Quark Matter and Its Realization in Nuclear Collisions

庄鹏飞
清华大学物理系

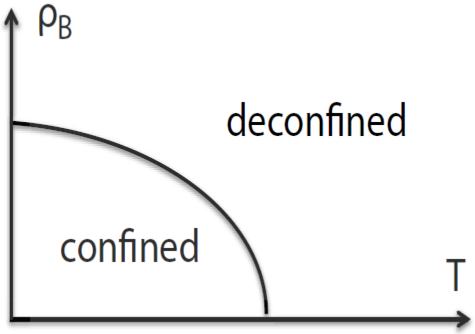
- *Progress*
- *Discussion*
  - ▲ *Chiral Crossover*
  - ▲ *Thermalization*
  - ▲ *Exotic States*
  - ▲ *High Baryon Density*

- *Progress*

QCD Phase Diagrams

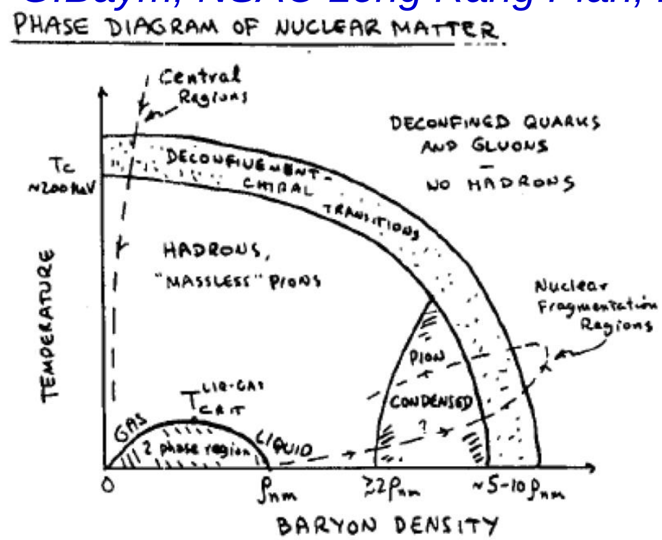
Deconfinement

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

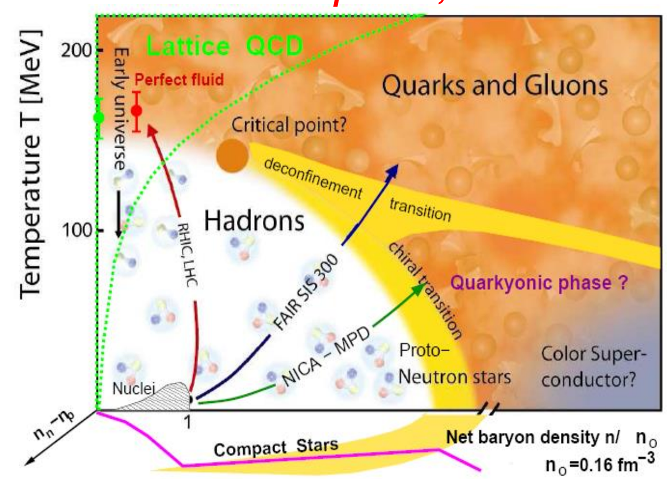


+ Chiral restoration

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

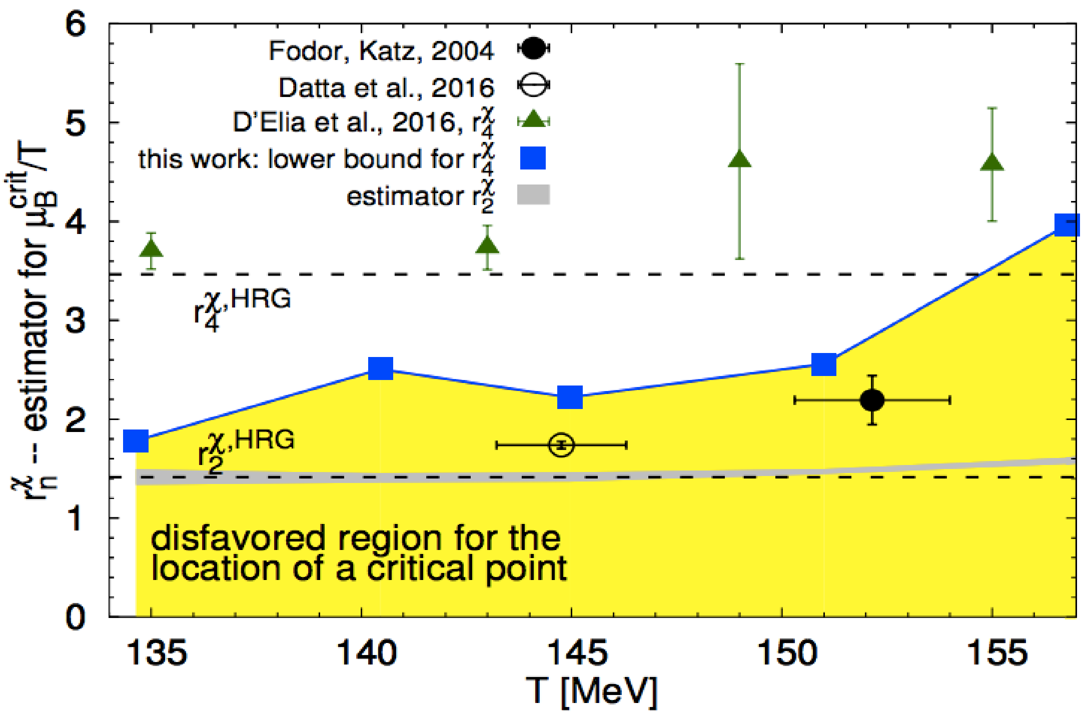
Effective models

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 !

Dynamical Fluctuations around Critical Point

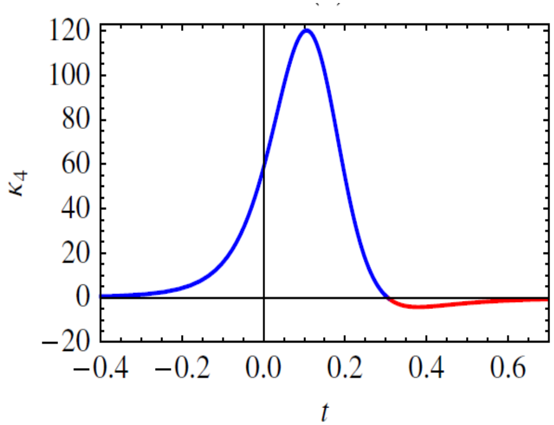
- Correlation length $\xi \to \infty$ at a critical point
- High order moments of conserved charges (B, Q, S) are more sensitive to ξ and cab be used to probe the critical point.

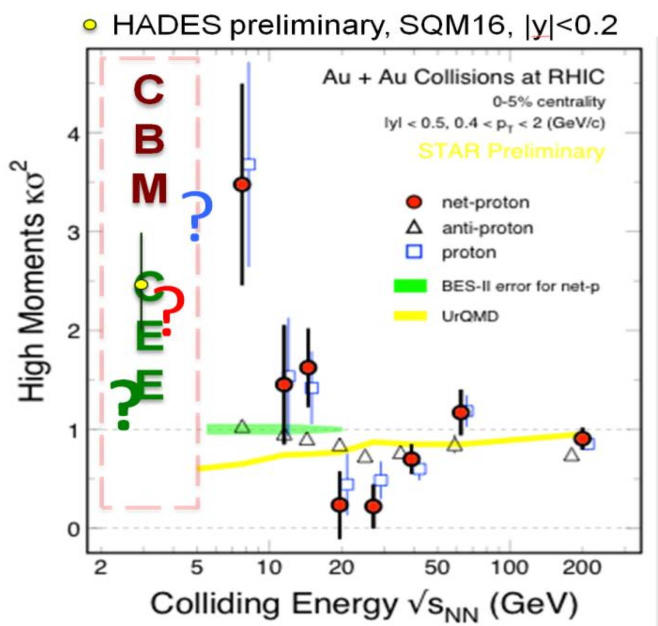
M.Stephanov, PRL102, 032301(2009)
M.Asakava, S.Ejiri, M.Kitazawa, PRL103, 262301(2009)

- 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: $C_4 > 0$





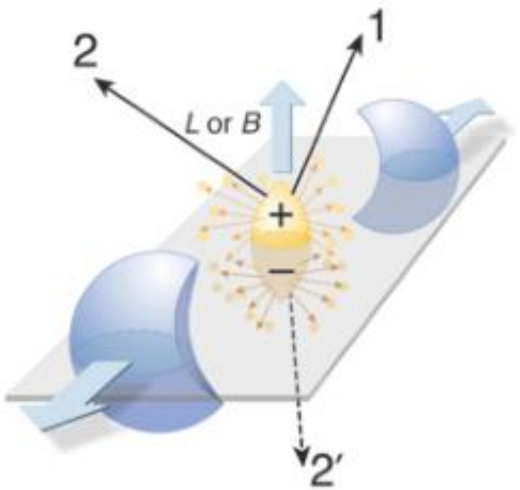
- Challenges in heavy ion collisions:
  - finite size effect
  - non-equilibrium state
  - background (elliptic flow, …)
  - precise data at lower energies

Chiral Magnetic Effect

见高建华，浦实报告

Strongest magnetic field (rotation)in heavy ion collisions:

W.T.Deng and X.G.Huang, Phys. Rev. C85,044907 (2012)



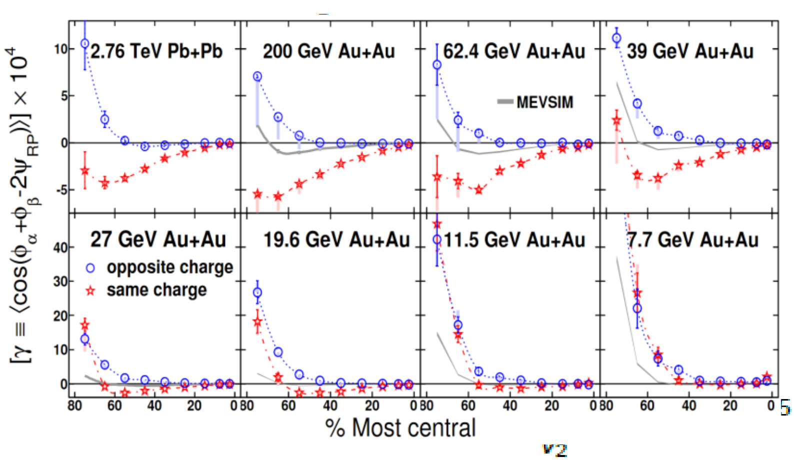
A chirality imbalance induced electric current in external magnetic field, a probe of nontrivial topology of QCD：

$$\partial_\mu \mathcal{J}_A^\mu = \frac{g^2 N_f}{16\pi^2} G_{\mu\nu}^a \tilde{G}_a^{\mu\nu}$$

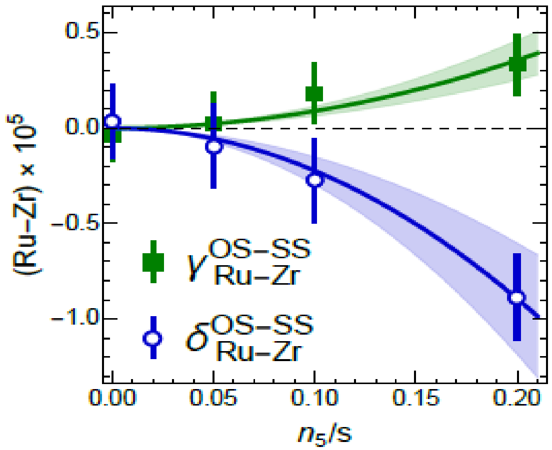
$$\mathbf{J}_V = \frac{N_c e}{2\pi^2} \mu_A \mathbf{B}$$

Charge separation in heavy ion collisions:

Kharzeev, Liao, Voloshin, Wang, PPNP88, 1(2016)
Huang, Rep. Prog. Phys., 2016, 79: 076302

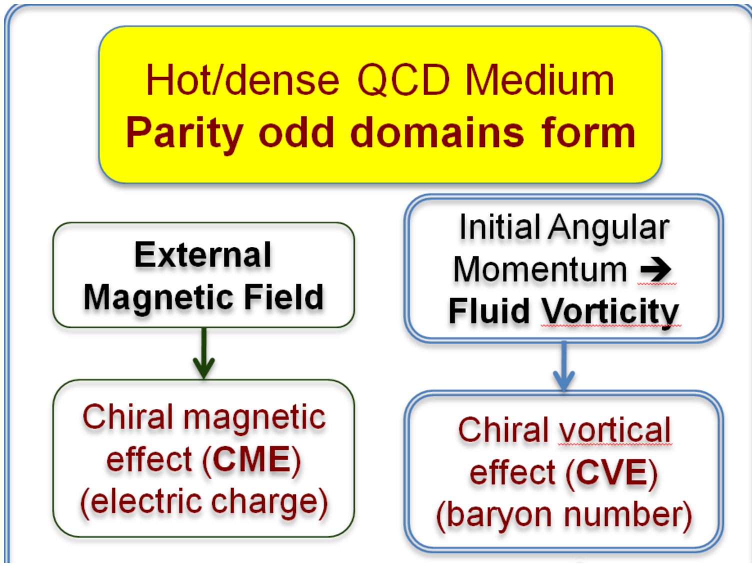


Shuzhe Shi, Hui Zhang, Defu Hou and Jinfeng Liao, QM2018



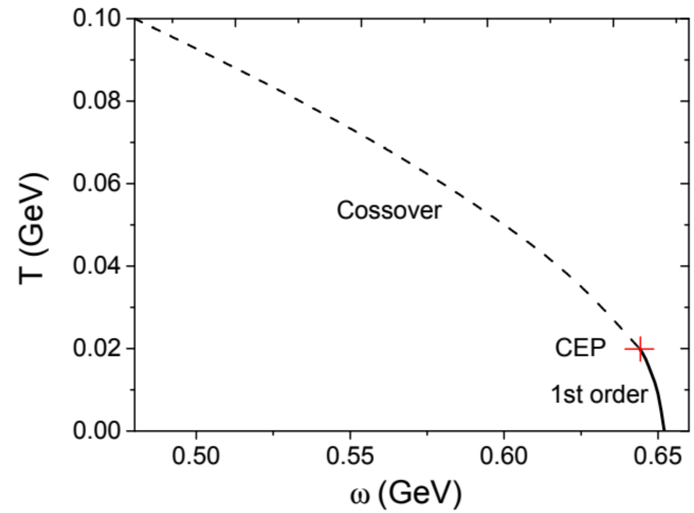
Chiral Vortical Effect

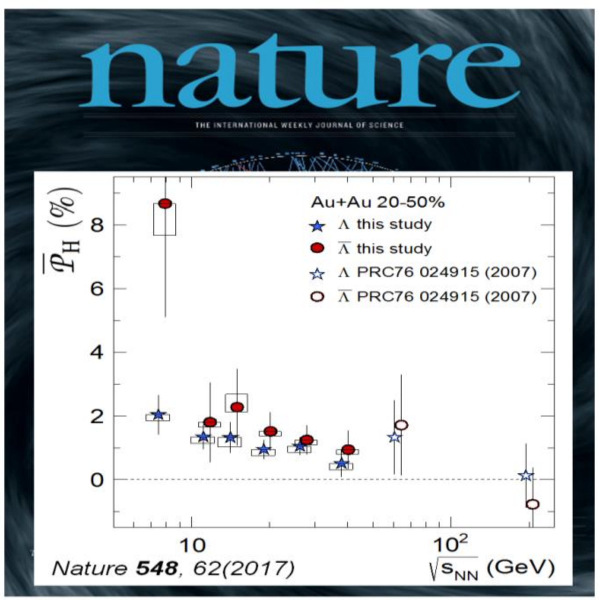
见黄旭光，何联毅报告



The Chiral phase diagram in T-ω plane

Y.Jiang, J.Liao, PRL117, 192302(2016)





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

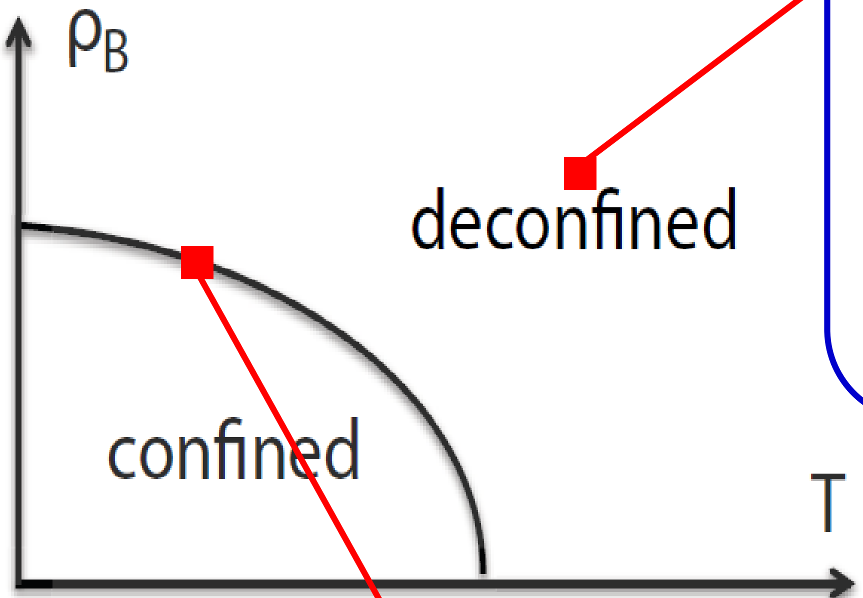
The signal is consistent with vorticity ***ω = (9 ± 1)x10^{21}/s****, greater than previously observed in any system.*

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

见刘玉鑫报告

Probes of QCD Phases

见张本威，张晓明报告



Probes of the deconfinement phase:
Jet quenching,
Quarkonium production,
Dilepton spectra,……

Probes of the chiral symmetry phase：
IMC,
CME,
CVE,……

Probes of the chiral phase transition:
Dynamical fluctuations of conserved charges.

Probes of deconfinement phase transition?

- *Discussion:* *Chiral Crossover*

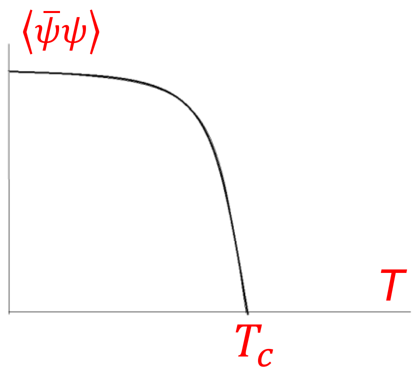
Chiral Crossover Temperature

In chiral limit the chiral phase transition T_c is defined by

1) the change of the order parameter $\langle\bar{\psi}\psi\rangle \neq 0 \leftrightarrow \langle\bar{\psi}\psi\rangle = 0$

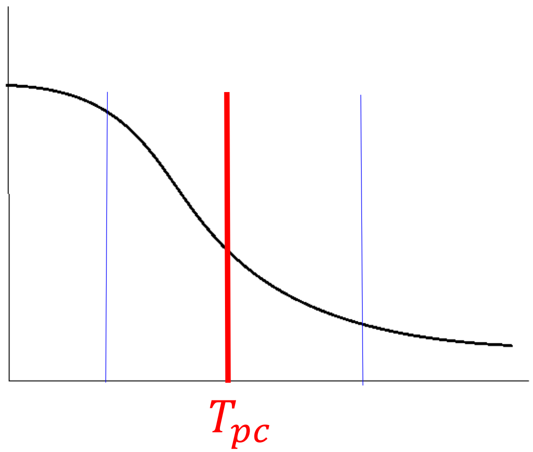
or 2) the Goldstone mode $m_\pi = 0 \rightarrow m_\pi \neq 0$

the two conditions are self-consistent.



However, in real case the chiral crossover is a region, not a point !

How to properly define the so-called crossover temperature T_{pc}?



The crossover temperature is normally defined through the maximum change of $\langle\bar{\psi}\psi\rangle$:

$$\frac{\partial^2\langle\bar{\psi}\psi\rangle}{\partial T^2} = 0 \quad \rightarrow \quad T_{pc}$$

Physics: the extension of maximum fluctuations around a continuous phase transition in chiral limit.

Lattice QCD result: $T_{pc}\sim 155$ MeV

***Question:** The definition of maximum change in $\langle\bar{\psi}\psi\rangle$ $(T_c = 155\ \mathrm{MeV})$ may break down the Goldstone theorem: The pseudo-Goldstone mode may already disappear at $T < T_{pc}$ or still exist at $T > T_{pc}$!*

Mott Transition

- Mott transition for the Goldstone mode π from bound state to resonant state:

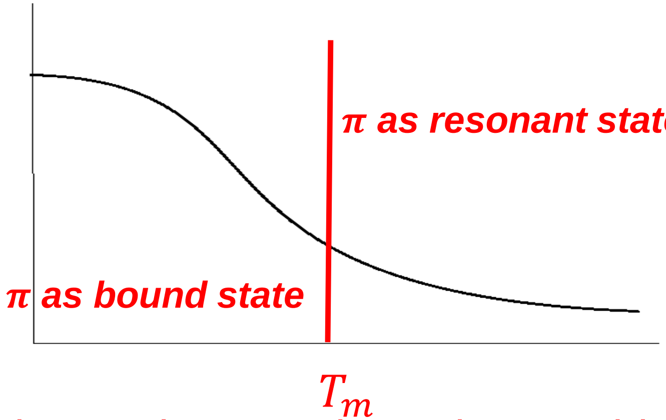
$$\pi \to q + \bar{q}$$

- The threshold temperature (energy) T_m:

$$m_\pi(T_m) = 2m_q(T_m)$$

$T < T_m$: bound state π as Goldstone mode,

$T > T_m$: resonant state π.



- T_m guarantees the Goldstone theorem, it can be considered as the chiral crossover temperature.

Lattice QCD: $T_{pc} = 155\ MeV$, $T_m = ?$

NJL model: $T_{pc} = 156\ MeV$, $T_m = 167\ MeV$

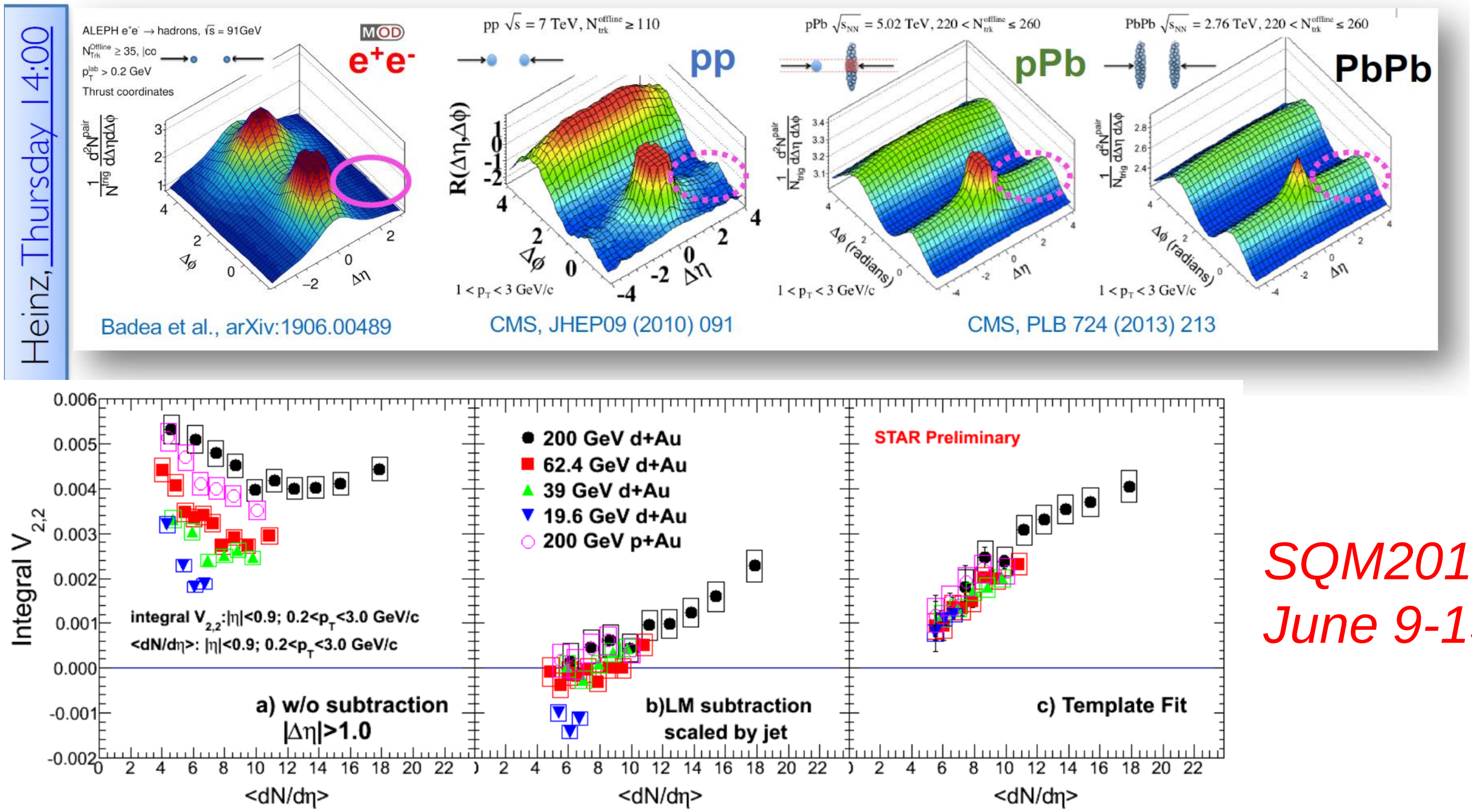
We encourage lattice people to calculate T_m as the chiral crossover temperature.

- *Discussion: Thermalization*

"Thermalization" in All Hadronic Collisions !

见宋慧超报告

- *Collectivity not only in Au-Au and Pb-Pb but also in p-p and p-Pb collisions !*



SQM2019
June 9-15, Bari

- *Even "thermal" distribution for fragments in low energy (~1 GeV) collisions !*

- *Do you believe the real thermalization in small systems? If not, what is the physics of the "thermal" distributions?*

Parton Induced “Thermal” Distribution

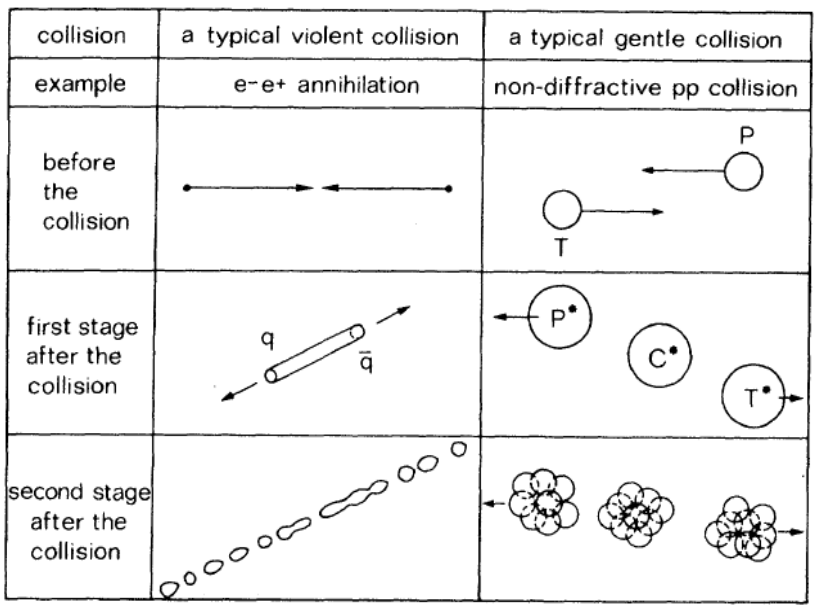
Relearning from Three-Fireball Model

PHYSICAL REVIEW D VOLUME 28, NUMBER 5 1 SEPTEMBER 1983

Koba-Nielsen-Olesen scaling and production mechanism in high-energy collisions

Chou Kuang-chao 周光召
Institute of Theoretical Physics, Academia Sinica, Beijing, China

刘连寿 Liu Lian-sou* and Meng Ta-chung 孟大中
Institut für Theoretische Physik der Freie Universität Berlin, Berlin, Gemany
(Received 14 March 1983)



Excitation energy:

$$E_i = E_{ip} + E_{iT} \qquad i = P^*, T^*, C^*$$

If fireball i obtains excitation energy independently from P and T, the probability:

$$F(E_i) = F_P(E_{iP})F_T(E_{iT})$$

Total probability

$$P(E_i) = 4\frac{E_i}{\langle E_i\rangle}e^{-2\frac{E_i}{\langle E_i\rangle}}$$

This Boltzmann-like distribution comes from the fact that hadrons are made of partons.

The “thermal” distribution works for pp, pA and AA, but not for e^+e^-!

- *Discussion: Exotic States*

Significant Ξ_{cc} and Ω_{ccc} Enhancement in AA

H.He, Y.Liu and PZ, PLB746, 59(2015)
J.Zhao, H.He and PZ, PLB771,349(2017)

Charm quark number $N_c \sim 100$ in AA at LHC !

The coalescence among uncorrelated charm quarks can significantly enhance the production probability,

$$N(\Xi_{cc}) \sim N_c^2, \quad N(\Omega_{ccc}) \sim N_c^3 \;!$$

$$\frac{dN}{d^2\mathbf{P}_T d\eta} = C\int_\Sigma \frac{P^\mu d\sigma_\mu(R)}{(2\pi)^3}\int \frac{d^4r_x d^4r_y d^4p_x d^4p_y}{(2\pi)^6} f(r_1,p_1)f(r_2,p_2)f(r_3,p_3)W(\mathbf{r}_x,\mathbf{r}_y,\mathbf{p}_x,\mathbf{p}_y)$$

$$f(\vec{r},\vec{p}\,) = \frac{1}{e^{p^\mu u_\mu/T}+1}$$

The coalescence probability is determined by 3-body Dirac equation, and local temperature and velocity are from the hydrodynamics.

Result: effective cross section per binary collision at 2.76 GeV

$$\sigma_\Omega \equiv \frac{N_\Omega}{N_{coll}\Delta\eta}\sigma_{pp} = 9\,nb \quad \text{for} \quad \sigma_{pp} = 62\,mb$$

in comparison with $\sigma(\Omega_{ccc})$ = 0.06~0.13 nb at 7 GeV in pp, the production in AA is enhanced by 2-3 orders !

ALICE will upgrade the detector to search for Ξ_{cc} and Ω_{ccc} !

SQM2019, June 9-15, Bari

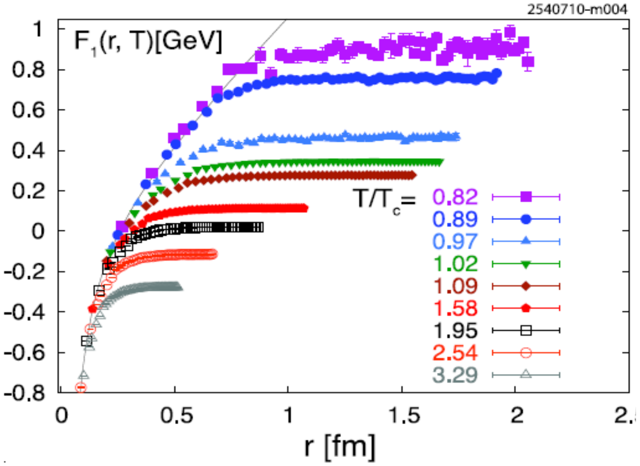
Ω_{ccc} as a Borromean Ring and an Efimov State

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

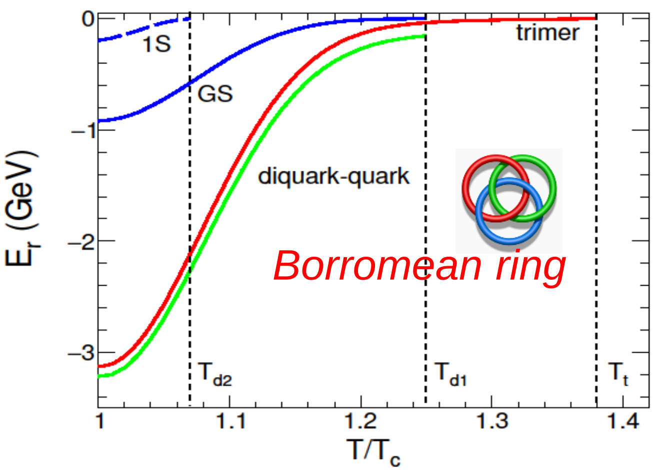
Efimov state is introduced in nuclear physics, PLB33, 563(1970).

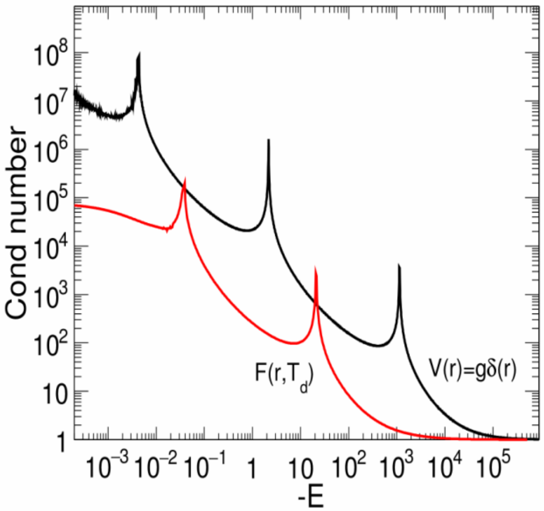
It was firstly discovered in cold atom gas, T.Kraemer et al., Nature 440, 315(2006).

Is it possible to realize Efimov state at quark level?
At zero temperature, No, due to the long range interaction.
How is about finite temperature?



short range potential at high T !





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

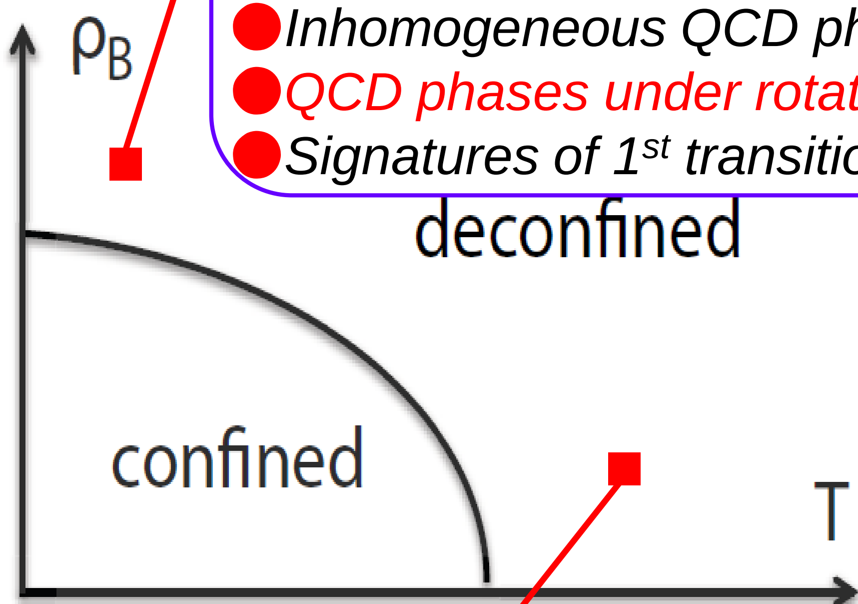
- *Discussion: High Baryon Density*

New Physics at High Baryon Density

见马永亮报告

What we should do now is the QCD matter at high μ_B:

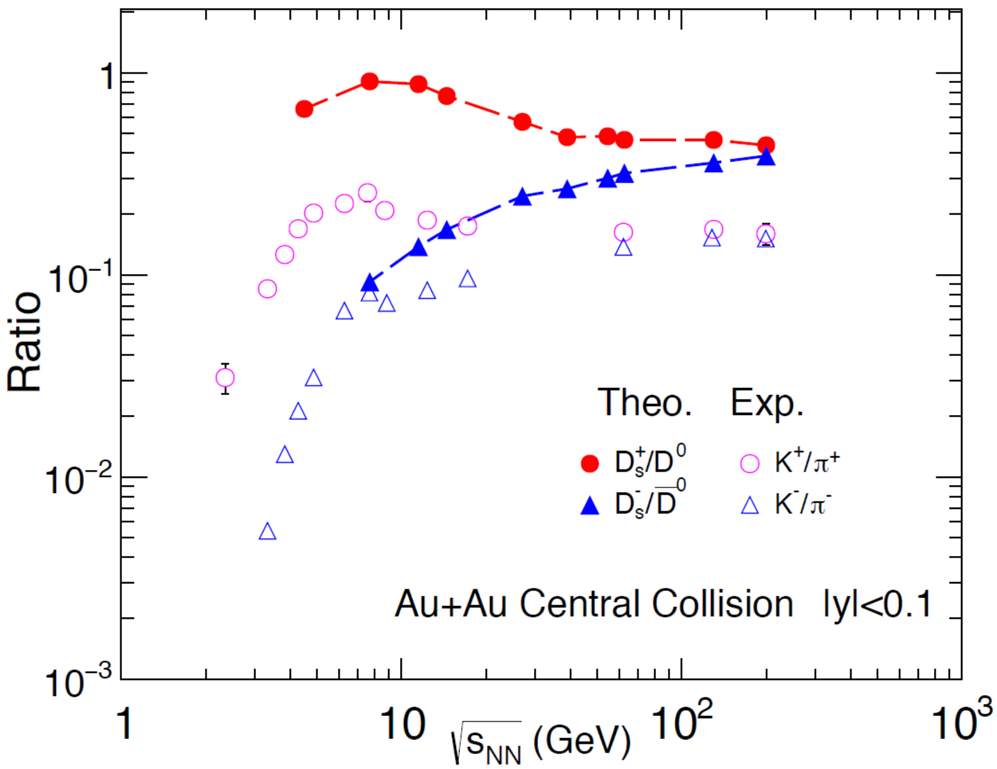
- *QCD phase transitions*
- *QCD critical point*
- *EoS of sQGP*
- *Inhomogeneous QCD phases*
- *QCD phases under rotation*
- *Signatures of 1^{st} transition*



What we have known is the QCD matter at high T:

- *Chiral crossover at T_c=155 MeV*
- *Signatures of sQGP*

A New Probe of High Density QCD Matter



J.Zhao, N.Xu and PZ:

Significant D_s/D_0 enhancement like K^+/π^+ at high baryon density !