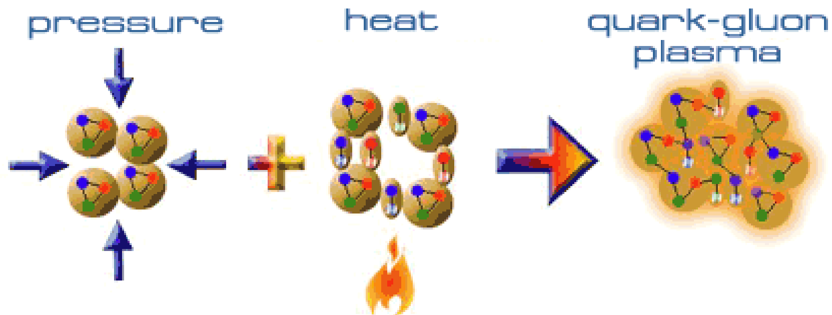
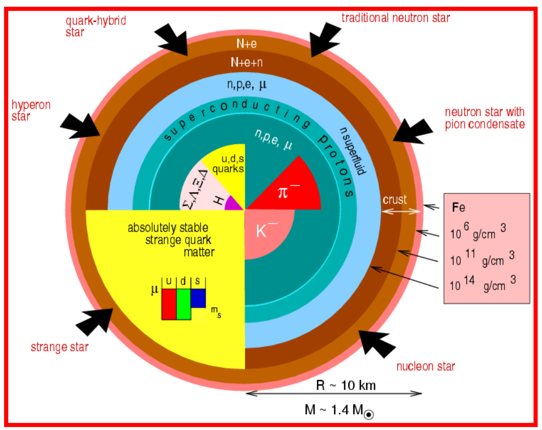
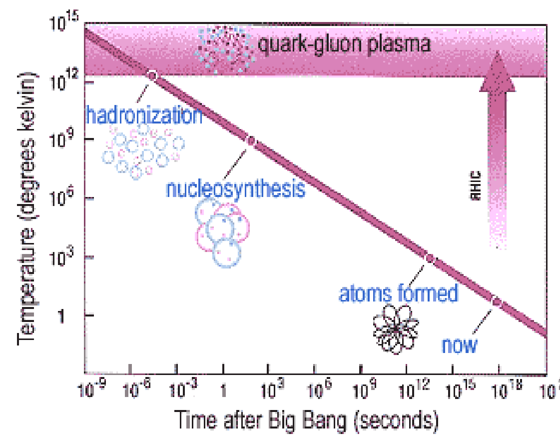
如何实现新的物质形态（QGP）

产生QGP的条件:

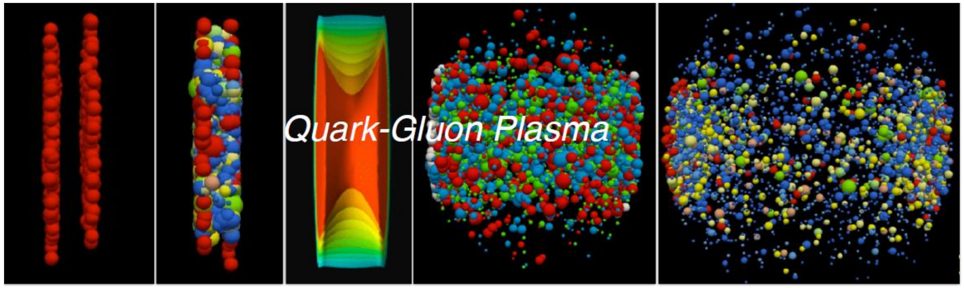




致密星体



早期宇宙

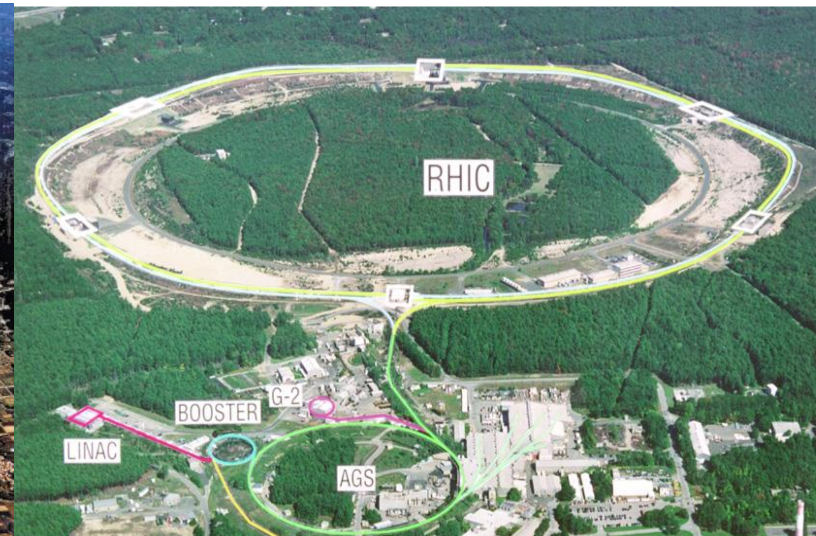


相对论重离子碰撞是在实验室产生QGP的唯一可能手段！

相对论重离子碰撞实验

LHC, Pb+Pb@√s = 5500 GeV, ALICE,ATLAS,CMS,LHCb

RHIC, Au+Au@√s = 200 GeV, STAR



FAIR, U+U@Elab = 40A GeV, CBM

CSR, U+U@Elab = 0.6A GeV, CEE

常用物理量

核几何

碰撞参数$\vec{b}$：两个碰撞核中心的相对位置，矢量。$\vec{b}=0$,中心碰撞。

参与碰撞核子数N_{part}：软过程数$\sim N_{part}$

参与碰撞的核子对数N_{coll}：硬过程数$\sim N_{coll}$

纵向快度（沿碰撞方向）$y=\frac{1}{2}ln\frac{E+p_z}{E-p_z}$, $\begin{cases} E=m_\perp cosh(y) \\ p_z=m_\perp sinh(y) \end{cases}$

优点：*Lorentz*变换时，快度相加 $y'=y+Y$

E_{lab}与$\sqrt{s}$的转换

$$\sqrt{s}=\sqrt{(E_1+E_2)^2-(\vec{p}_1+\vec{p}_2)^2}=\sqrt{(E_{lab}+m_N)^2-\vec{p}_1^{\,2}}=\sqrt{2m_N(m_M+E_{lab})}$$

正常核物质的能量密度

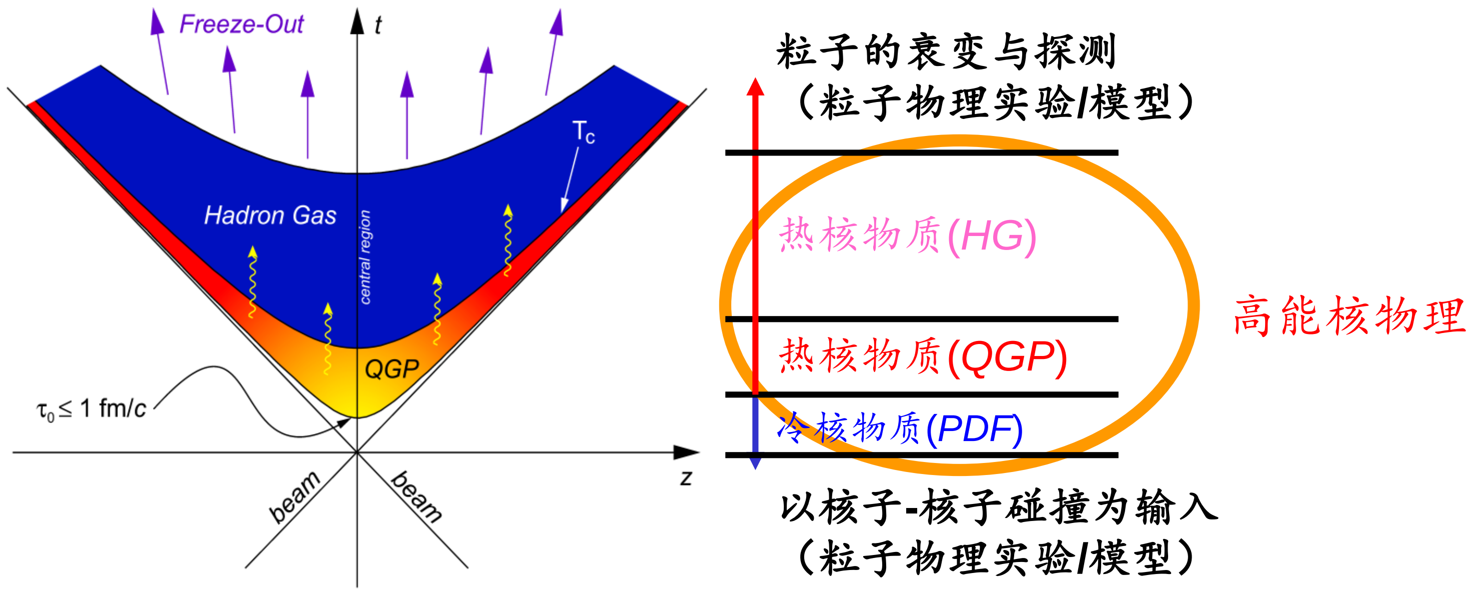
核内核子数密度 $n_0=0.17/fm^3$，核内能量密度$\varepsilon_0=m_Nn_0\sim 0.17\text{GeV}/fm^3$

产生QGP的最低能量密度

即核子内的能量密度 $\varepsilon_{min}=\frac{m_N}{\frac{4}{3}\pi r_N^3}\xrightarrow{r_N=0.8\,fm}0.5\text{ GeV}/fm^3$

QGP的信号

QGP只是重离子碰撞的中间态，即使在RHIC和LHC产生了QGP，也不能在末态直接观测到，只能通过携带QGP信号的末态粒子来判断。



希望看到什么？

1）与$p+p$碰撞的差别 → 有新的物理

核修正因子：$R_{AA}=\frac{\sigma_{AA}}{N_{coll}\sigma_{pp}}$

2）与强子气体的差别 → QGP的产生！

热密物质的时空演化—流体力学

Landau: 用流体力学描述高能碰撞后至衰变前体系的时空演化。

忽略粘滞效应的理想流体力学方程

$$\begin{cases} \partial_\mu T^{\mu\nu} = 0 & (\text{能动量守恒}) \\ \partial_\mu n^\mu = 0 & (\text{重子数守恒}) \end{cases}$$

$$T^{\mu\nu} = -Pg^{\mu\nu} + (\varepsilon + P)u^\mu u^\nu, \qquad n^\mu = n_B u^\mu, \qquad u_\mu u^\mu = 1$$

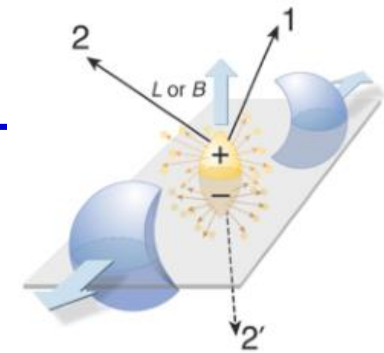
+ *Equation of state* $\epsilon(P)$ （*QGP or Hadron gas from QCD thermodynamics*）

$\rightarrow\ u_\mu(x), T(x), \mu_B(x), P(x)$

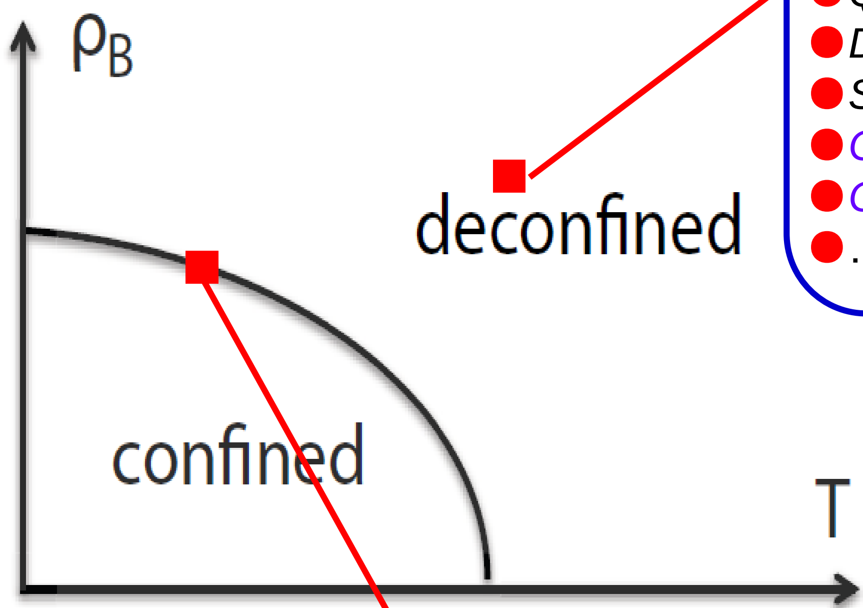
一维膨胀→快度中心区的能量密度(*Bjorken*估计)

$$\begin{cases} \varepsilon(\tau) = \epsilon(\tau_0)\left(\dfrac{\tau_0}{\tau}\right)^{1+c_s^2} \\ n(\tau) = n(\tau_0)\dfrac{\tau_0}{\tau} \\ T(\tau) = T(\tau_0)\left(\dfrac{\tau_0}{\tau}\right)^{c_s^2} \end{cases}$$

Probes of QCD Phases



- *Collective flow*
- *Jet quenching*
- *Quarkonium suppression*
- *Dileptons*
- *Strangeness enhancement……*
- *Chiral magnetic effect (CME)*
- *Chiral vortical effect (CVE)*
- ……



Quantum fluctuations

Probes of the chiral critical point:
Dynamical fluctuations of conserved charges.

Dynamical Fluctuations around Critical Point

- *Correlation length* $\xi \to \infty$ *at a critical point*, *strong dynamical fluctuations!*
- *Order parameter field* $\sigma(x)$

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

  Cumulants:

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

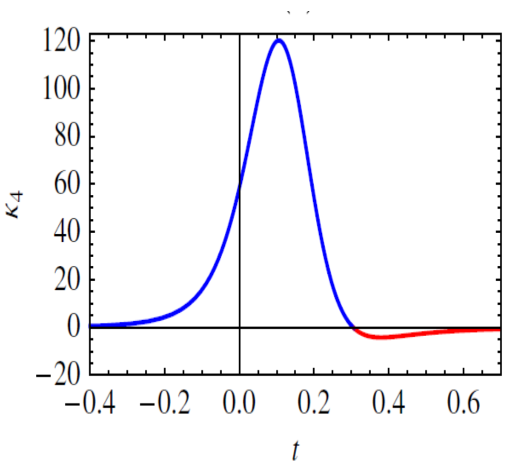
High order cumulants are more sensitive to the fluctuations and cab be used to sensitively probe the critical point.

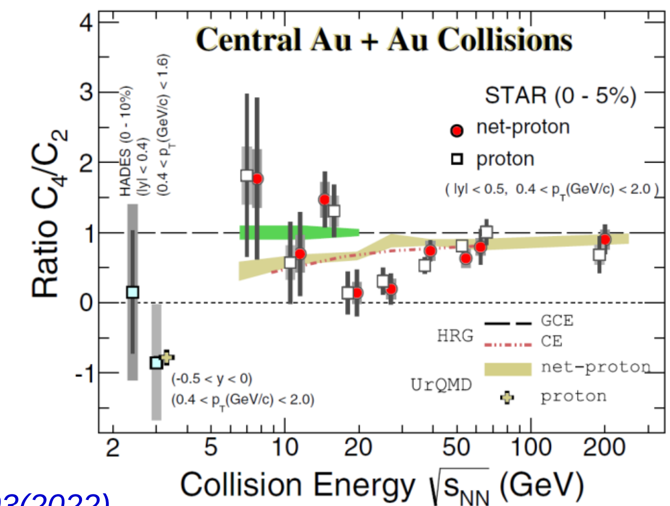
M.Stephanov, PRL102, 032301(2009)
M.Asakava, S.Ejiri, M.Kitazawa, PRL103, 262301(2009)

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

M.Stephanov, PRL107, 052301(201

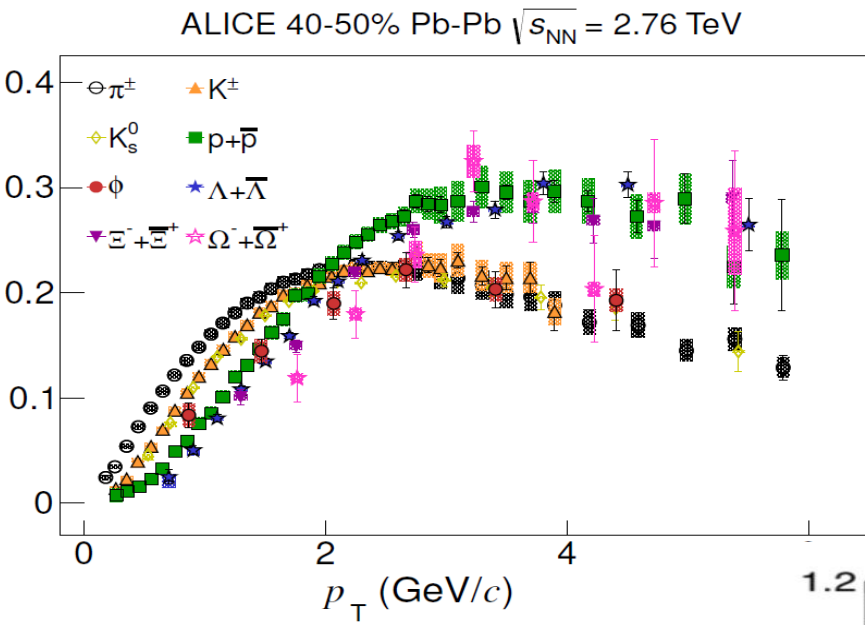
Far from CP: $C_4 = 0$
Crossover side: $C_4 < 0$
First order side: $C_4 > 0$





STAR（罗晓峰，许怒等）， PRL128, 202303(2022)

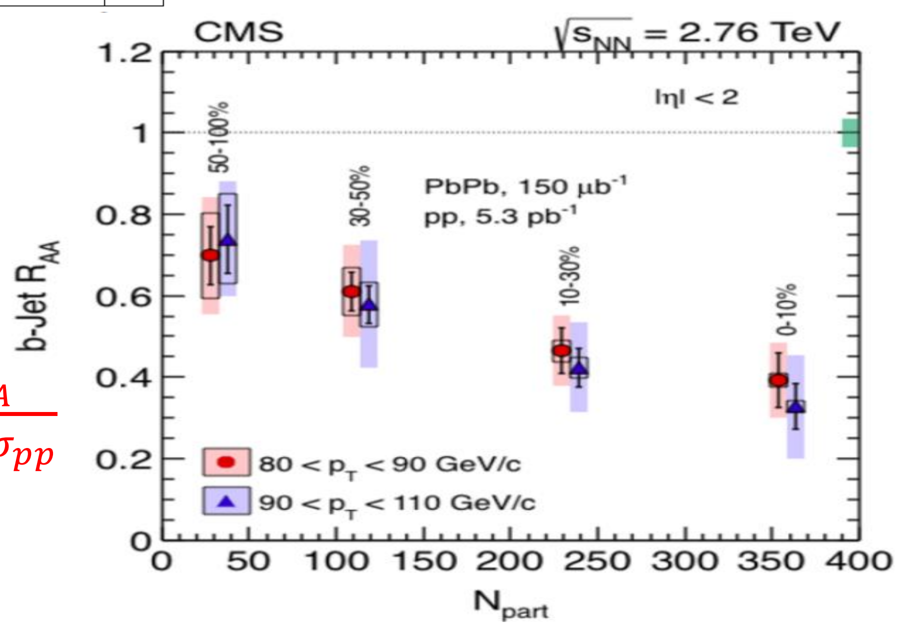
Collective Flow & Jet Quenching



- Collective flow $v_2 = \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2}$

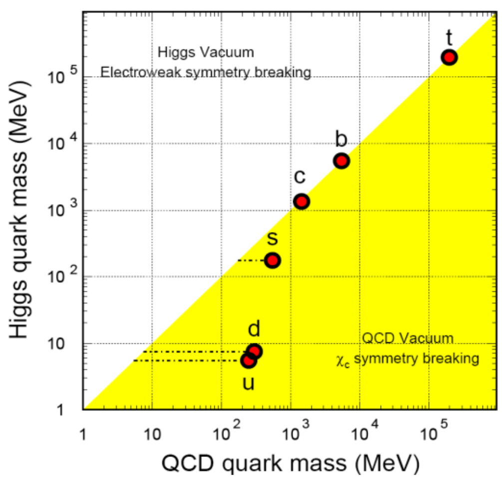
- Jet suppression

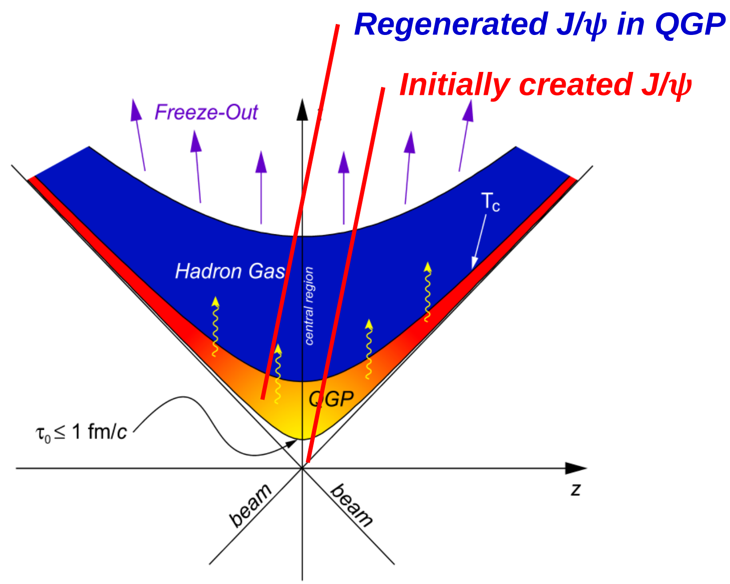
Nuclear modification factor $R_{AA} = \frac{\sigma_{AA}}{N_{coll}\sigma_{pp}}$



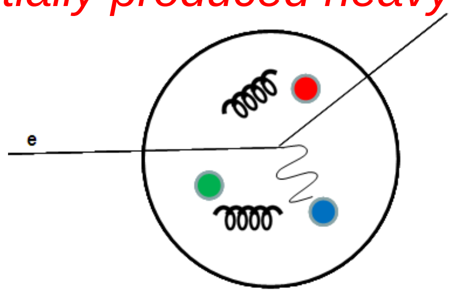
Heavy Flavor as a Probe of QGP

- *QCD → NRQCD → pNRQCD, a relatively solid calculation*
- *Medium-independent heavy-quark mass*

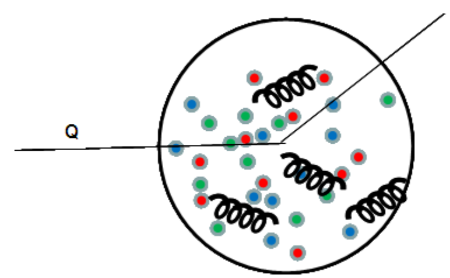




→ Initially produced heavy quarks pass through the QGP and carry its information.



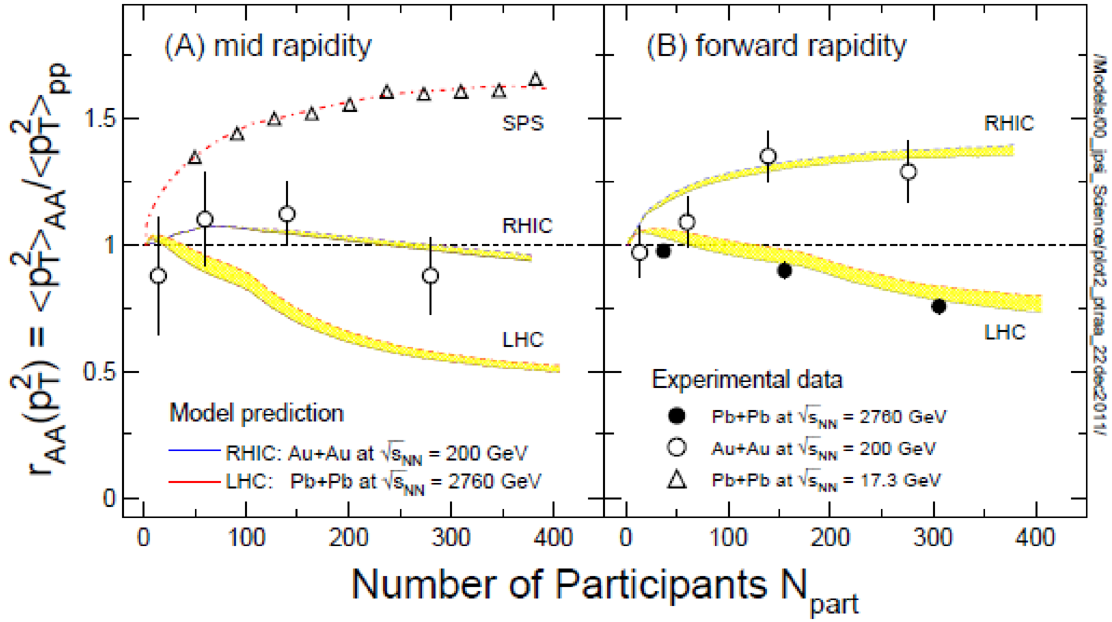
electrons as a probe of nucleon structure

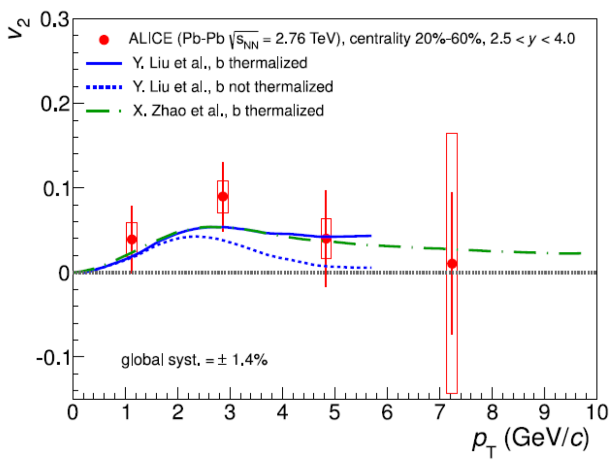


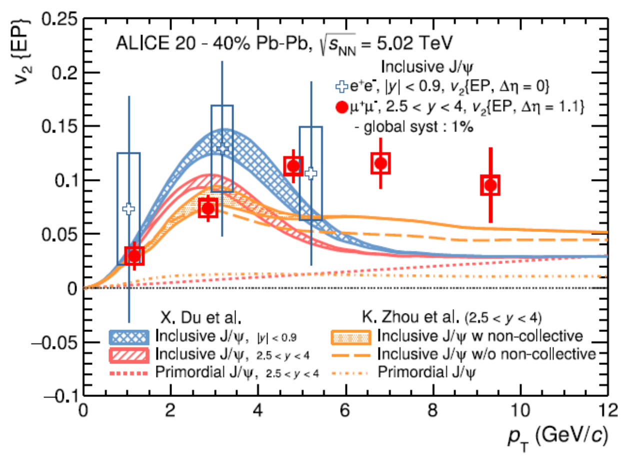
heavy quarks as a probe of QGP structure

J/ψ r_{AA} and v_2

J.Zhao, K.Zhou, S.Chen and PZ,
Prog.Part.Nucl.Phys.114 (2020),103801

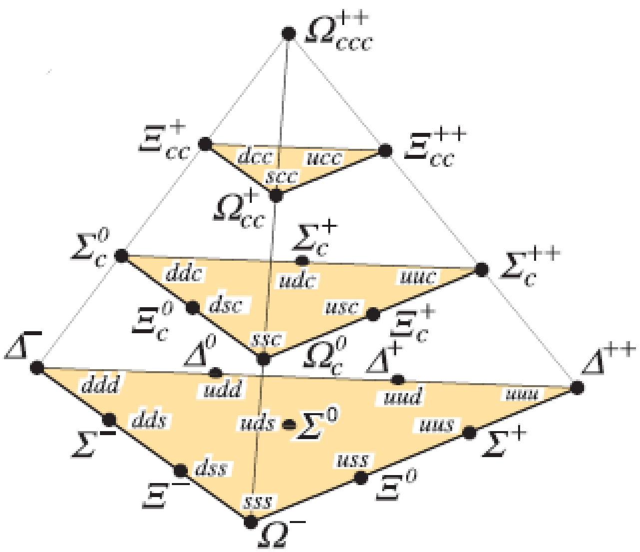


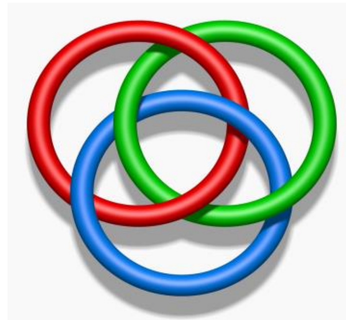




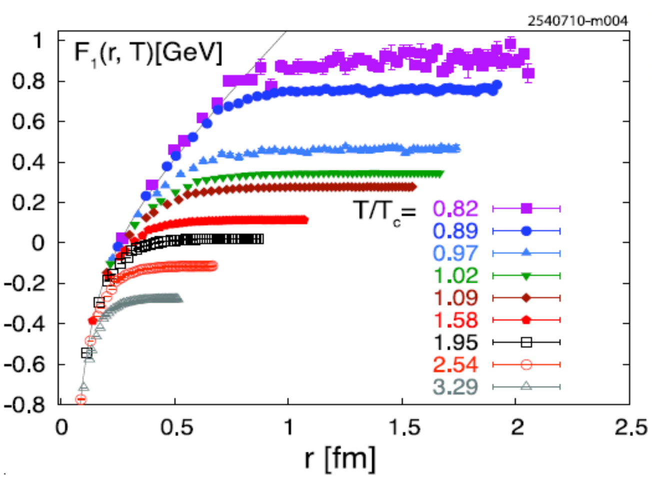
Ω_{ccc} as a Borromean Ring and an Efimov State

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

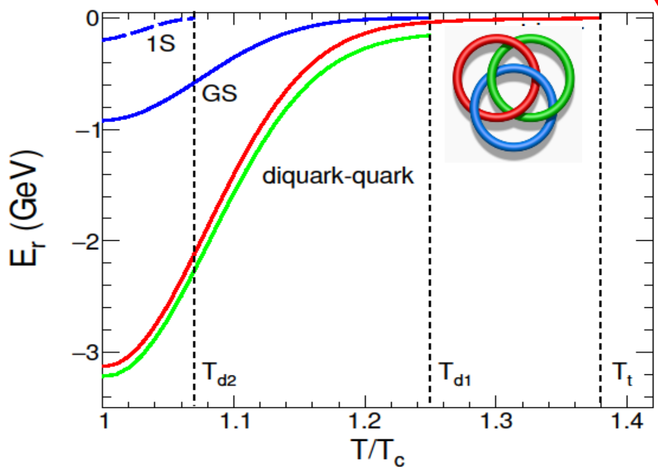


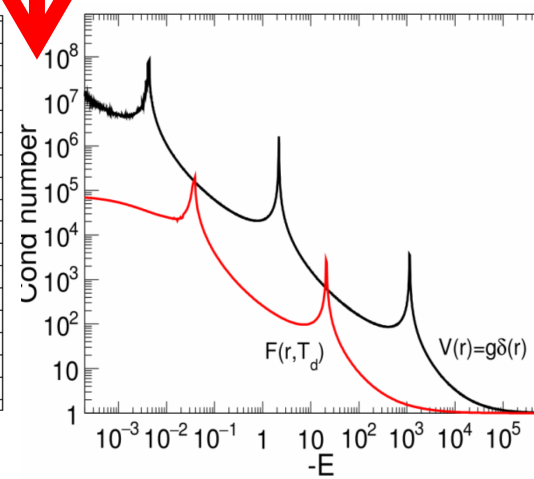


3-body Schroedinger equation



short range potential at high T !





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

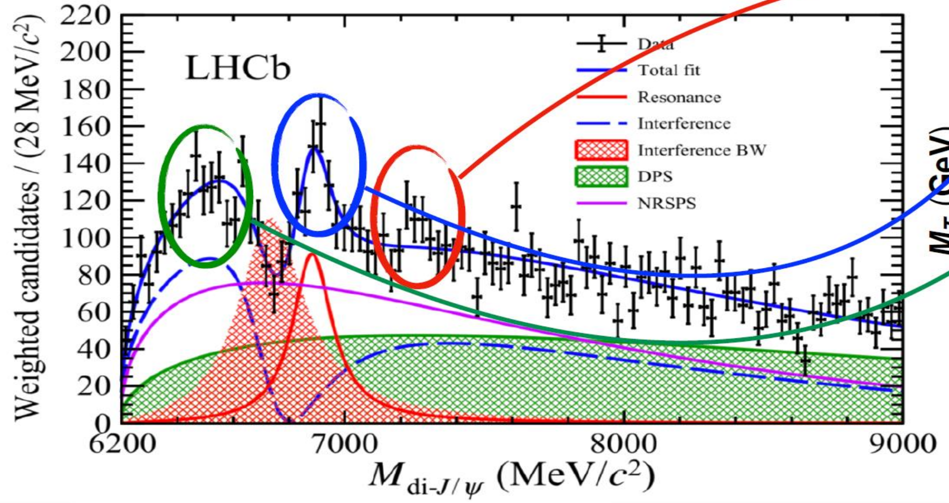
A challenge to experimentalists:

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

Exotic Hadrons

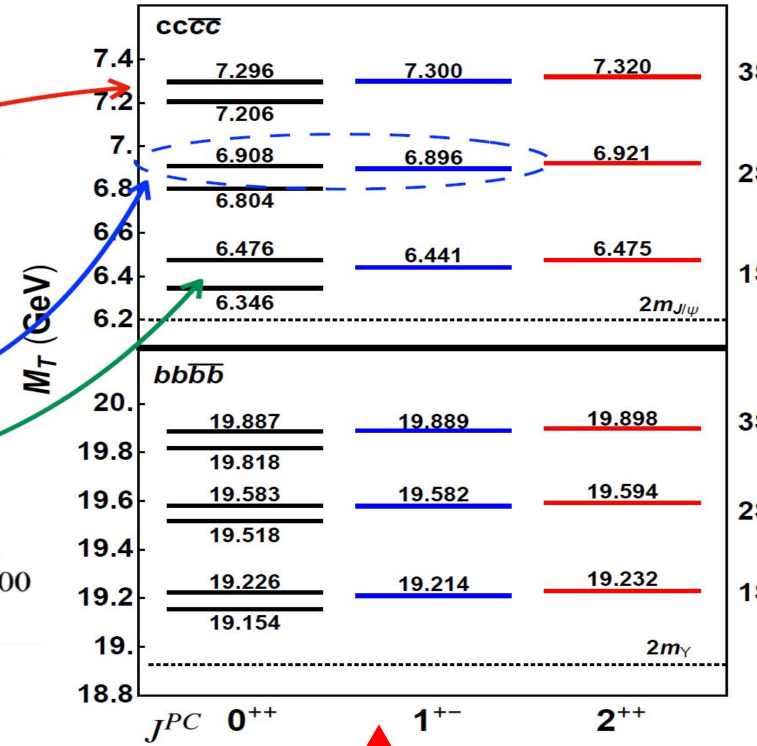
J.Zhao, S.Shi and PZ, PRD102, 114001 (2020)

- 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!



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

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



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

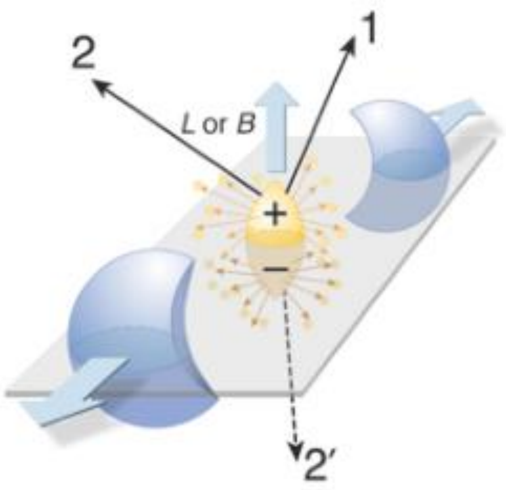
4-body Schroedinger equation

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

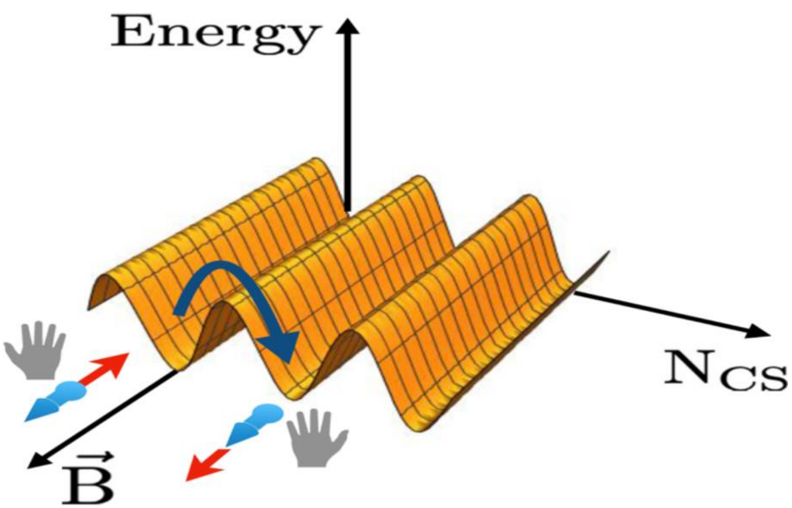
【参见廖劲峰的前沿报告】

Chiral Magnetic Effect

D.Kharzeev and J.Liao, Nature Rev. Phys. 3(2021), 55



W.Deng and X.Huang, PRC85,044907 (2012)



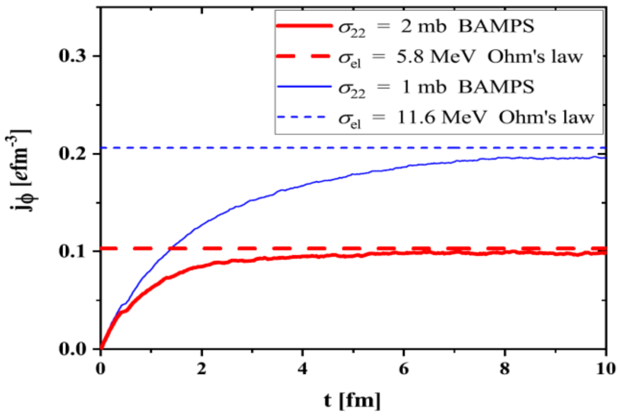
A chirality imbalance induced electric current in magnetic field is a probe of nontrivial topology of QCD.

A reason why it is hard to observe CME in HIC:

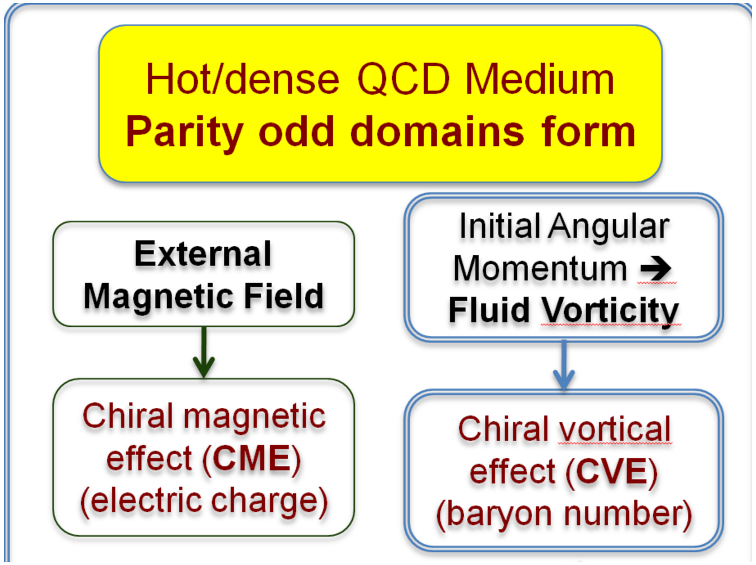
重离子碰撞中破缺的欧姆定律:

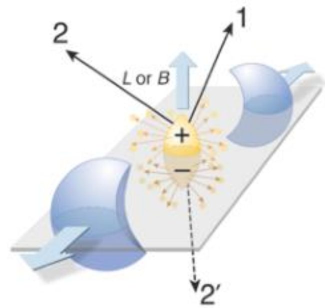
$$\vec{J}_{ohm} \le \sigma_{el}\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

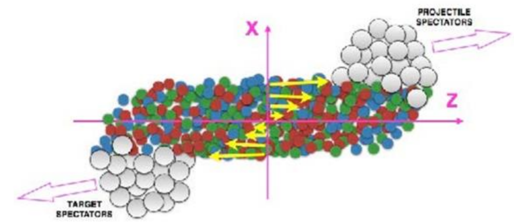
Wang, Zhao, Greiner, Xu and Zhuang,
PRC105, L041901(2022), Letter, Featured in Physics



Chiral Vortical Effect



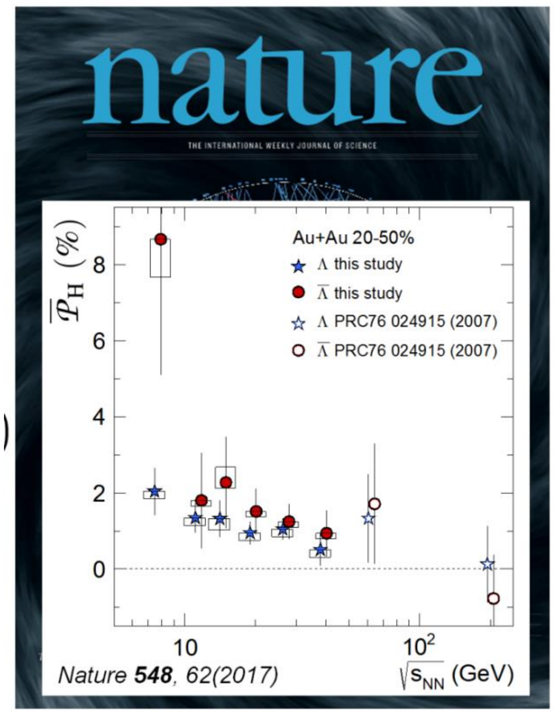




Global collision angular momentum generates QGP vorticity

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

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



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

Comments

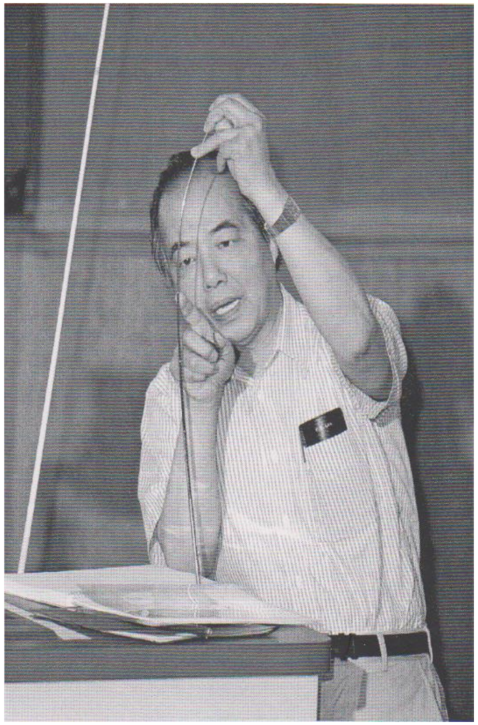
- *Nuclear collision is a complex system (strong interaction and many-body system, both are key problems in physics), it is the field of quantum computing.*

- *Since QGP is an intermediate state in HIC, we cannot directly measure it. At the moment there is no a unique signal observed in experiments, we need to characterize the QGP properties comprehensively.*

- *Some sensitive signals like high-order moments, CME and CVE are quantum fluctuations, we need precise measurement and carefully excluding the influence from the background.*

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】