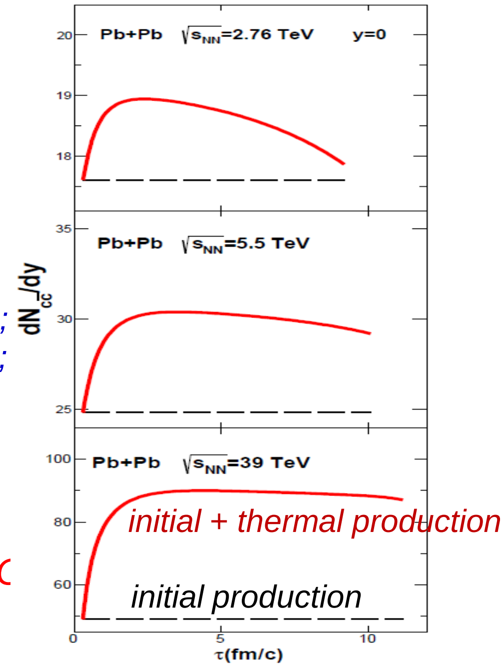
Shadowing effect can explain J/ψ, but the difference between J/ψ and ψ' shows a sizeable hot medium effect, especially the ψ' p_t.

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),……

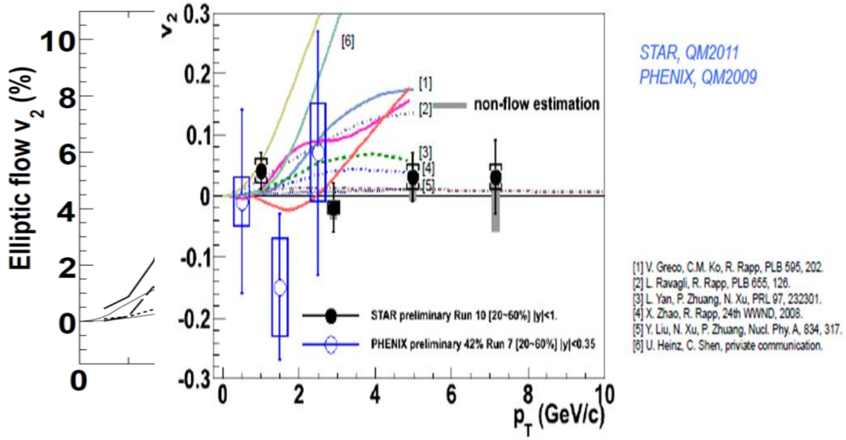
80% enhancement at FCC



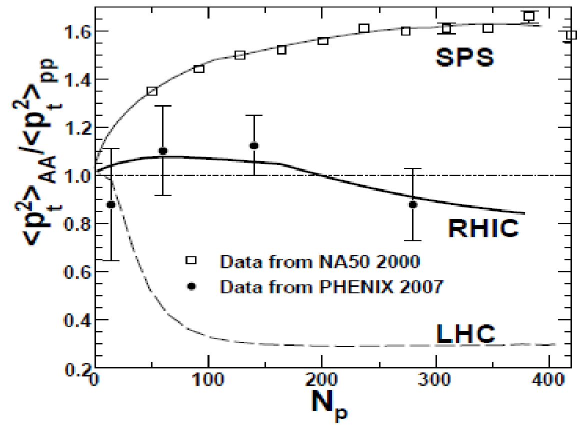
Zhou, Chen, Greiner, Zhuang, PLB758, 434(2016)

Quarkonia in p+A and A+A

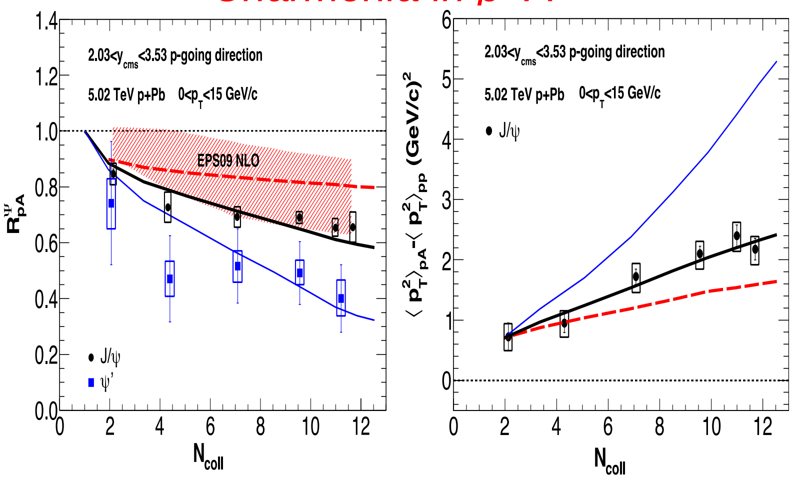
Quarkonium V_2 in A+A



Quarkonium $r_{AA} = \frac{\langle p_t^2 \rangle_{AA}}{\langle p_t^2 \rangle_{pp}}$ in A+A



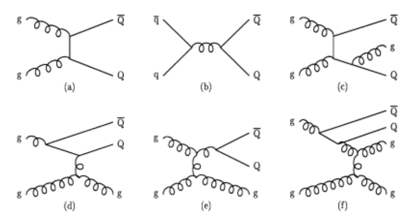
Charmonia in p+A



Chen, Guo, Liu, Zhuang, PLB765, 323(2017)

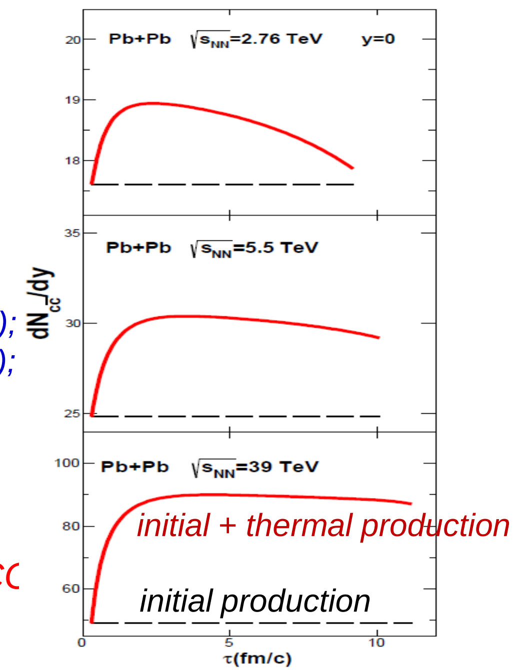
Shadowing effect can explain J/ψ, but the difference between J/ψ and ψ' shows a sizeable hot medium effect, especially the ψ' p_t.

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),……

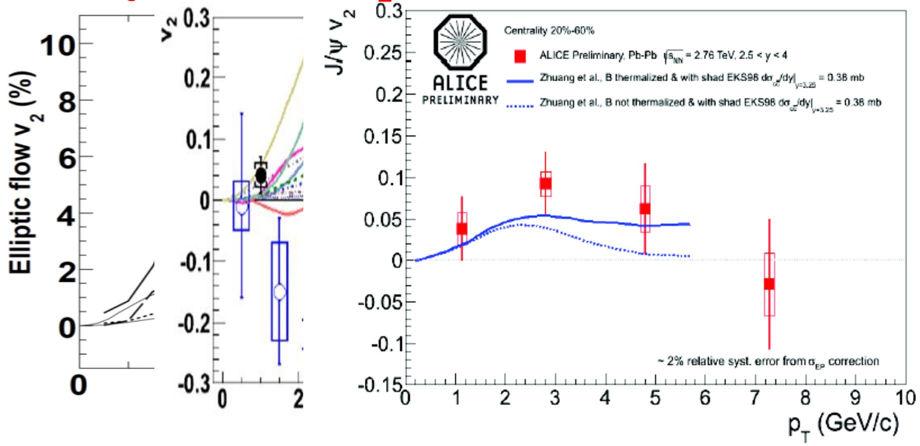
80% enhancement at FCC



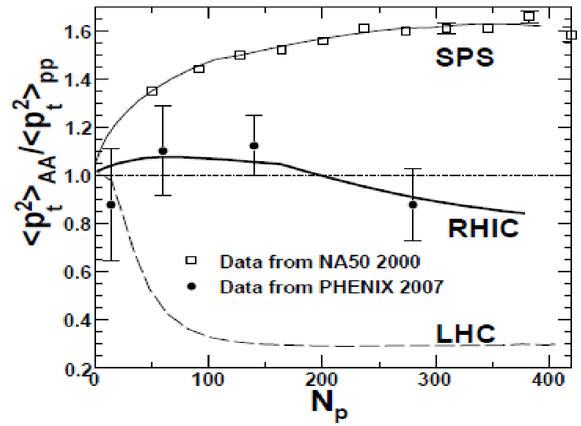
Zhou, Chen, Greiner, Zhuang, PLB758, 434(2016)

Quarkonia in p+A and A+A

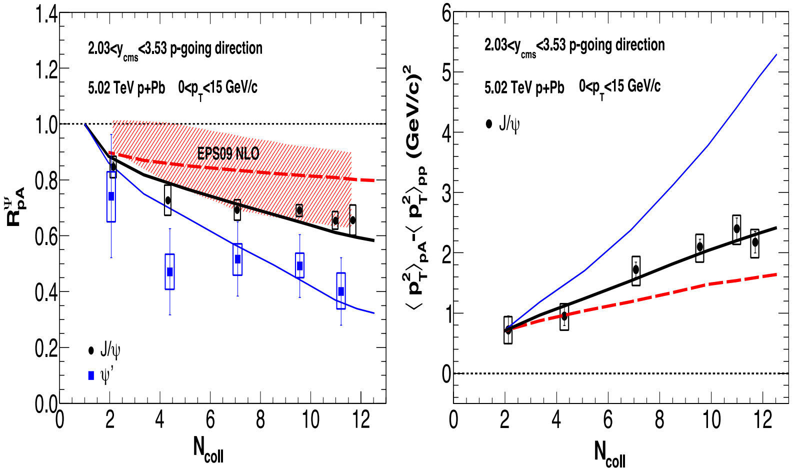
Quarkonium V_2 in A+A



Quarkonium $r_{AA} = \frac{\langle p_t^2 \rangle_{AA}}{\langle p_t^2 \rangle_{pp}}$ in A+A



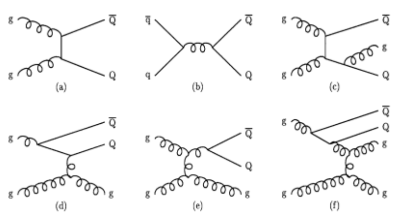
Charmonia in p+A



Chen, Guo, Liu, Zhuang, PLB765, 323(2017)

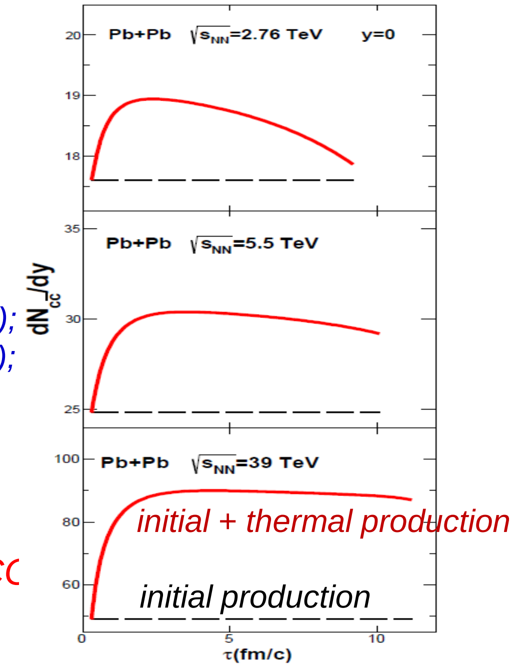
Shadowing effect can explain J/ψ, but the difference between J/ψ and ψ' shows a sizeable hot medium effect, especially the ψ' p_t.

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),……

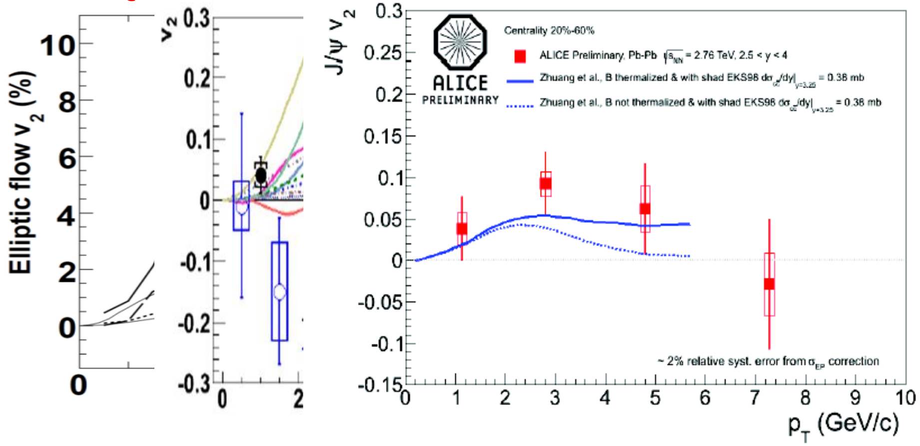
80% enhancement at FCC



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

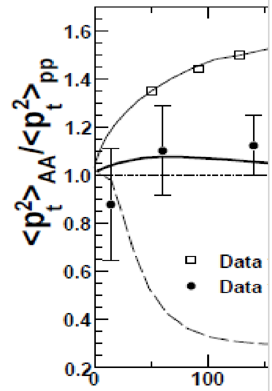
Quarkonia in p+A and A+A

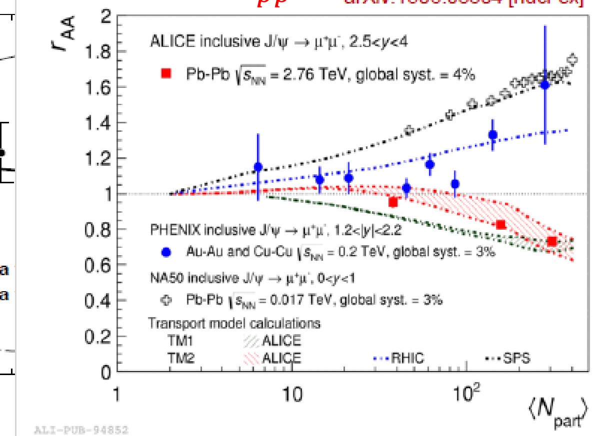
Quarkonium V_2 in A+A



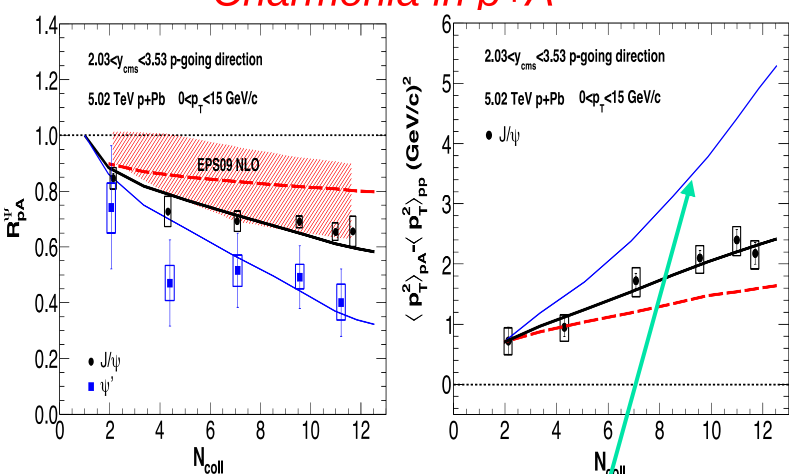
Quarkonium $r_{AA} = \frac{\langle p_t^2 \rangle_{AA}}{\langle p_t^2 \rangle_{pp}}$ in A+A

arXiv:1506.08804 [nucl-ex]





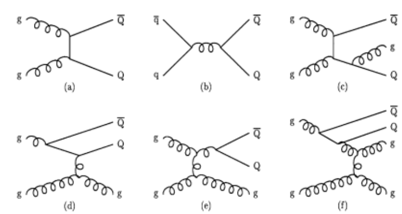
Charmonia in p+A



Chen, Guo, Liu, Zhuang, PLB765, 323(2017)

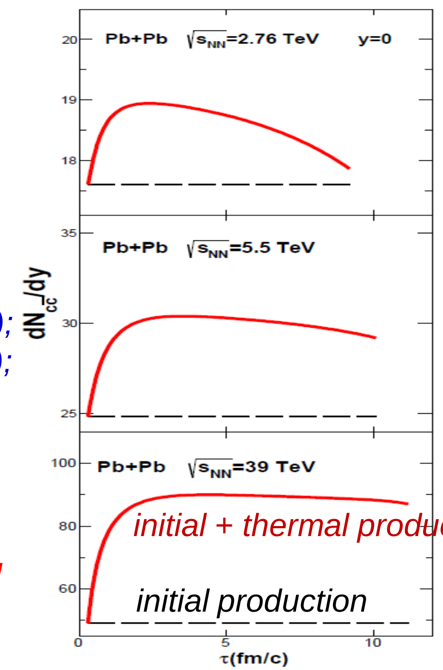
Shadowing effect can explain J/ψ, but the difference between J/ψ and ψ' shows a sizeable hot medium effect, especially the ψ' p_t.

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),……

80% enhancement at FCC !



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

Ξ_{cc} and Ω_{ccc} in HIC

July 7, 2017: Ξ_{cc} was discovered by LHCb !

$N_c \sim 100$ $in\ Pb + Pb\ at\ LHC,$
$N_{\Xi_{cc}} \sim (N_c)^2$ and $N_{\Omega_{ccc}} \sim (N_c)^3$ in coalescence mechanism.
It is most probable to discover Ξ_{cc} and Ω_{ccc} in A+A at LHC, and the discovery is a unique signal of QGP formation.

He, Liu, Zhao, Zhuang, PLB746, 59(2015); 771, 349(2017)

$$\left[\sum_{i=1}^{3}\frac{\hat{p}_i^2}{2m_i} + V(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)\right]\Psi = E\Psi \qquad V(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) = \sum_{i<j} V_{qq}(r_i,r_j) \qquad W(\mathbf{r},\mathbf{p}) = \int d^6\mathbf{y}e^{-i\mathbf{p}\cdot\mathbf{y}}\Phi(\mathbf{r}+\frac{\mathbf{y}}{2})\Phi^*(\mathbf{r}-\frac{\mathbf{y}}{2})$$

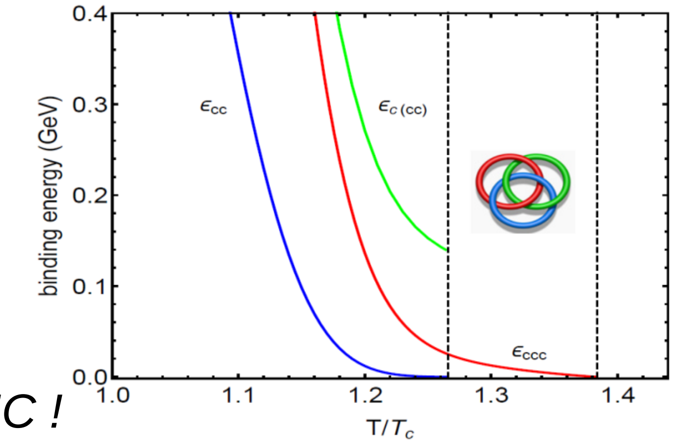
Lattice QCD potential at finite T

$$\frac{dN}{d^2\mathbf{P}_T d\eta} = C\int \frac{P^\mu d\sigma_\mu(R)}{(2\pi)^3}\frac{d^4r_x d^4r_y d^4p_x d^4p_y}{(2\pi)^6} f_c(\tilde{r}_1,\tilde{p}_1)f_c(\tilde{r}_2,\tilde{p}_2)f_q(\tilde{r}_3,\tilde{p}_3)W(r_x,r_y,p_x,p_y)$$

In central Pb+Pb at 2.76 TeV, $\sigma_\Omega \sim 3.5\times 10^4\ nb$
In p+p at 7 TeV, $\sigma_\Omega \sim 0.1$ nb
Bjorken 1986
Chen, Wu, JHEP 08, 144(2011).

Conclusion: Ω_{ccc} enhancement by 6 orders !

Possible realization of Borromean rings in HIC !



Summary & Outlook

What we have known:

- A crossover from hadron gas to QGP at $\mu_B = 0$ and T_c=155 MeV
- Very rich structure of QCD condensed matter at high density
- Signatures of sQGP discovered at RHIC and LHC

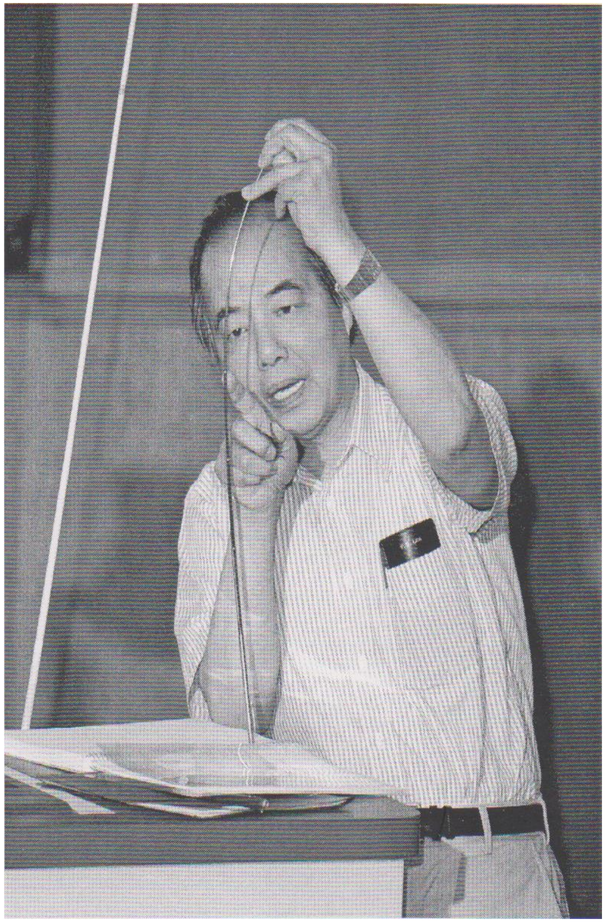
What we are doing and will do:

- QCD phase transitions at finite density
- QCD critical point
- EoS of sQGP
- Inhomogeneous QCD phases
- QCD phases in strong electromagnetic fields
- Initial thermalization in HIC
- Viscos hot medium in HIC
- Signatures of sQGP (hard and soft probes)

To Know the Smallest, We Need the Largest

T.D.Lee

Theory Workshop on Relativistic Heavy Ion Collisions, July 8-19, 1996, BNL



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。

Thank you for your patience !

Due to the time limit and due to my knowledge limit, some important progresses in the field are not included in my talk, I am sorry.

I thank the following colleagues during the preparation of the talk: Hengtong Ding, Huan Huang, Xuguang Huang, Zuotang Liang, Jinfeng Liao, Xiaofeng Luo, Ralf Rapp, M. Stephanov, Nu Xu, Benwei Zhuang,……