Perfect Liquid at RHIC

---夸克胶子等离子体简介

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Thanks to X.F. Luo, S.S. Shi and N. Xu for exciting discussions !

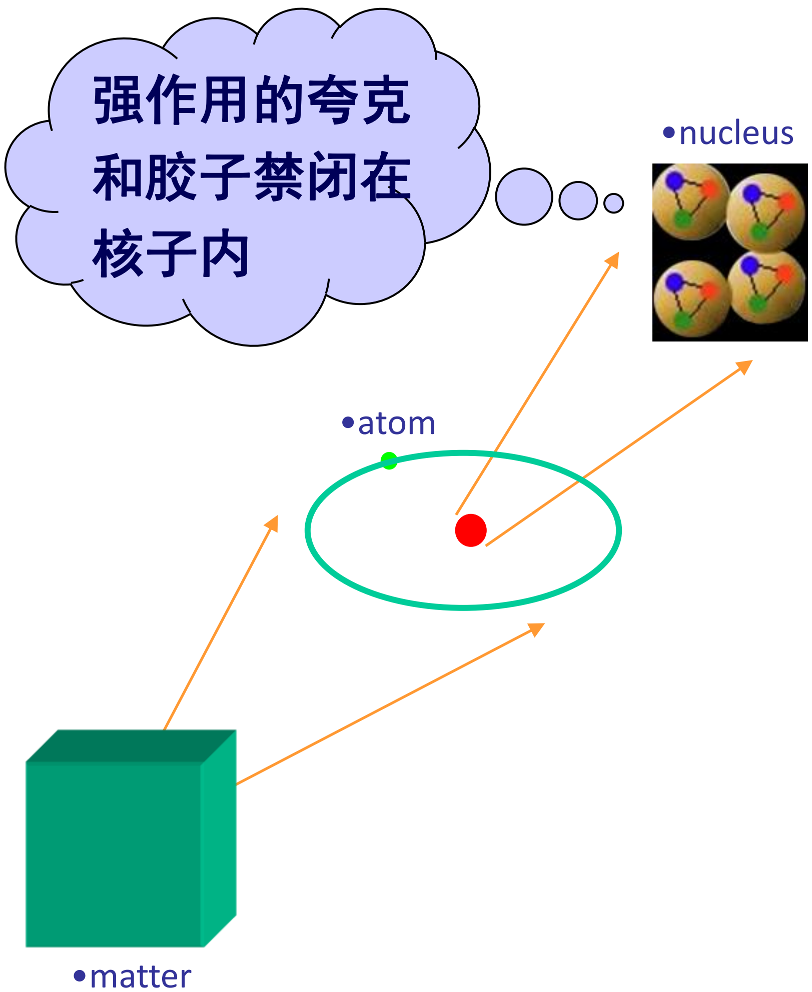
2023年8月 大连

Outline

- Introduction
- Perfect Liquid
- Summary and Outlook

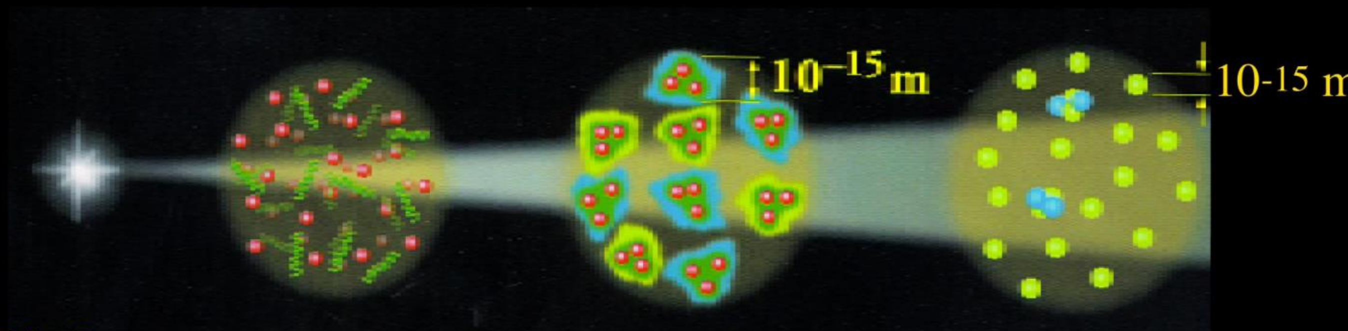
Two Puzzles of Modern Physics

-- T.D.Lee



- **Missing Symmetry – all present theories are based on symmetry, but most symmetry quantum numbers are NOT conserved.**
- **Unseen Quarks – all hadrons are made of quarks, yet NO individual quark has been observed.**

History of the Universe

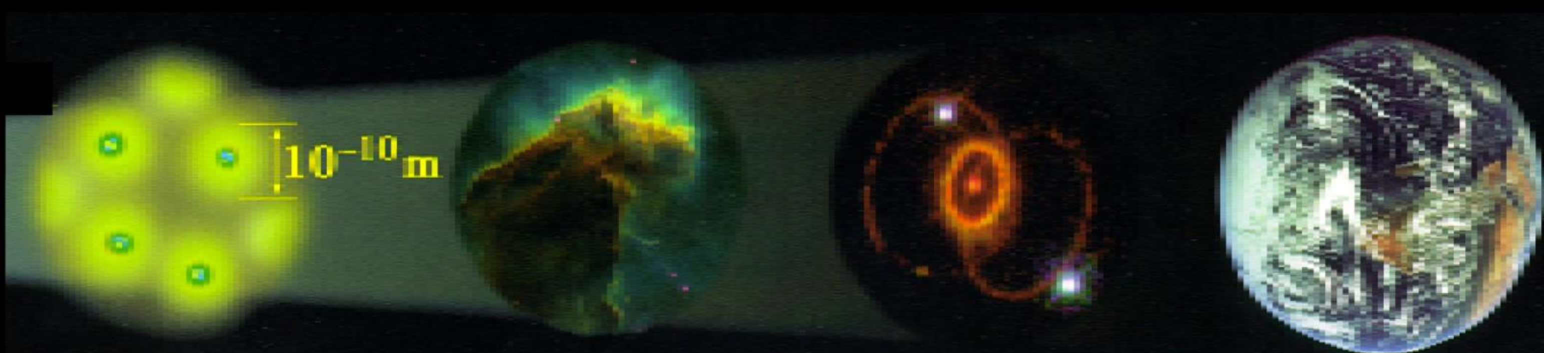


Big Bang

Quark-Gluon Plasma
10^{13}K, 10^{-6}s

Protons& Neutrons
10^{12}K, 10^{-4}s

Low-mass Nuclei
10^{9}K, 3 min



Neutral Atoms
4000K, 10^{5}y

Star Formation
10^{9}y

Heavy Elements
$>10^{9}$y

Today

Source: Nuclear Science Wall Chart

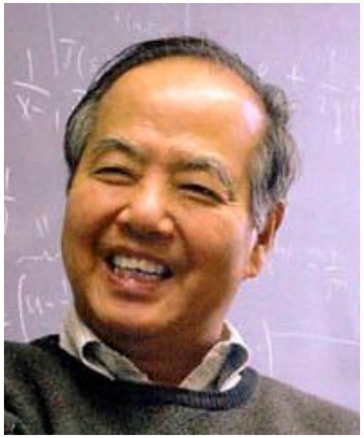
How to Address the Problem?

The confinement:

Quarks are the basic building blocks of matter.

No free quarks are seen, confined within hadron:

$\Delta v_0 \sim 1\ fm^3$, $\rho_0 \sim 0.16\ fm^{-3}$, $\varepsilon_0 \sim 0.15\ GeV/fm^3$



T.D. Lee

重要的科学问题：

夸克能否解除禁闭，产生新物质形态—夸克胶子等离子体（QGP）？

QCD 相结构？ 相变临界点是否存在？

Heavy ion collisions: Large, hot/dense system

$\Delta v \sim 1000\ fm^3 = 1000\ v_0$

$\rho >> 3\ fm^{-3} \sim 20\ \rho_0$ $\Rightarrow$ **Quark Gluon Plasma (QGP)**

$\varepsilon >> 3\ GeV/fm^3 \sim 20\ \varepsilon_0$

QGP: Quarks and gluons are 'freely' moving in a large volume

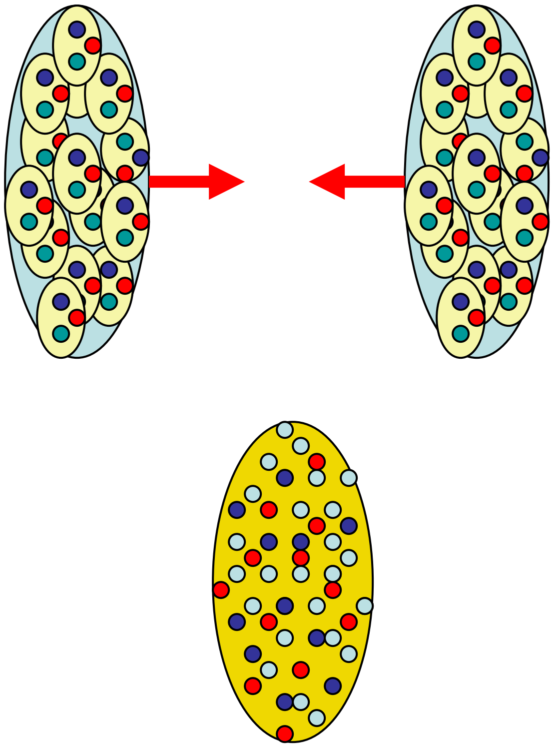
New form of ***matter with partonic degrees of freedom***

QCD Phase Structure

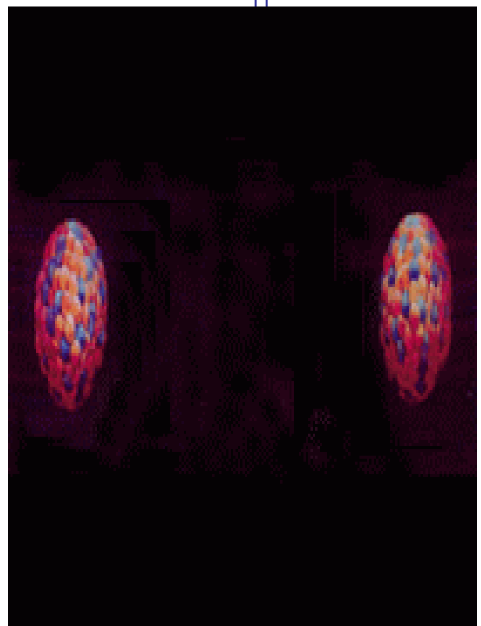
- Connection with other fields，cosmology, origin of the universe, evolution of the universe quantum statistics with partons

The Melting of Quarks and Gluons
-- Quark-Gluon Plasma --

Matter Compression:

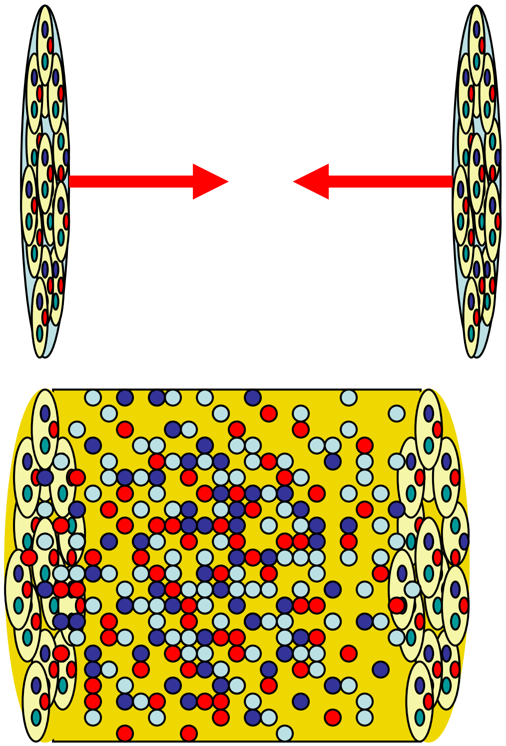


High Baryon Density
-- low energy heavy ion collisions
-- neutron star→quark star



Deconfinement

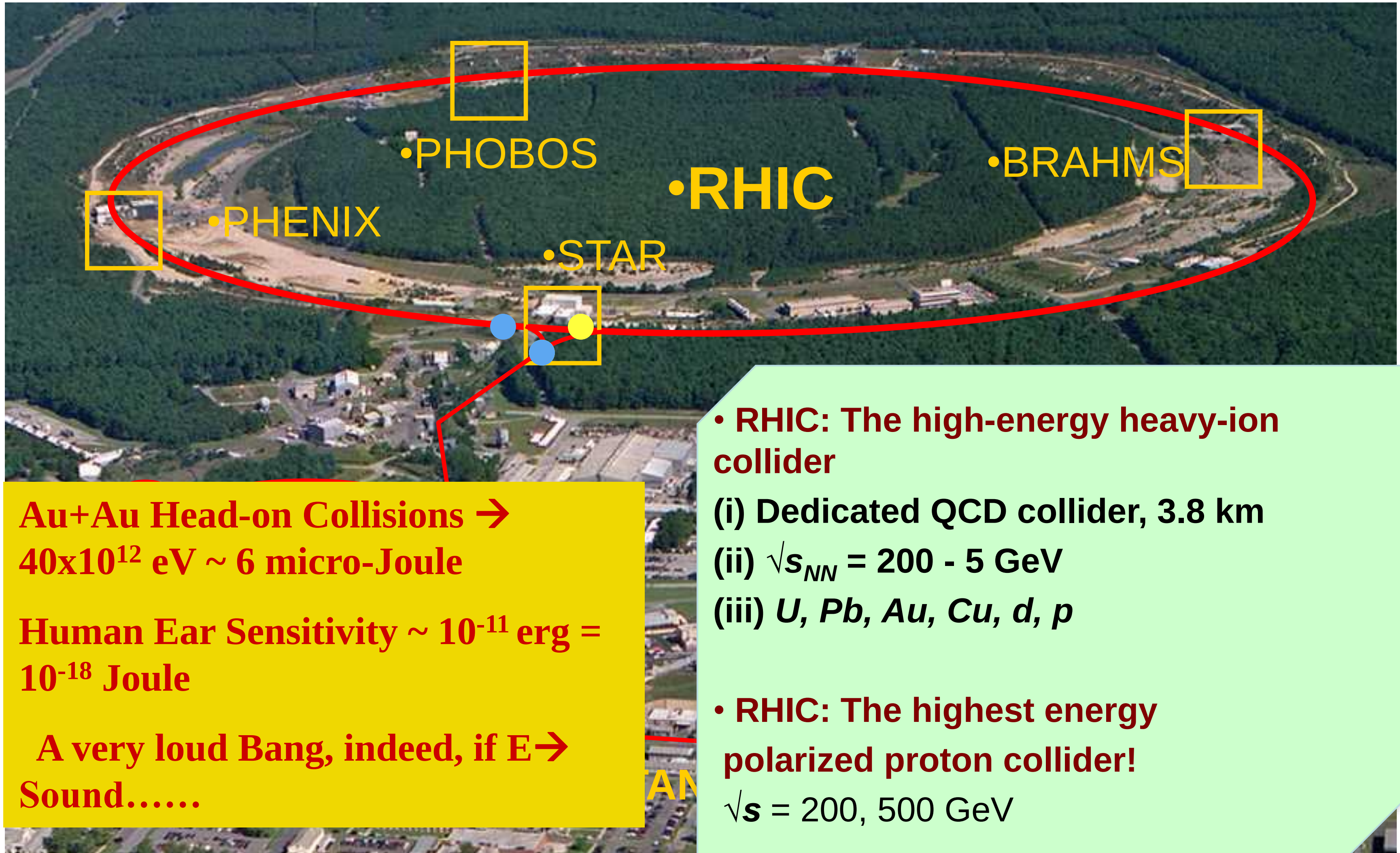
Vacuum Heating:



High Temperature Vacuum
-- high energy heavy ion collisions
-- the Big Bang

Relativistic **H**eavy **I**on **C**ollider

Brookhaven National Laboratory (BNL), Upton, NY



Au+Au Head-on Collisions →
40×10^{12} eV ~ 6 micro-Joule

Human Ear Sensitivity ~ 10^{-11} erg = 10^{-18} Joule

A very loud Bang, indeed, if E→ Sound……

- **RHIC: The high-energy heavy-ion collider**

(i) Dedicated QCD collider, 3.8 km

(ii) $\sqrt{s_{NN}}$ = 200 - 5 GeV

(iii) *U, Pb, Au, Cu, d, p*

- **RHIC: The highest energy polarized proton collider!**

$\sqrt{s}$ = 200, 500 GeV

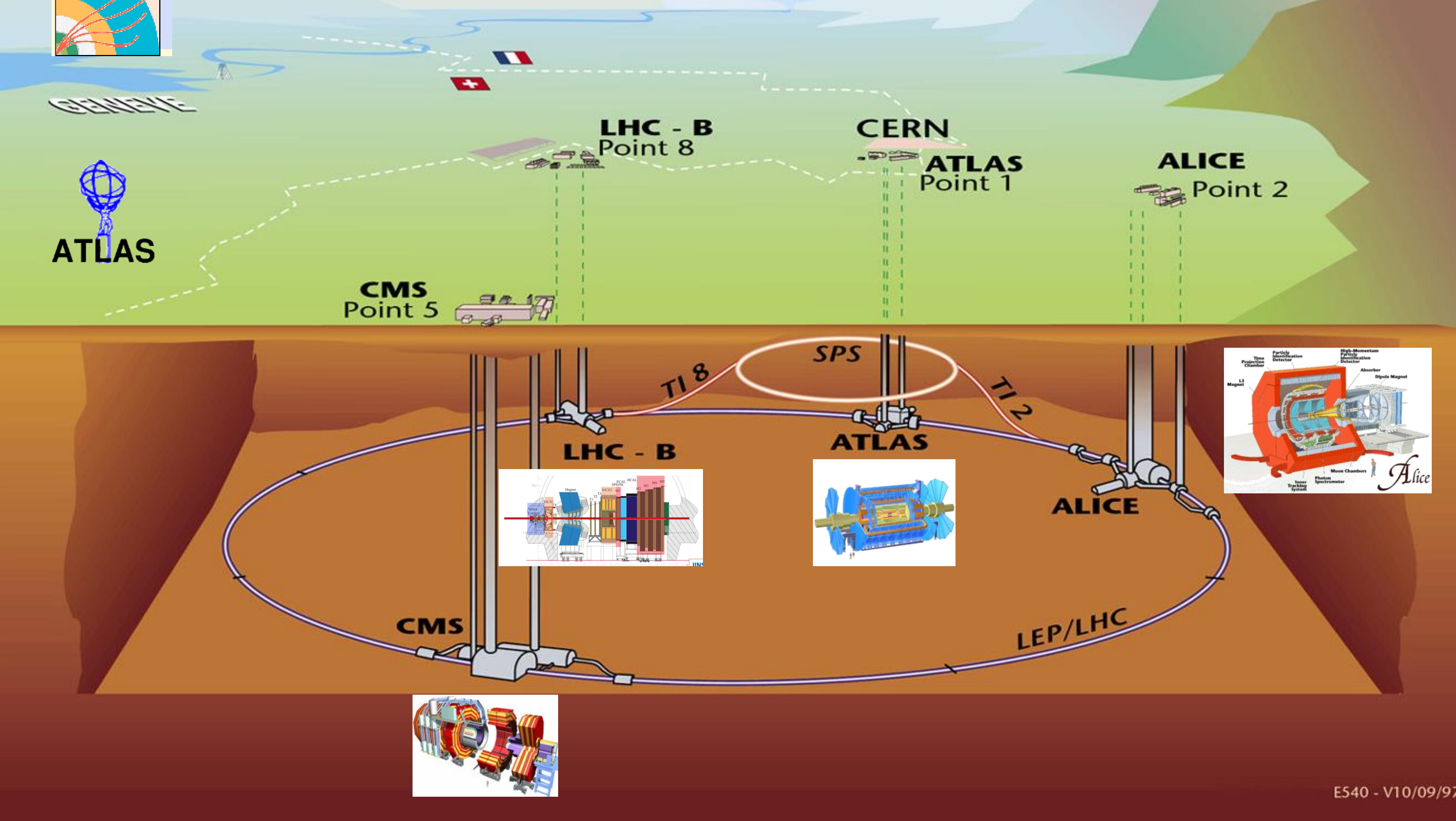
•*Animation M. Lisa*

Overall view of the LHC experiments.

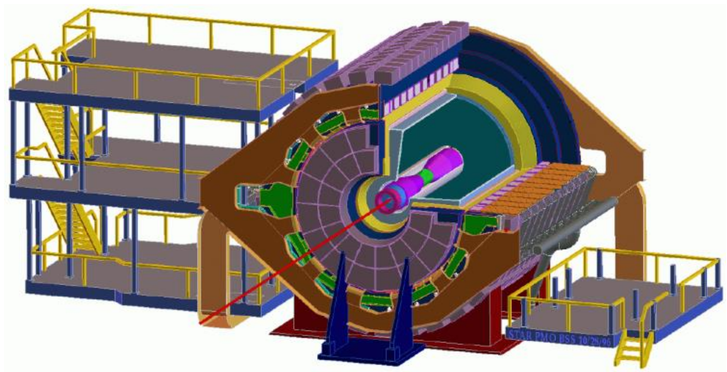
One dedicated HI experiment: ALICE

Three pp experiments with HI program:

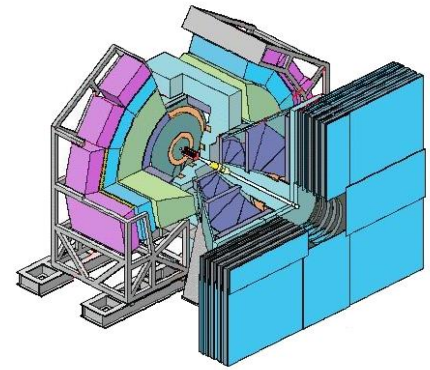
ATLAS CMS LHCb



High-Energy Nuclear Collider Experiments

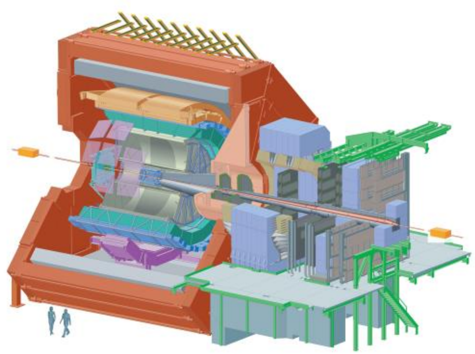


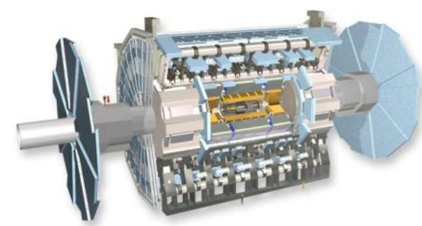
STAR (Solenoidal Tracker At RHIC)



PHENIX (Pioneering High Energy Nuclear Ion Experiment)

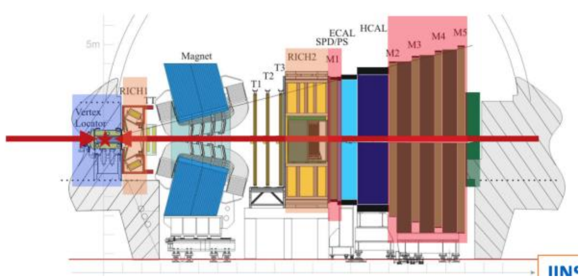
ALICE (A Large Ion Collider Experiment)





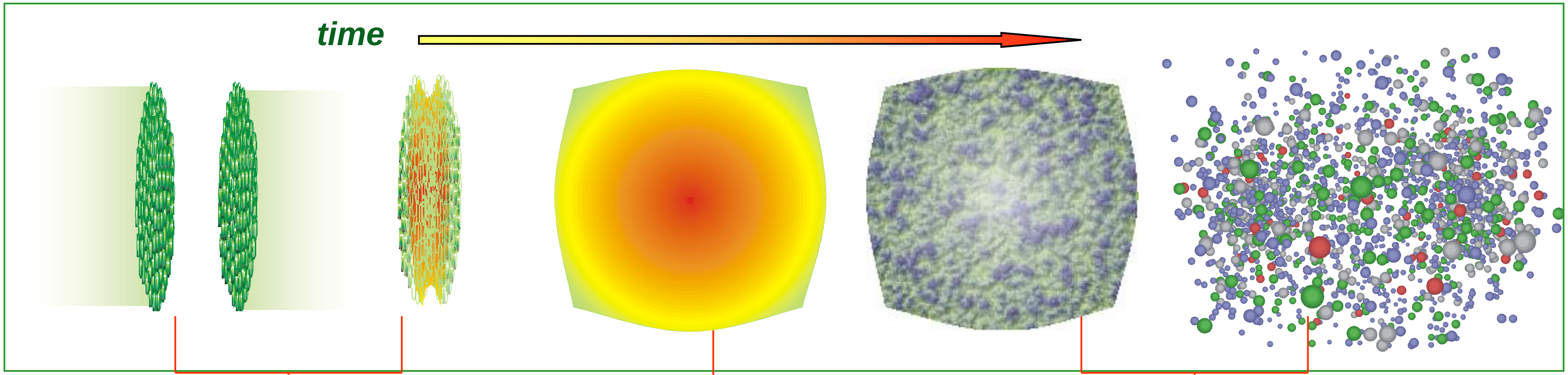
•**ATLAS** (A Toroidal LHC Apparatus)

LHCb



CMS (Compact Muon Solenoid)

High-energy Nuclear Collisions



Initial conditions and interactions

Hot and Dense

Cooling down freezing out

Experimental probes:

1) ***Penetrating probes:*** "jets" **Energy loss**

2) ***Bulk probes*** **:Elliptic flow, radial flow**

3) ***Fluctuation*:**

Physics Goals at RHIC

Identify and study the properties of matter with partonic degrees of freedom.

Penetrating probes

- direct photons, leptons
- "jets" and heavy flavor

Bulk probes

- spectra, v_1, v_2 …
- partonic collectivity
- fluctuations

Hydrodynamic Flow = Collectivity ⊗ Local Thermalization

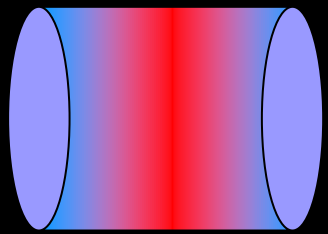
Outline

- **Introduction**
- **Perfect Liquid**
  - **Energy loss**
  - **Spectra**
  - **Elliptic flow v_2**
  - **Perfect Liquid**
- **Summary and Outlook**

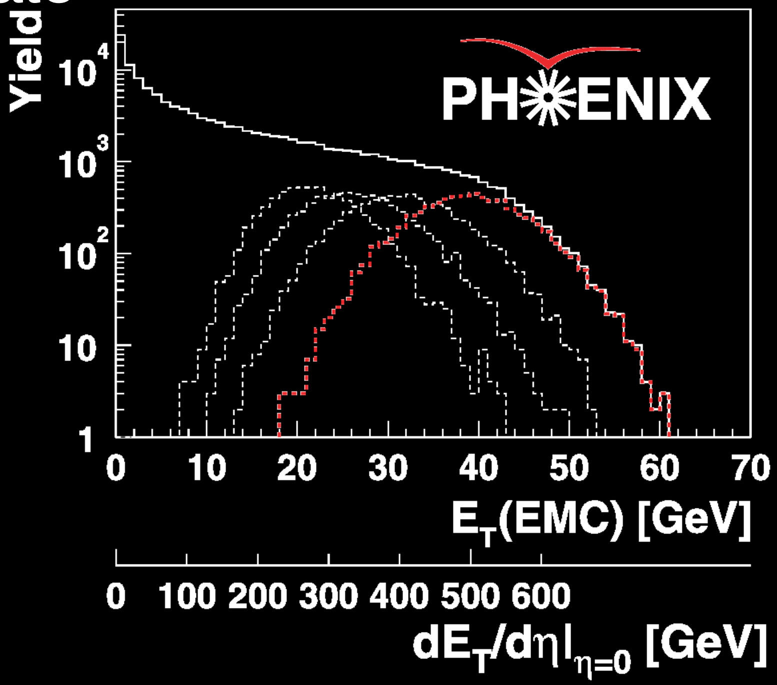
Transverse Energy and Energy Density

- Bjorken energy density estimate

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$



$dz = \tau_0 dy$



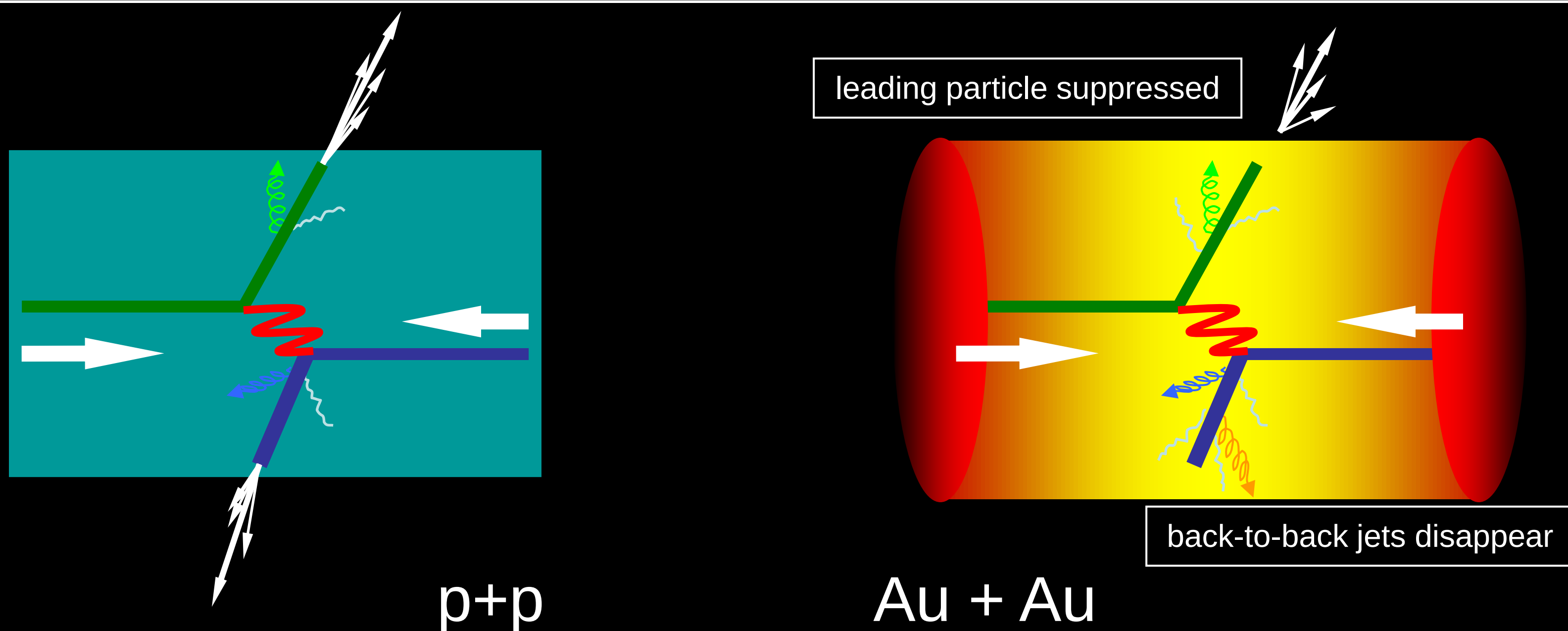
$$\varepsilon_{BJ} = 4.6\,\mathrm{GeV/fm^3}$$

$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\ \mathrm{GeV}$$

- Much larger than the critical energy density !!

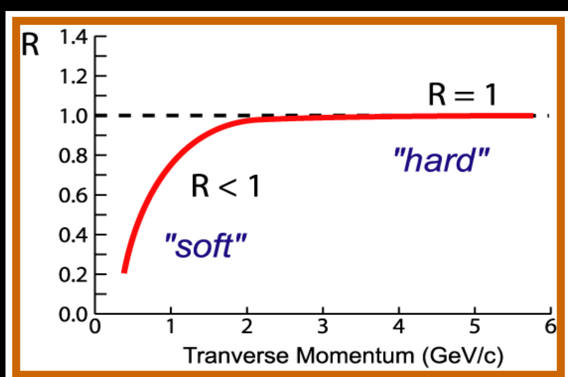
$$\varepsilon_{BJ} >> \varepsilon_0 \sim 0.15\ \mathrm{GeV/fm^3}$$

Energy Loss in A+A Collisions

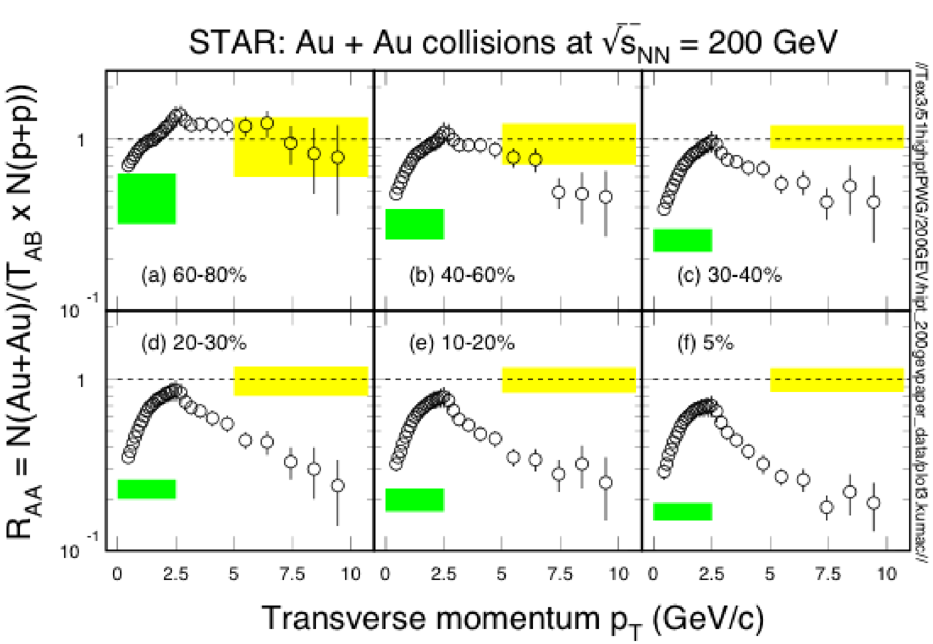


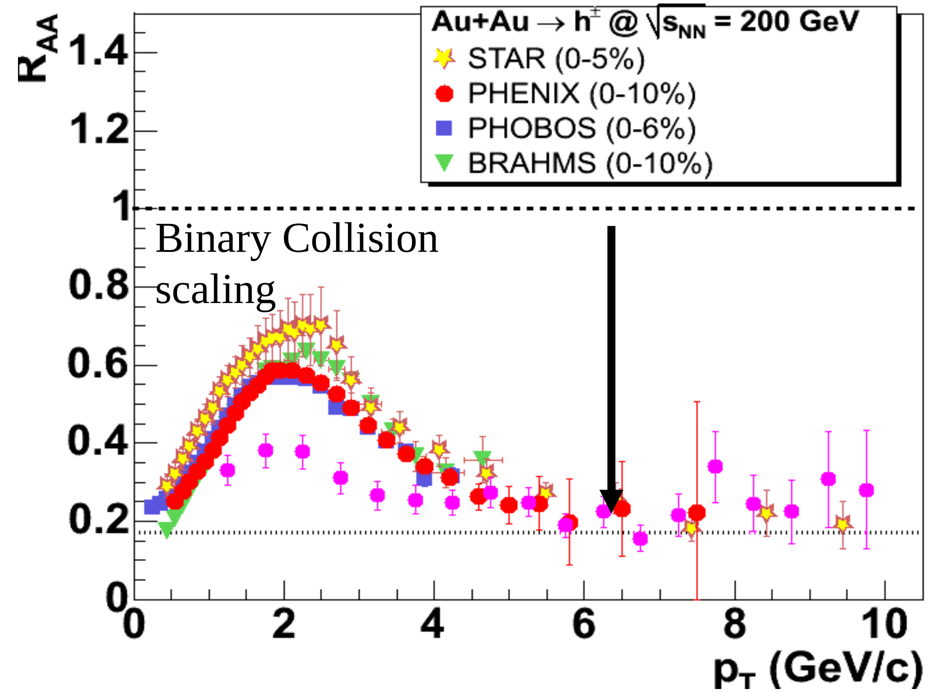
Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{(dN/dp_T)_{AA}}{\langle N_{coll}\rangle (dN/dp_T)_{pp}}$$



Hadron Suppression at RHIC





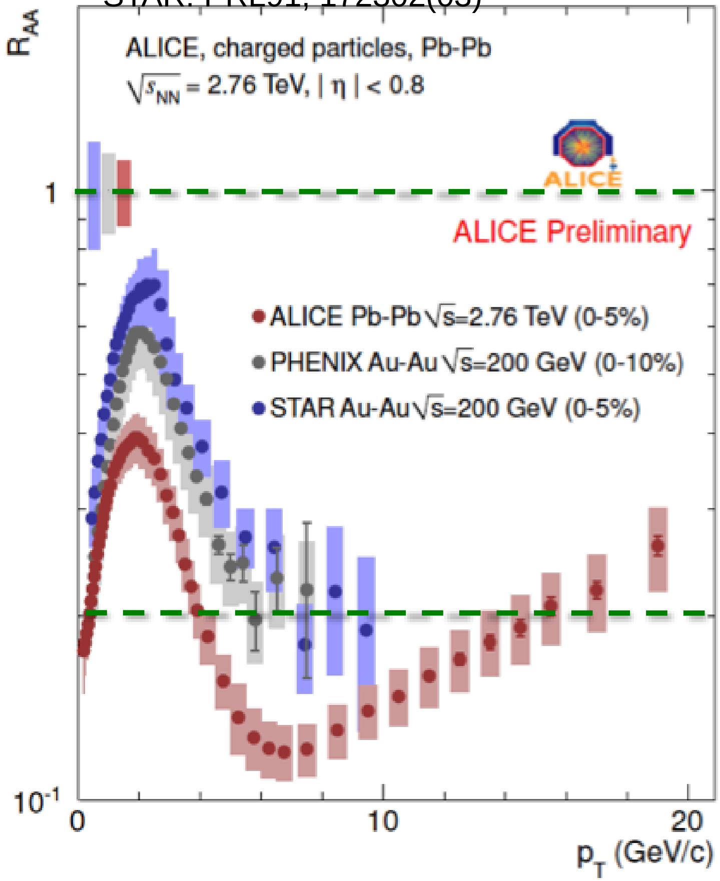
$$R_{AA}(p_T) = \frac{(dN/dp_T)_{AA}}{\langle N_{coll}\rangle (dN/dp_T)_{pp}}$$

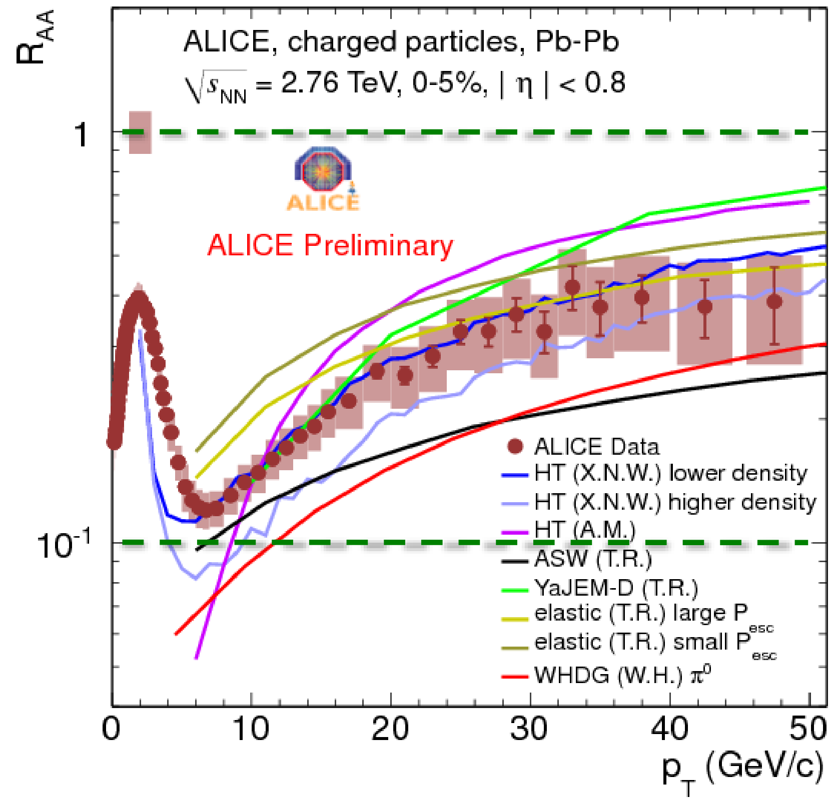
Factor 5 suppression: large effect
pQCD+energy loss: initial density ~30 times cold nuclear matter

Nuclear Modification Factor

•PHENIX: PRC69, 034910(04)

•STAR: PRL91, 172302(03)





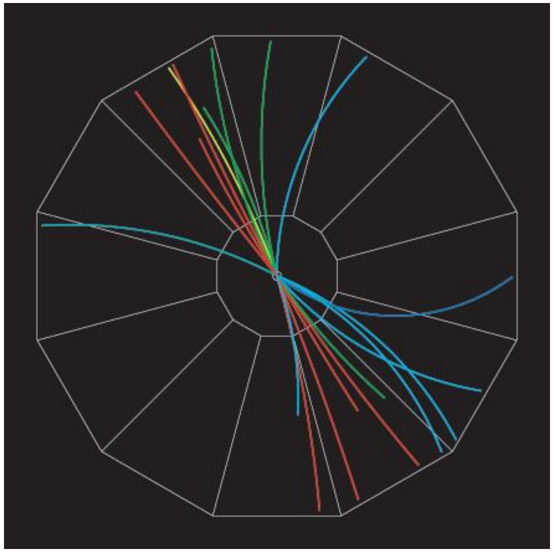
1) At LHC(2.76TeV), the energy loss is stronger than that from RHIC (0.2TeV)

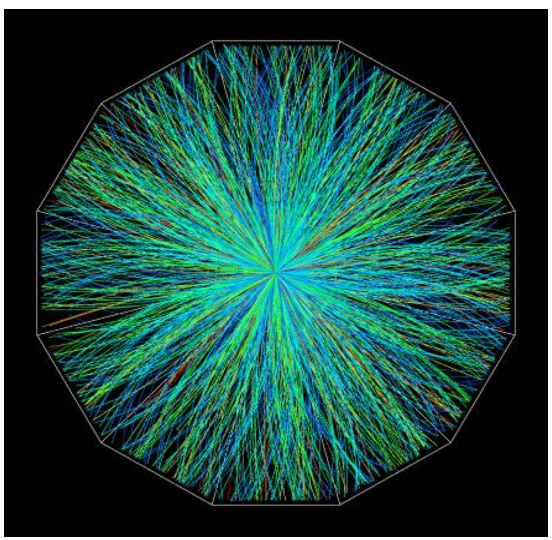
➔ hotter/denser medium created at higher collision energy

2) pQCD predictions consistent at larger p_T region: > 10 GeV/c

Jets

p+p → dijet

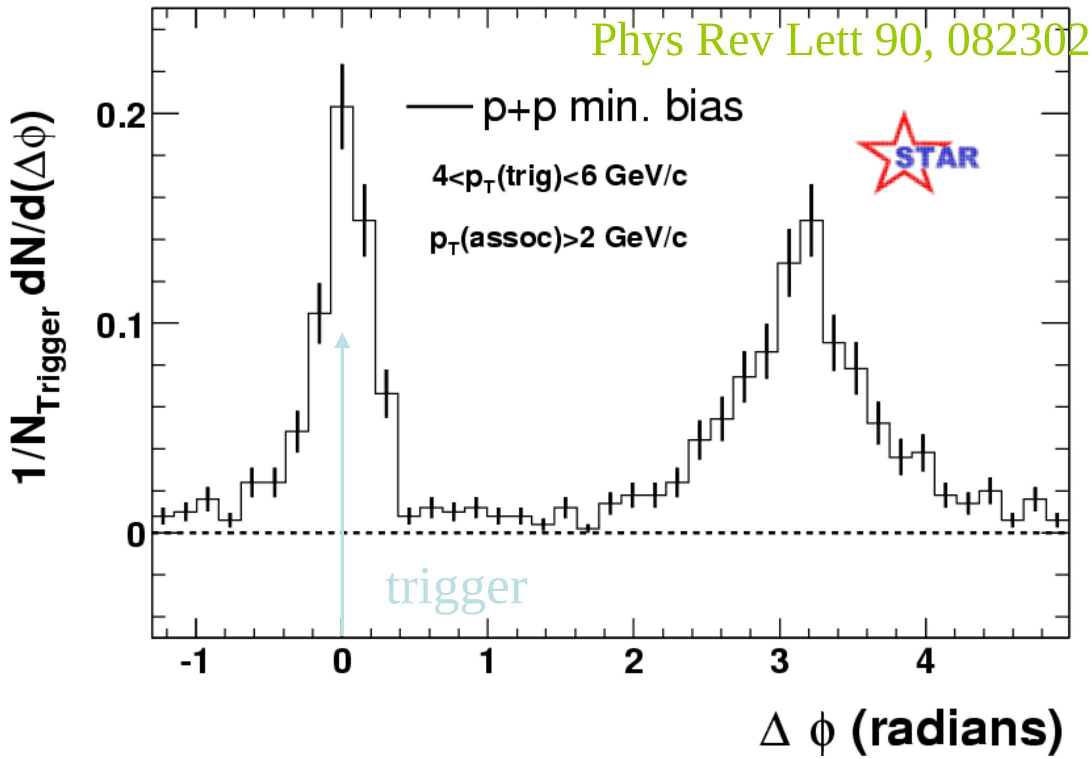




trigger: highest p_T track, p_T>4 GeV/c

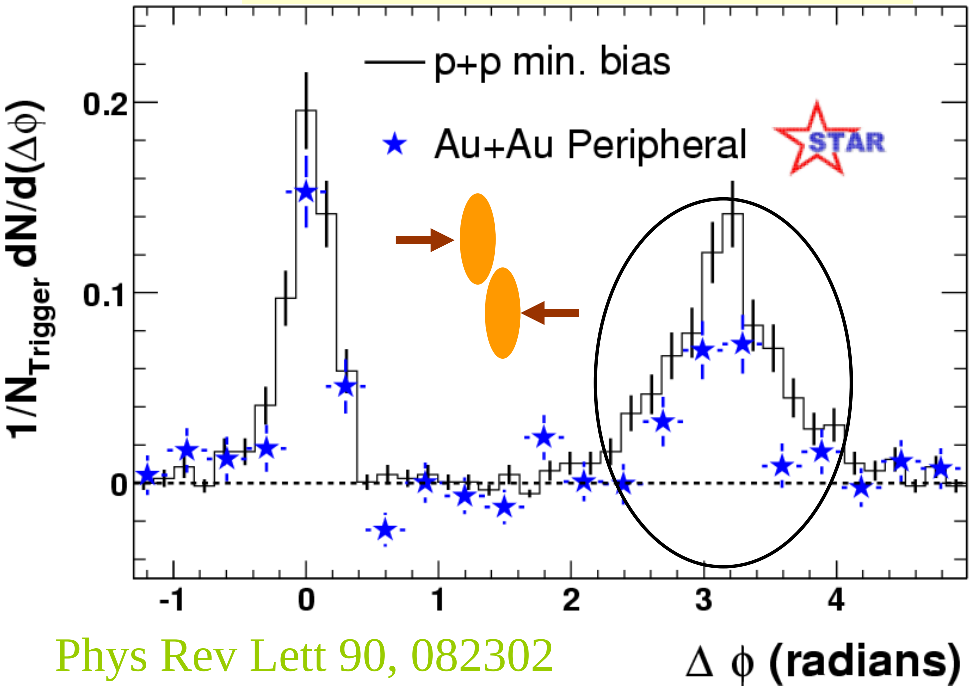
$\Delta\phi$ distribution: 2 GeV/c<p_T<$p_T^{trigger}$

normalize to number of triggers



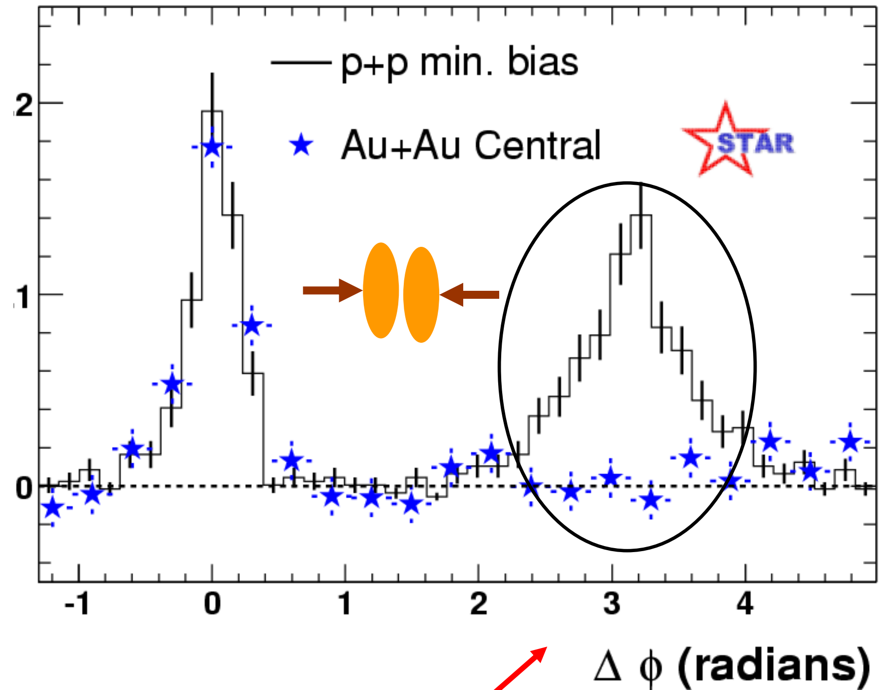
Dihadrons in Au+Au vs p+p

Au+Au peripheral
(large impact parameter)

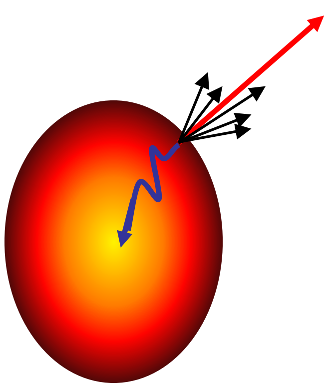


Phys Rev Lett 90, 082302

Au+Au central (head-on)



Strong suppression of back-to-back correlations in central Au+Au



Transverse Flow Observables

$$\frac{dN}{p_t dp_t dy d\varphi} = \frac{1}{2\pi}\frac{dN}{p_t dp_t dy}\left[1 + \sum_{i=1} 2v_i \cos(i\varphi)\right]$$

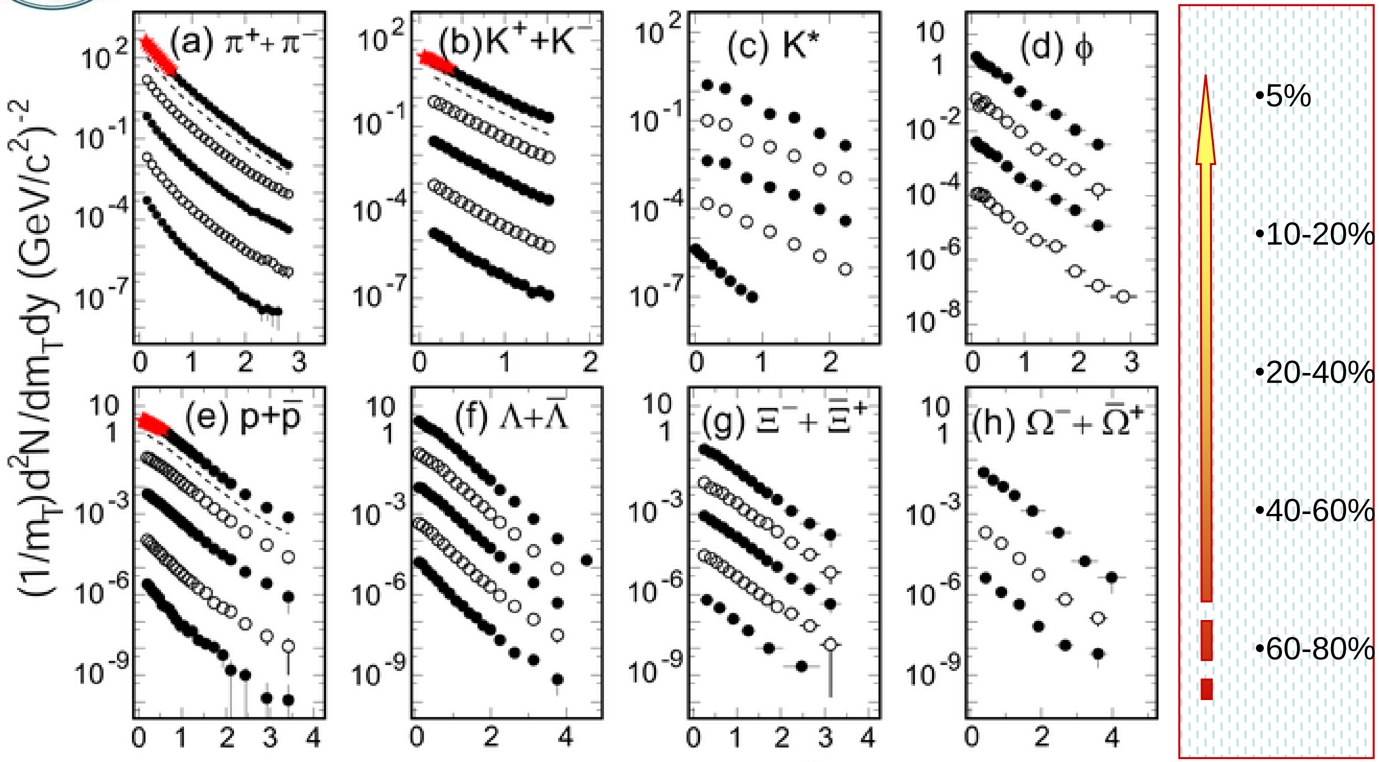
$$p_t = \sqrt{p_x^2 + p_y^2}, \qquad m_t = \sqrt{p_t^2 + m^2}$$

As a function of particle mass: $v_n = \langle \cos n\varphi \rangle$

- Radial flow – integrated over whole evolution
- Directed flow (v_1) – early
- Elliptic flow (v_2) – early
- Triangular flow (v_3) –
- Note on collectivity:

1) Effect of collectivity is accumulative – final effect is the sum of all processes.
2) Thermalization is not needed to develop collectivity - pressure gradient depends on ***density gradient*** and ***interactions***.

Hadron Spectra From RHIC



$m_T = \sqrt{p_T^2 + m^2}$

•mid-rapidity, p+p and Au+Au collisions at 200 GeV

STAR:NPA757,102(05)
(F. Wang) NPA715, 466c (03) , JPG30, S693(04) .
PHENIX: PRC 69 , 034909(04) .
(Huang, Long) *PRL **89**, 092301(02);*
F. Wang) *PLB **595**, 143(04).*
(Nu) *PRC 70, 041901 (04)*,
(F. Liu, F. Wang)*PRL 92, 112301(04)*

- Hadron spectra reflect the properties of the bulk of the matter at kinetic freezeout
- In central collisions, m_T distributions become more concave $\Rightarrow$ collective flow !

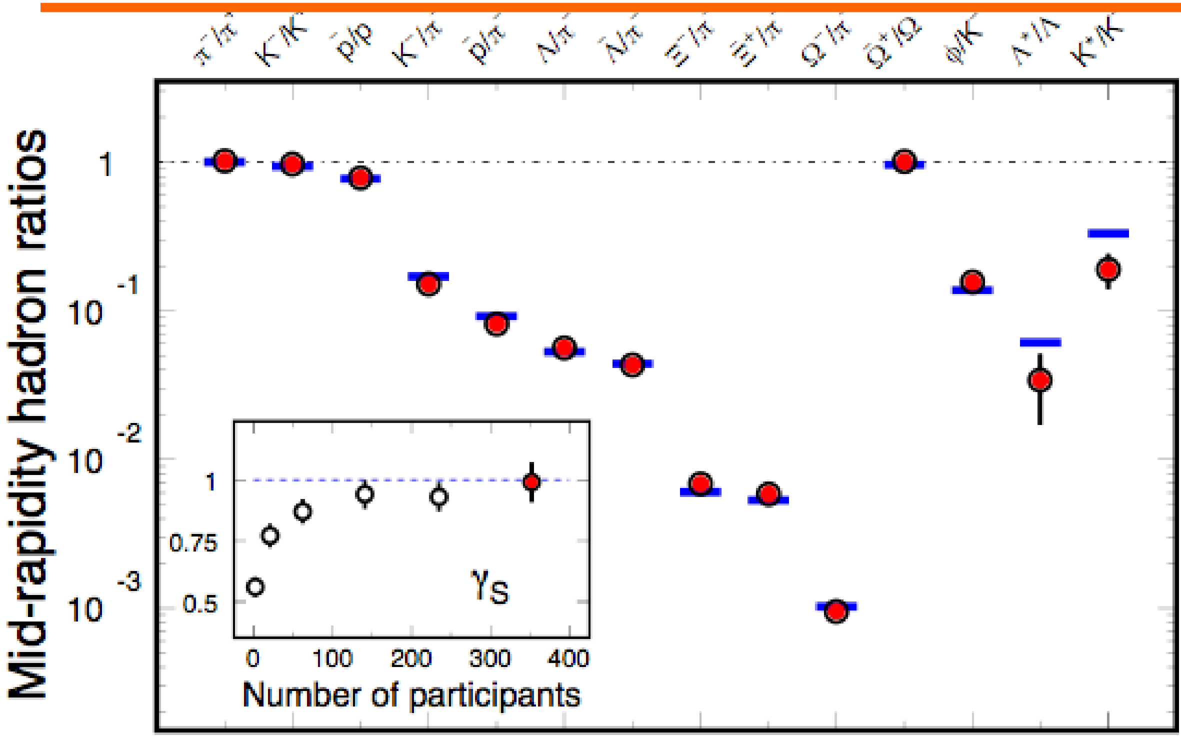
Statistical Model Fits

- **Assume thermally (constant T_{ch}) and chemically (constant n_i) equilibrated system at chemical freeze-out**
- System composed of non-interacting hadrons and resonances
- Given T_{ch} and μ_i 's (+ system size), n_i's can be calculated in a grand canonical ensemble

$$n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$

- T_{ch} and μ_i ***i=B,Q,S***
- Obey conservation laws: Baryon Number, Strangeness, Isospin
- Short-lived particles and resonances need to be taken into account

Yields Ratio Results: RHIC



200 GeV ^{197}Au + ^{197}Au central collision

1) Chemical fits well for all hadron ratios at RHIC:
   T_{ch} = 160 $\pm$ 10 MeV
   μ_B = 25 $\pm$ 5 MeV

Necessary for QGP!

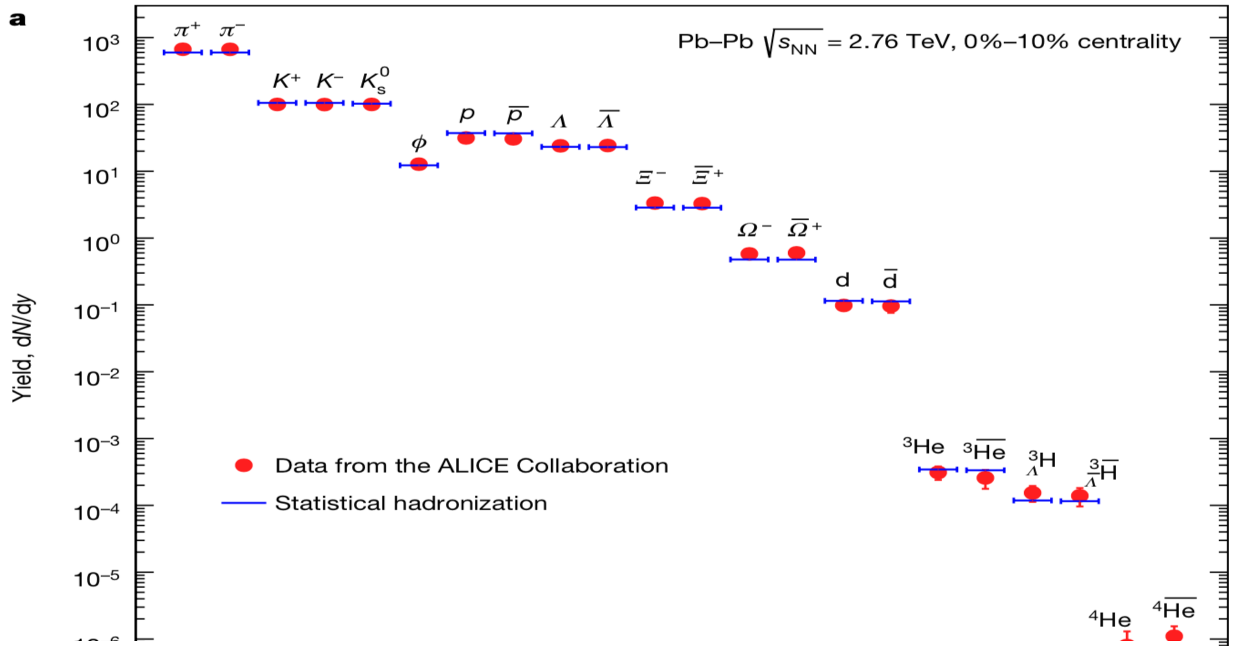
2) The temperature parameter T_{ch} is close to the critical temperature T_C predicted by LGT calculations ➔ chemical equilibrium at the phase boundary (?)

Review: P. Braun-Munzinger *et al.* nucl-th/0304013

- In central collisions, thermal model fit well with γ_S = 1.
  → **The system is thermalized at RHIC.**
- Short-lived resonances show deviations.
  → **There is life after chemical freeze-out.**

RHIC white papers - 2005, Nucl. Phys. A757, STAR: p102; PHENIX: p184.

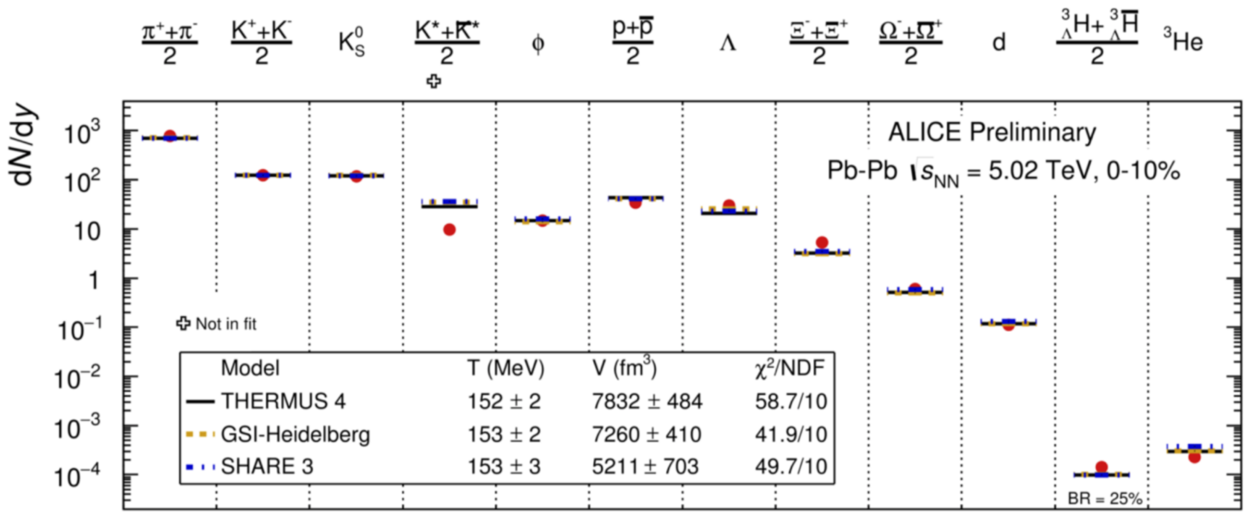
Hadron abundances and predictions of the statistical hadronization model: ALICE



Chemical fits well for all hadron ratios at 2.76 TeV:
T_{ch} = 156.5 ± 1.5 MeV
μ_B = 0.7 ± 3.8 MeV

LQCD pseudo-cretical T
Tc = 154 ± 9 MeV

A. Andronic, P. Braun Munzinger, K. Redlich, J. Stachel Nature 561(2018) 321



Chemical fits well for all hadron ratios at 5.02TeV:
T_{ch} = 152 ± 2 MeV

Fit at 5.02 TeV converges to slightly lower Tch than at 2.76 TeV (153 w.r.t to 156 MeV) due to proton yield

F. Bellini QM2018

Thermal Model Fits (Blast-Wave)

Source is assumed to be:

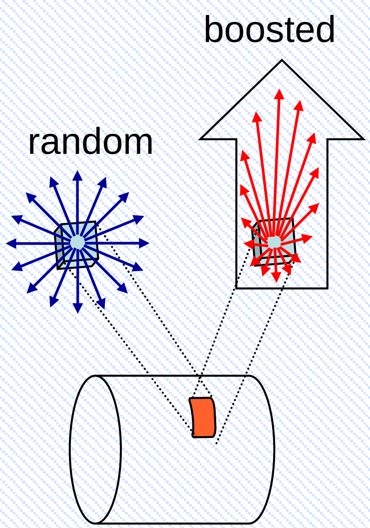
- Local thermal equilibrated
- Boosted radically

E.Schnedermann, J.Sollfrank, and U.Heinz, Phys. Rev. ***C48****, 2462(1993)*

$$E\frac{d^3N}{dp^3} \propto \int_\sigma e^{-(u^\mu p_\mu)/T_{fo}} p d\sigma_\mu \Rightarrow$$

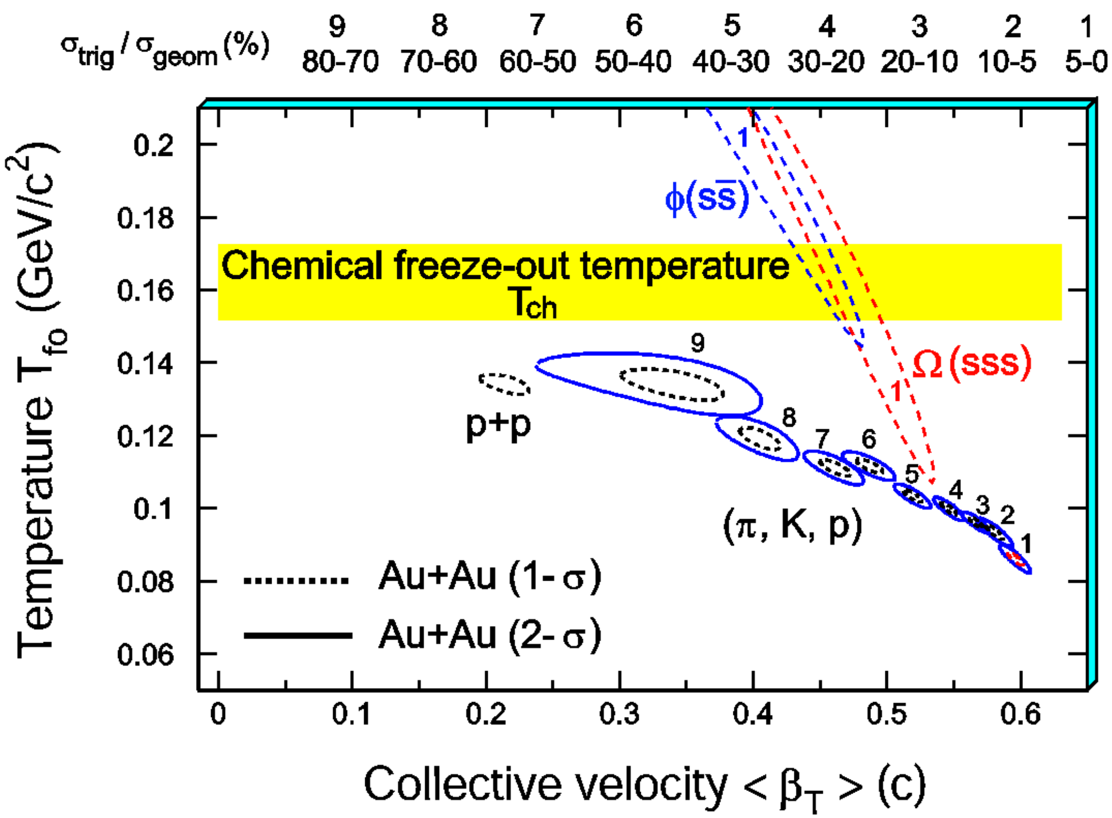
$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr m_T K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right) I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right)$$

$$\rho = \tanh^{-1}\beta_r \qquad \beta_r = \beta_S\left(\frac{r}{R}\right)^\alpha \qquad \alpha = 0.5, 1, 2$$



Extract thermal temperature T_{fo} and velocity parameter $\langle\beta_T\rangle$

Thermal fits: T_{fo} vs. < β_T > at 200GeV



1) π, K, and p change smoothly from peripheral to central collisions.

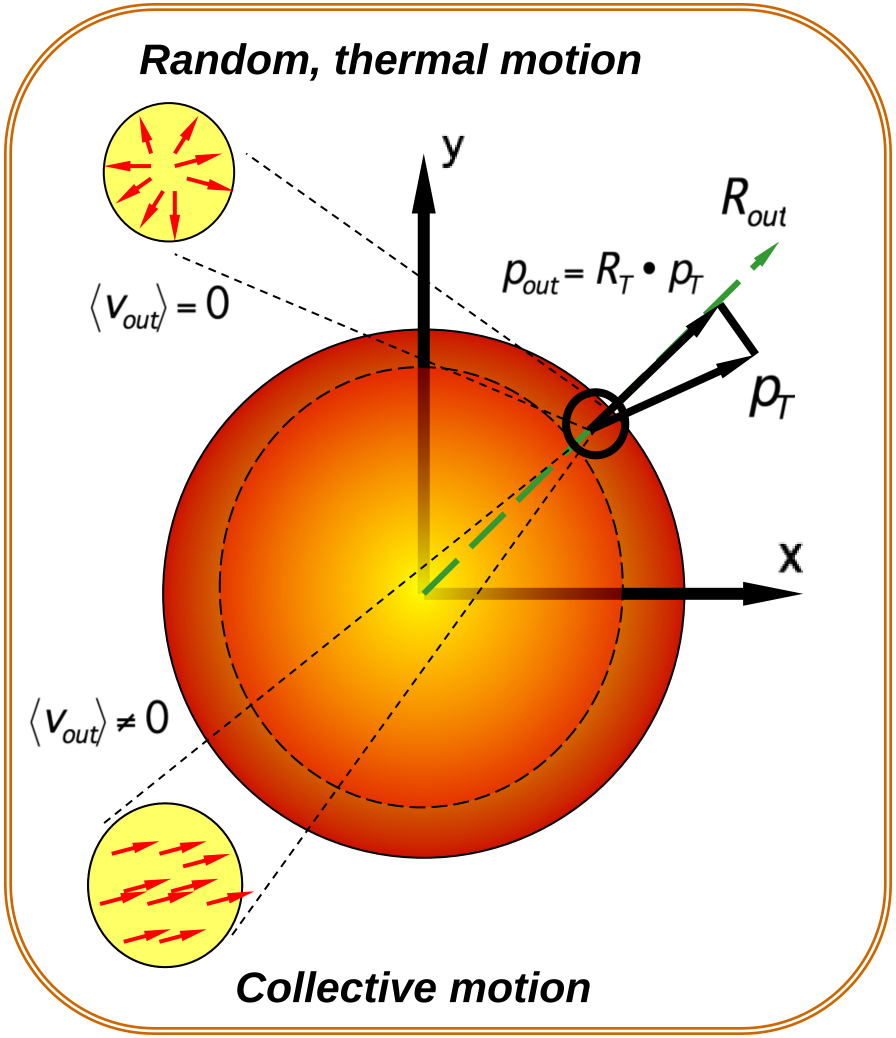
2) At the most central collisions, <β_T> reaches 0.6c.

3) Multi-strange particles ϕ, Ω are found at higher T_{fo} ($T \sim T_{ch}$) and lower <β_T>

- **Sensitive to early partonic stage!**
- **How about v_2?**

- STAR:NPA757,102(05) , (F. Wang) NPA715, 466c (03) ;
- P. Braun-Munzinger, J. Stachel, J. Wessels, N. Xu, Phys. Lett. B 344 (1995) 43;
- P. Braun-Munzinger, I. Heppe, J. Stachel, Phys. Lett. B 465 (1999) 15.

Pressure, Flow, …



Matter flows – all hadrons have the similar collective velocity

Random Thermal ⊕ ***Collective***

$$\langle p_T \rangle \propto \langle p_T \rangle_{thermal} + mass \langle v_T \rangle$$

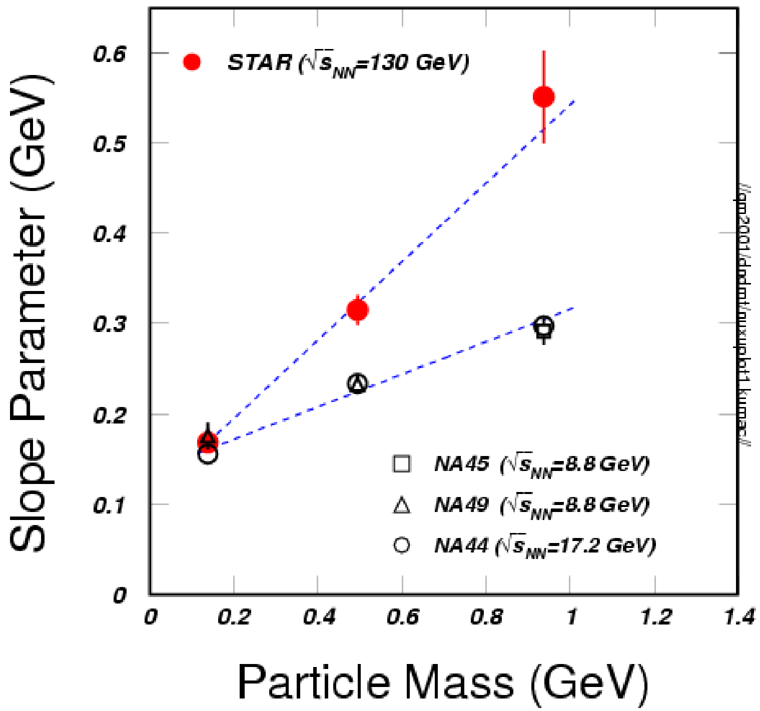
$$T \propto T_{thermal} + mass \langle v_T \rangle^2$$

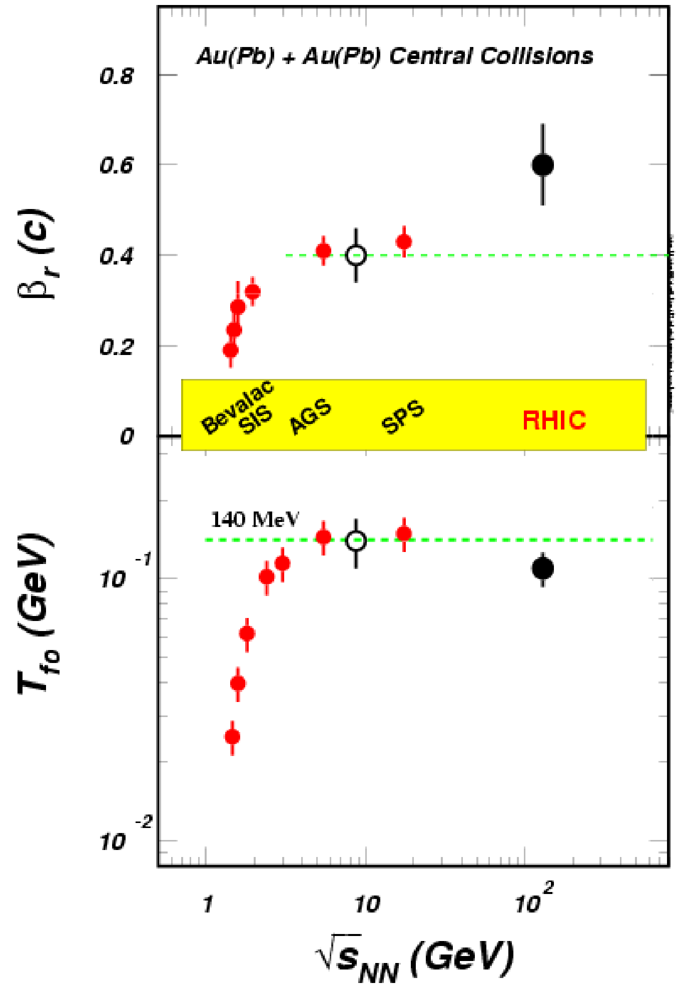
$$\langle p_T \rangle_{thermal} \propto \sqrt{mass\ T_{thermal}}$$

*I.Bearden et al, Phys. Rev. Lett. **78**, 2080(1997).*

Mass Dependence of Slopes

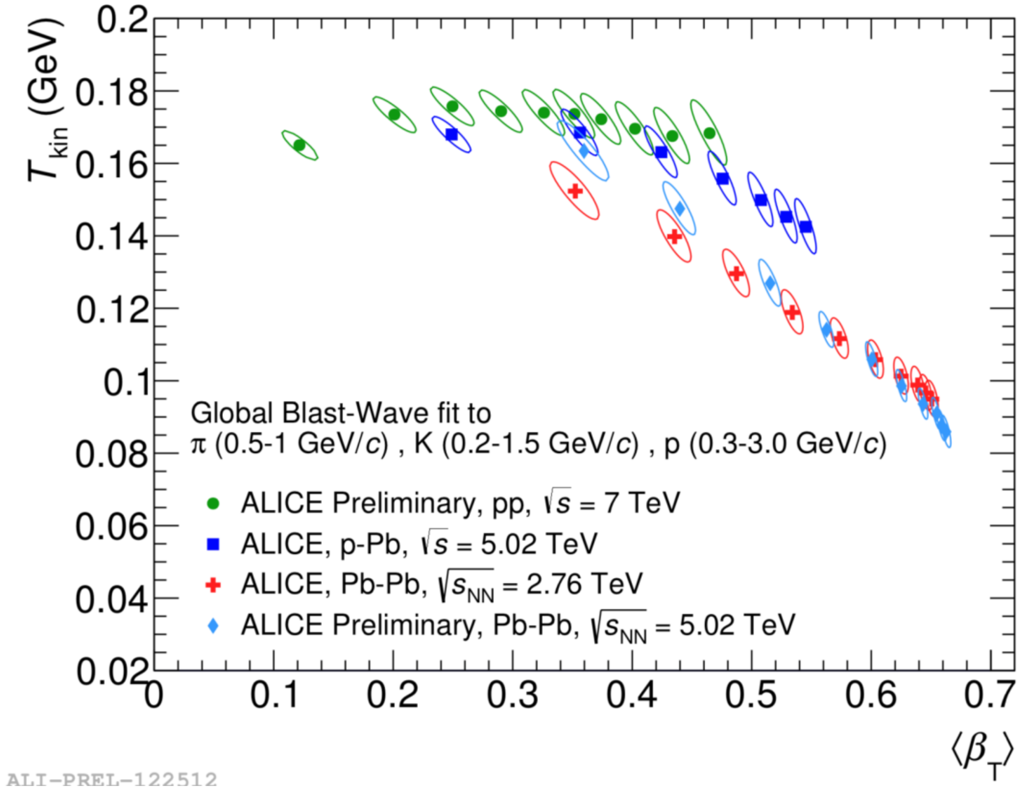
$$T = T_{fo} + mass * \beta_r^2$$





Explosive expansion at RHIC!

Blast Wave Fits: LHC

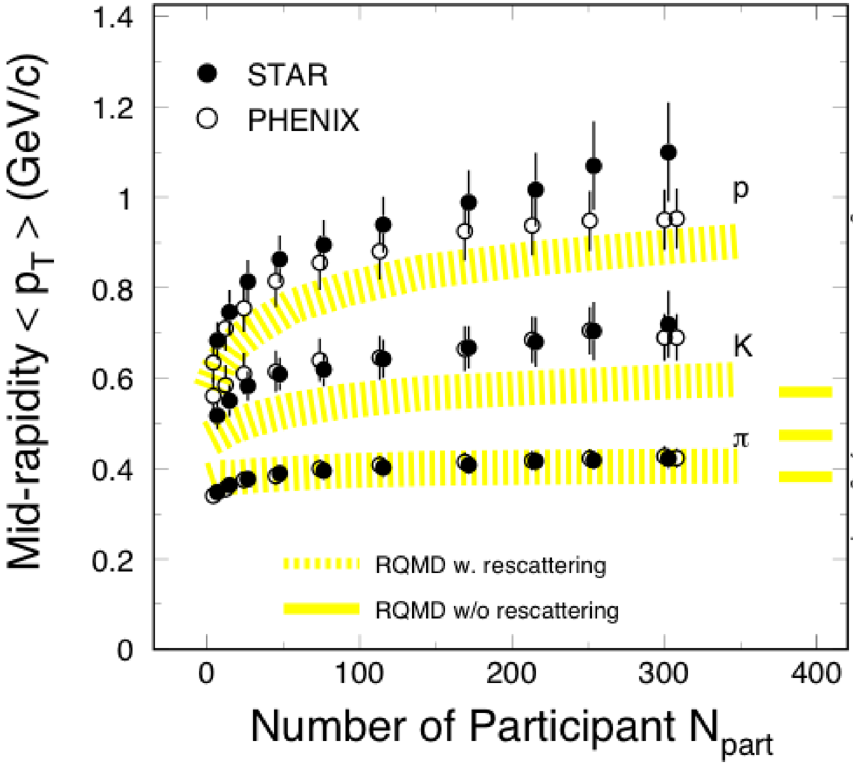


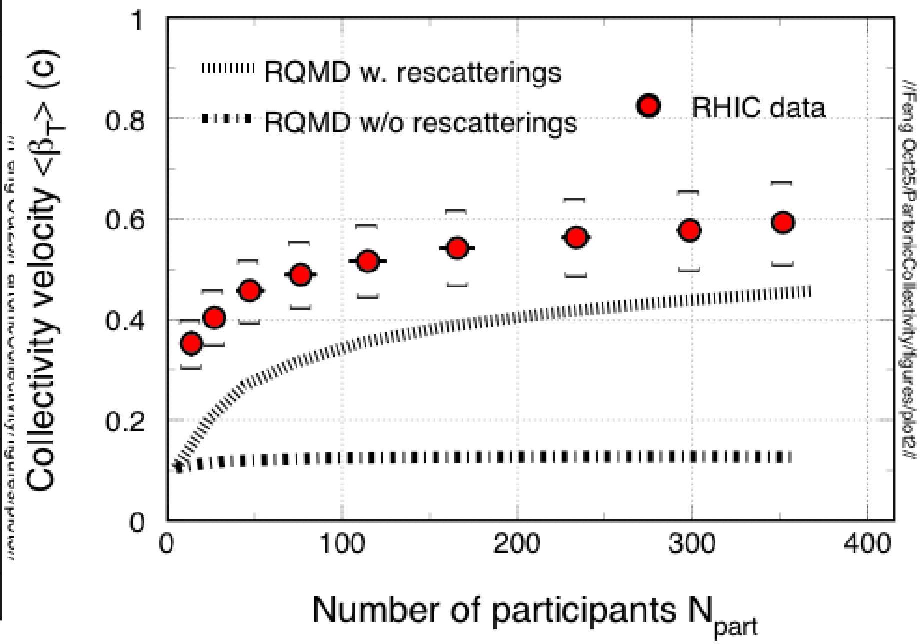
N. Jacazio
ALICE QM2017

Kinetic Freeze-out at LHC similar to that from RHIC. Collective velocity parameter ***β*** is stronger in the most central collisions => Stronger collective expansion at LHC!

ALICE: B. Abelev et al, Phys. Rev. Lett. **109**, (12) 252301; Phys. Rev. **C88**, (13) 044910

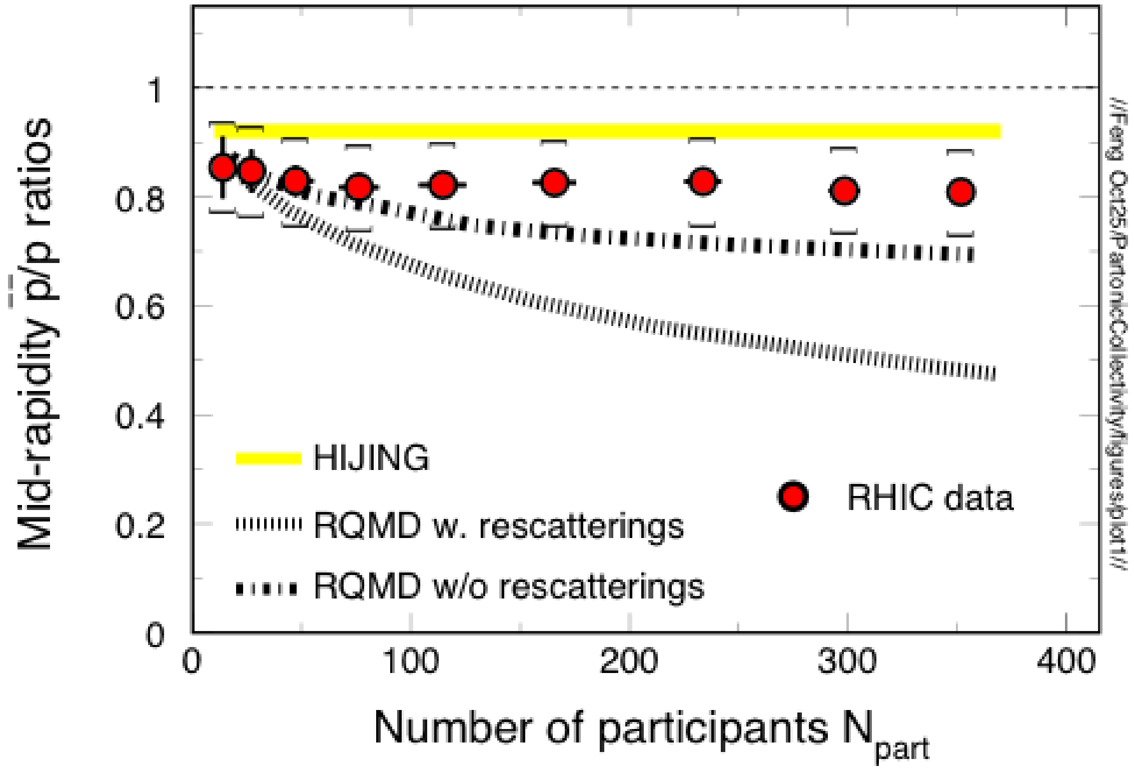
Tests with Transport Model





(1) The <pt> increases vs. centrality $\Rightarrow$ collective expansion
(2) Hadronic transport model RQMD calculations reproduced the collectivity for copiously produced hadrons π, K, p.
(3) Re-scatterings are import for collectivity !

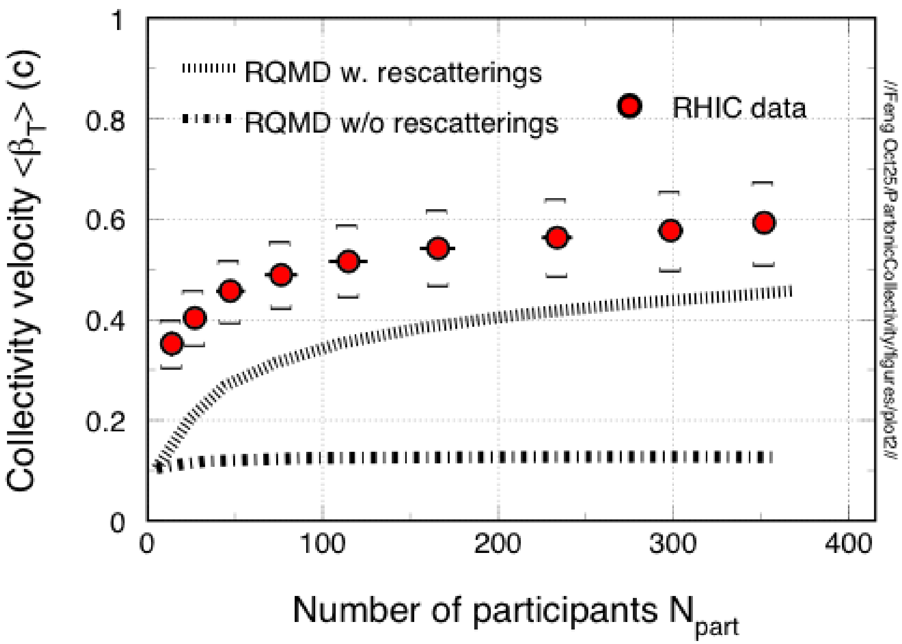
Tests with Transport Model

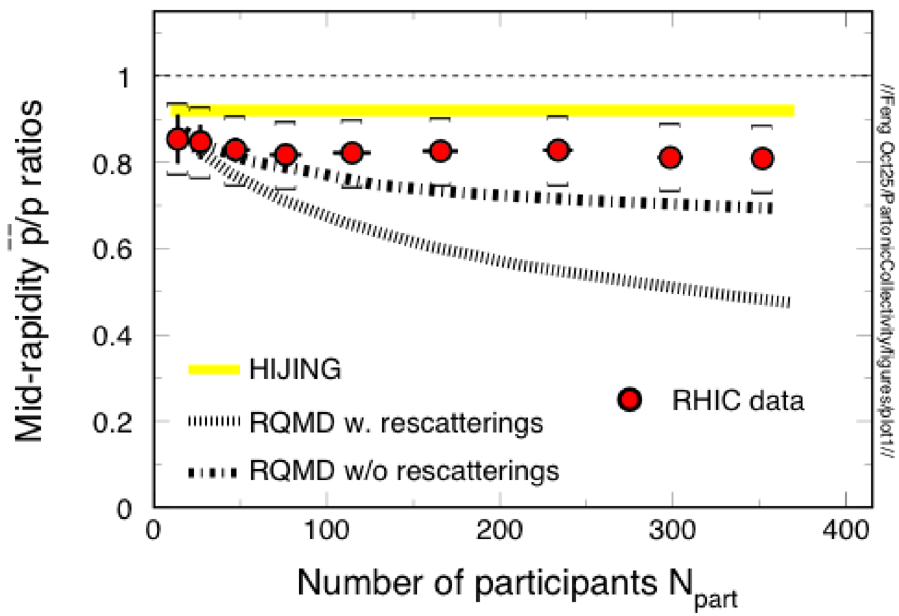


(1) Hadronic transport model RQMD can not reproduced the anti-proton over proton ratios as a function of centrality.

(2) RQMD underestimates pbar yield due to large annihilation X-section

Tests with Transport Model





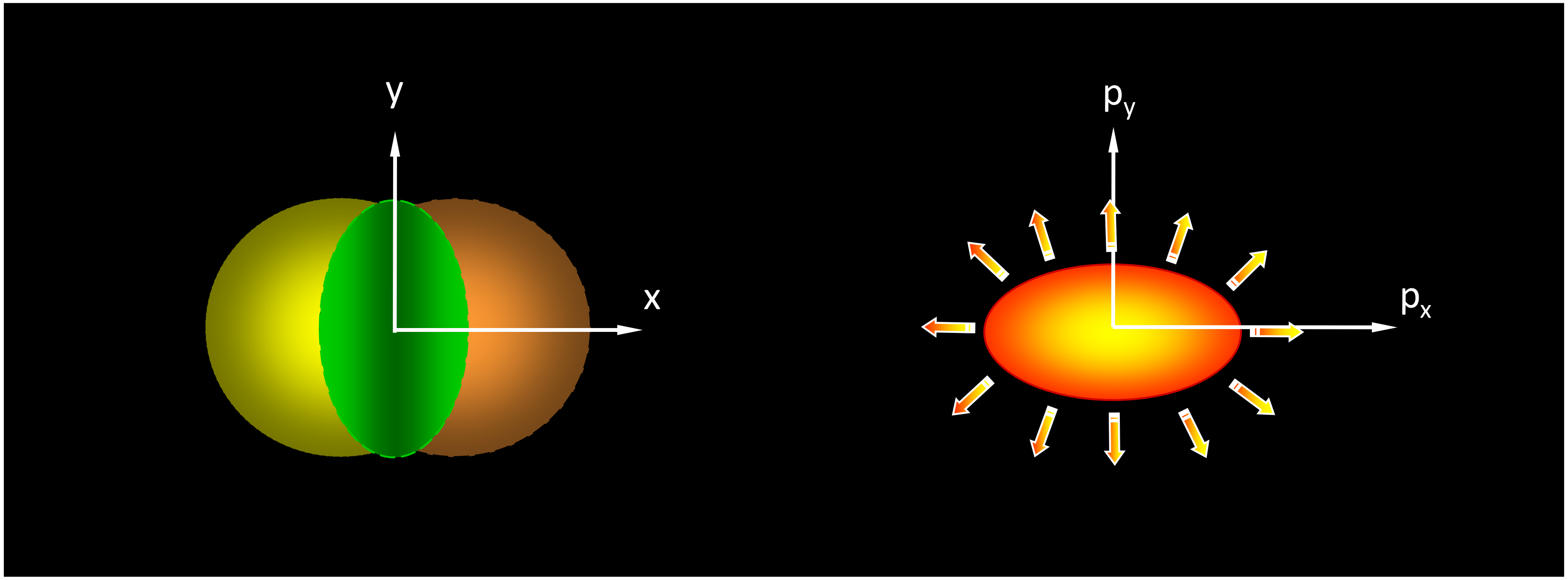
Re-scatterings are import for collectivity !

RQMD underestimates pbar yield due to large annihilation X-section

⇒ re-scattering at earlier pre-hadronic stage?

Anisotropy parameter v_2

Sensitive to initial/final conditions and equation of state (EOS) !
coordinate-space-anisotropy ⇔ momentum-space-anisotropy

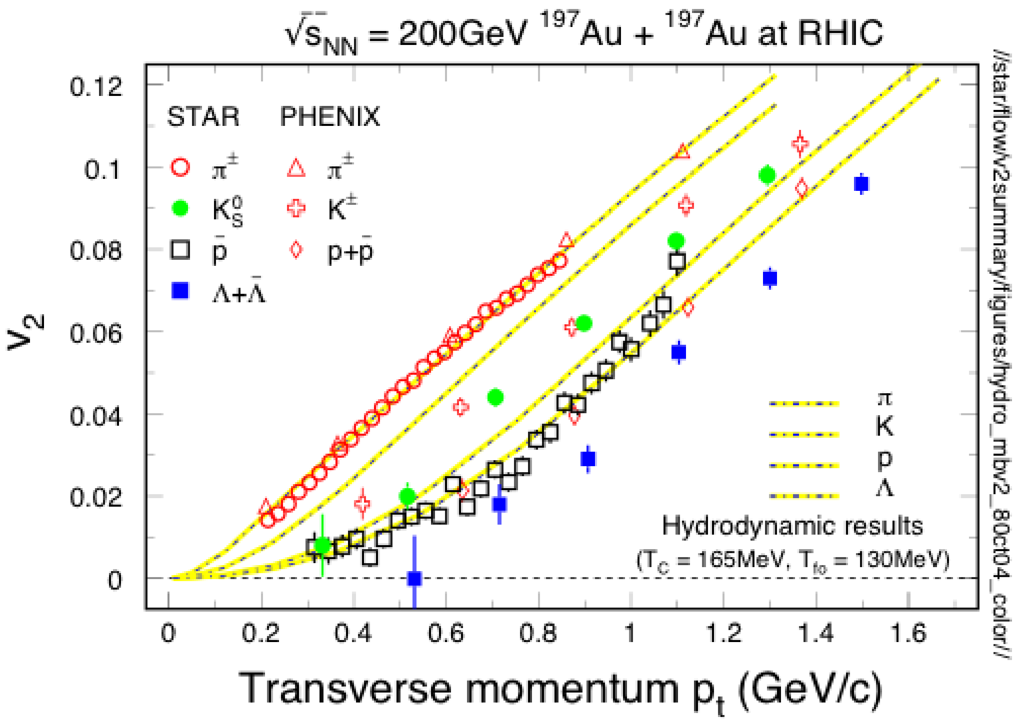


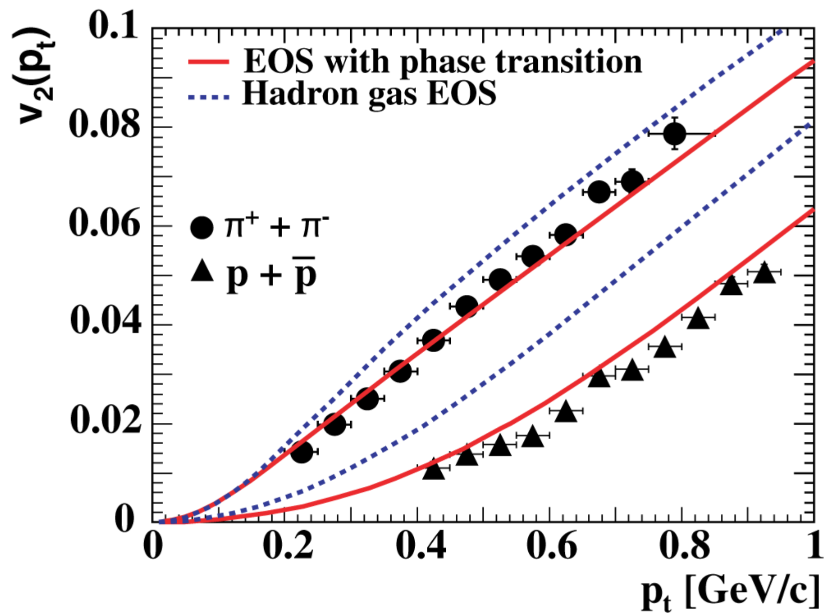
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

v_2 : a probe of the dynamics governing the system' s evolution

Flow : represents the collective motion of particles.

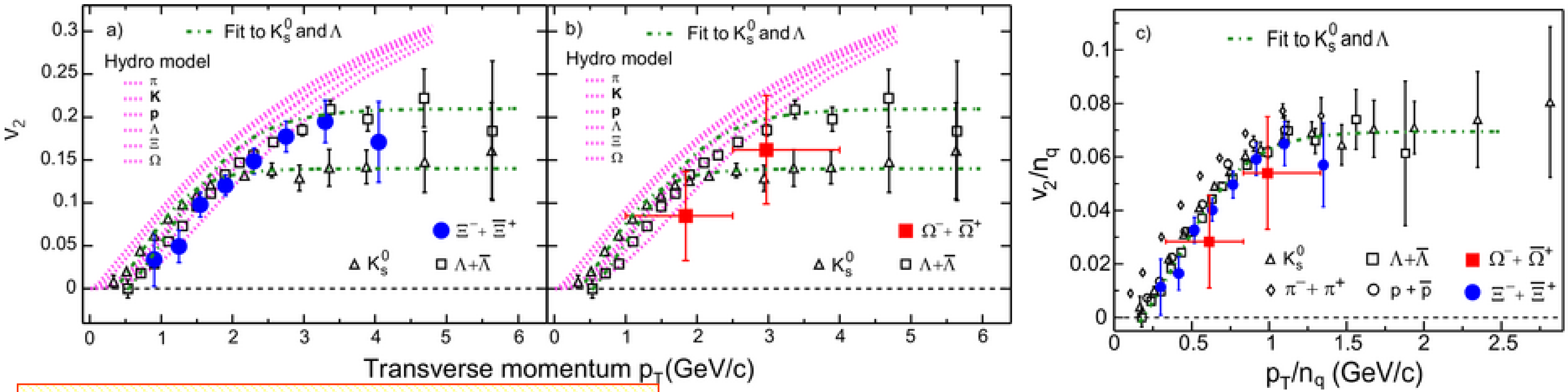
v_2 at Low p_T Region：Mass dependence





- pions to Cascade follow the mass dependence at low-p_t
- Ideal hydro provides a reasonable description (common velocity and common freeze-out!)

NQ Scaling for Identified Particles



For hadron formation by coalescence of co-moving partons

$$v_2^{meson}(p_T) \approx 2 \cdot v_2^{quark}(p_T/2)$$

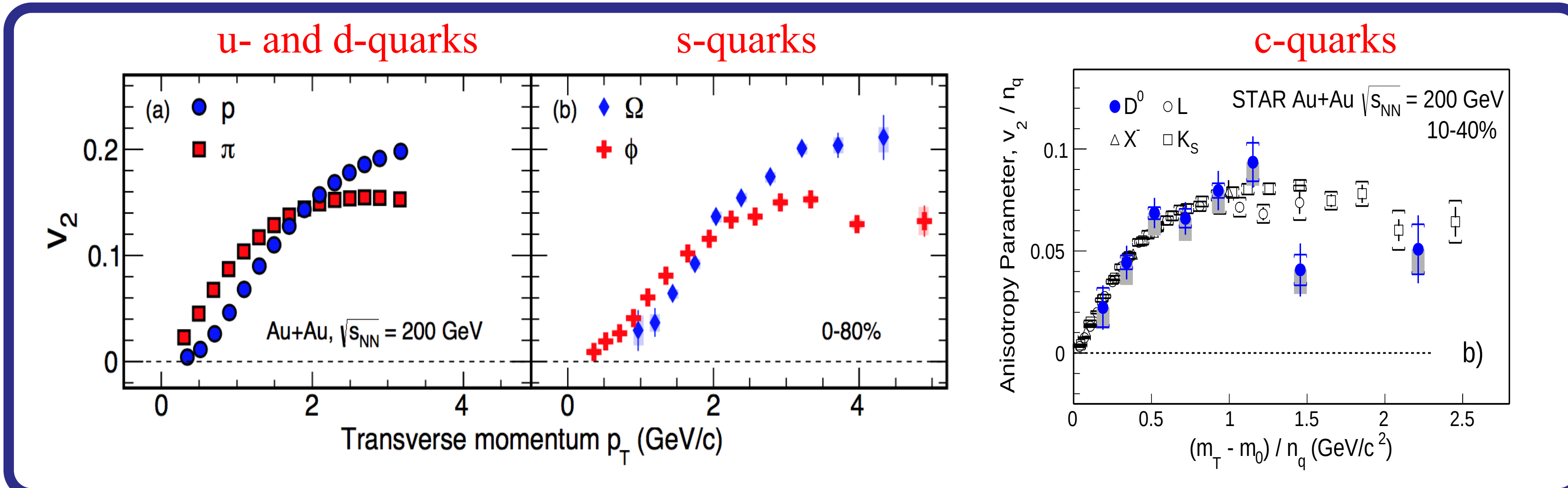
$$v_2^{baryon}(p_T) \approx 3 \cdot v_2^{quark}(p_T/3)$$

STAR： Nucl. Phys. A 757, 102, (2005); PRL 92,052302 (2004) ;
J. Phys. G 30, S1207, (2004); PHENIX: PRL 91,182301, (2003) .
Fit: X. Dong, S. Esumi, P. Sorensen, N. Xu, Z. Xu, PLB 597, 328 (2004)
.

- Minimum bias data!
- At intermediate p_T, v_2 scales with the number of quarks.
- Coalescence/Reco models can account for NQ scaling.

Partonic collectivity, de-confinement at RHIC.

Partonic Collectivity at RHIC



Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering

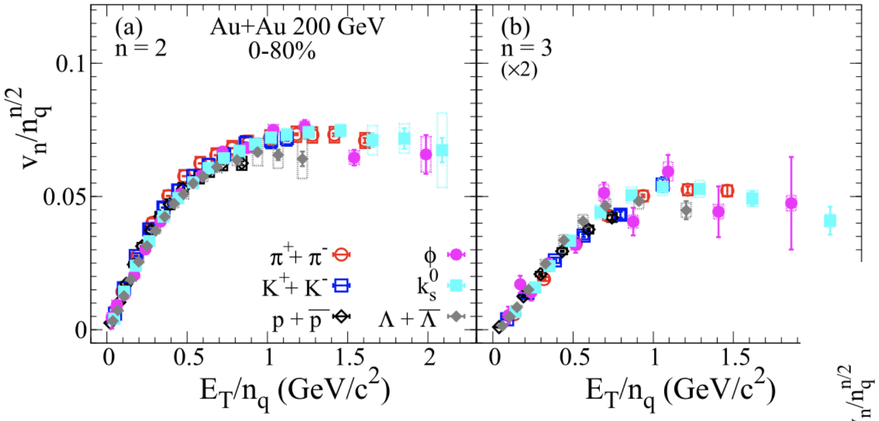
High p_T (> 2 GeV/c): ***number of quarks scaling***

含有 *u, d, s, c*-夸克的强子中都表现出很强的集体运动，这表明夸克-胶子等离子体 (QGP) 热化核物质在高能核-核碰撞中的产生;

➔ ***Partonic Collectivity, necessary for QGP!***

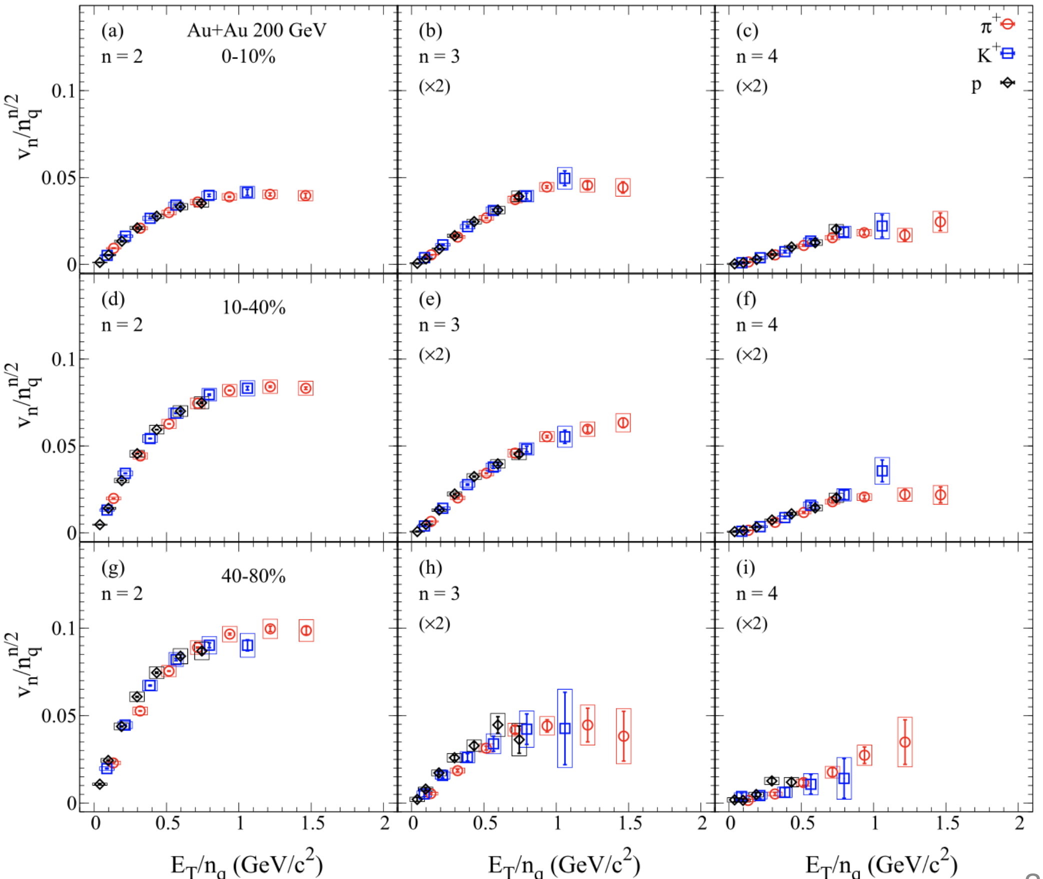
➔ ***De-confinement in Au+Au collisions at RHIC!***

Higher-order Flow in 200 GeV



RHIC top energy

STAR: Phys. Rev. C.105, 064911 (2022)



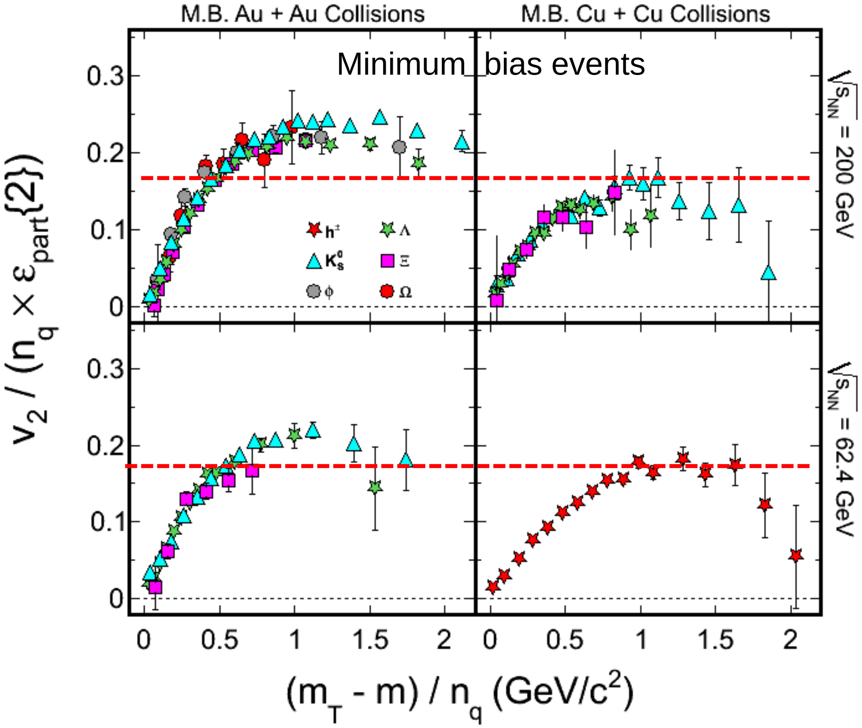
- Light flavor, strange particles and φ mesons
- Follow the NCQ scaling up to v_4

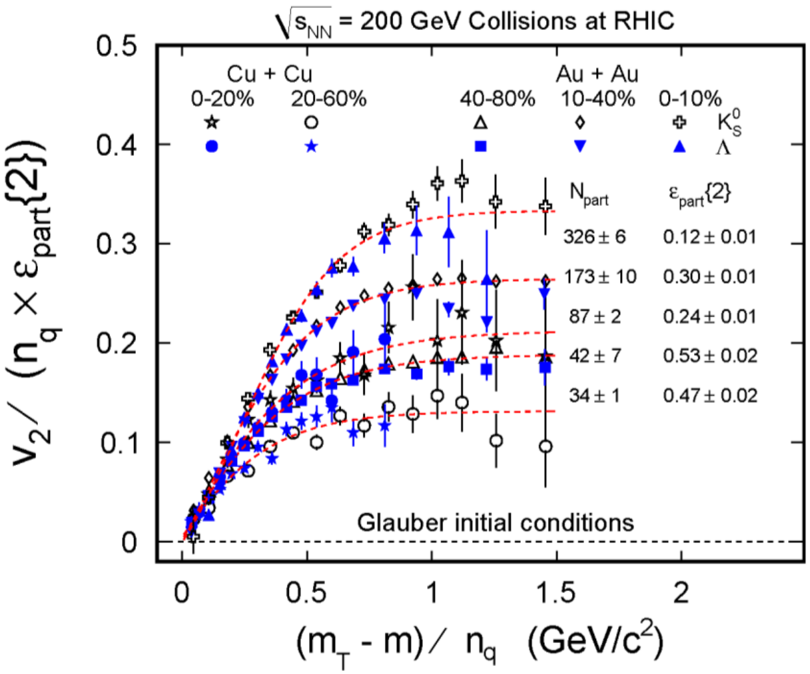
Partonic collectivity

System 、 Energy and Centrality Dependence

•STAR Au + Au 62.4 GeV : PRC75, 054906 (2007), PRC81, 044902 (2010),

•$\varepsilon_{part}\{2\}$: J. Y. Ollitrault, A. M. Poskanzer and S. A. Voloshin, PRC80, 014904 (2009)





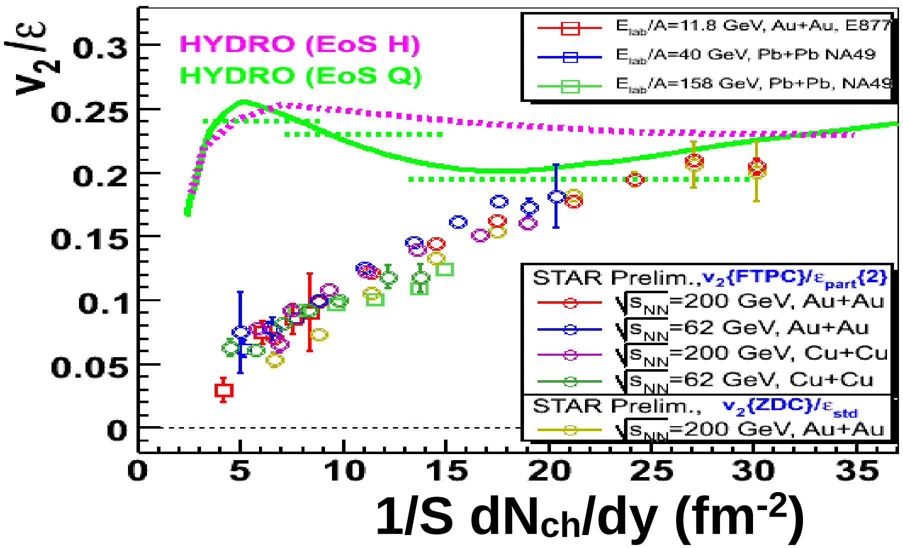
Au+Au and Cu+Cu at 200 GeV **Scaled by eccentricity** remove the initial geometry

- ➢NQ scaling for each centrality bin

➢Collective flow: depends on the number of participants

- ➢Larger v_2/ε_{part} indicates stronger collective flow in more central collisions.

Perfect Liquid at RHIC

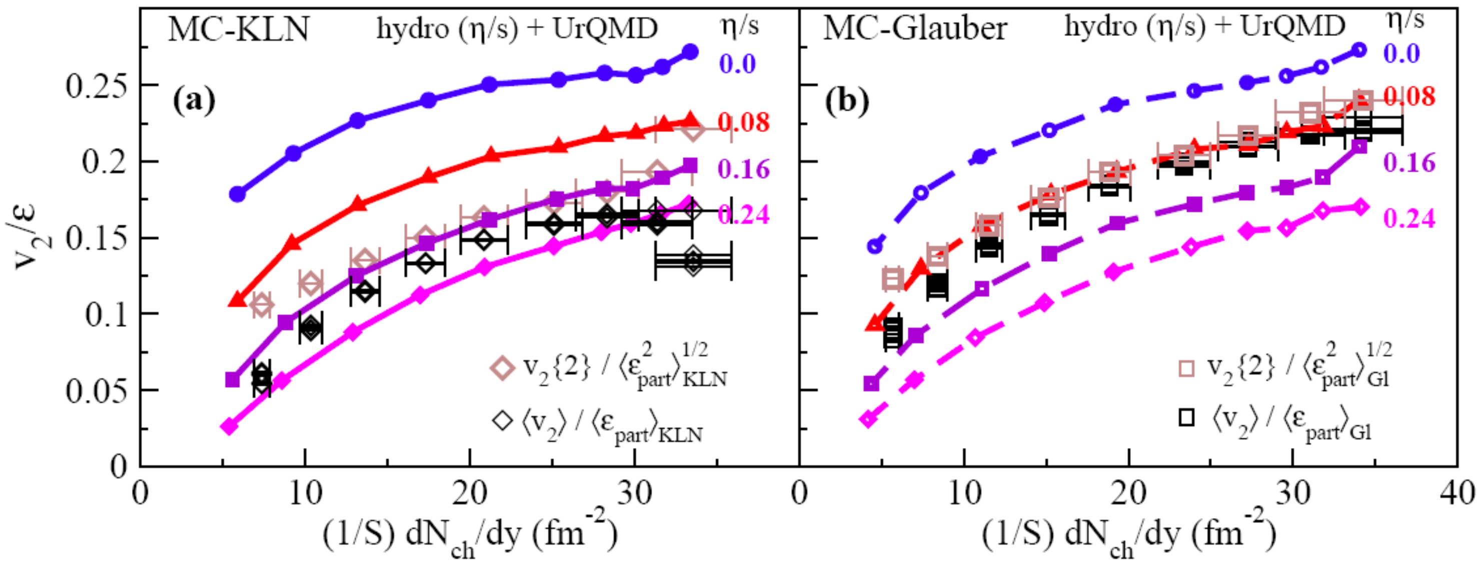


v_2/ε approaches the limit of ideal hydrodynamics

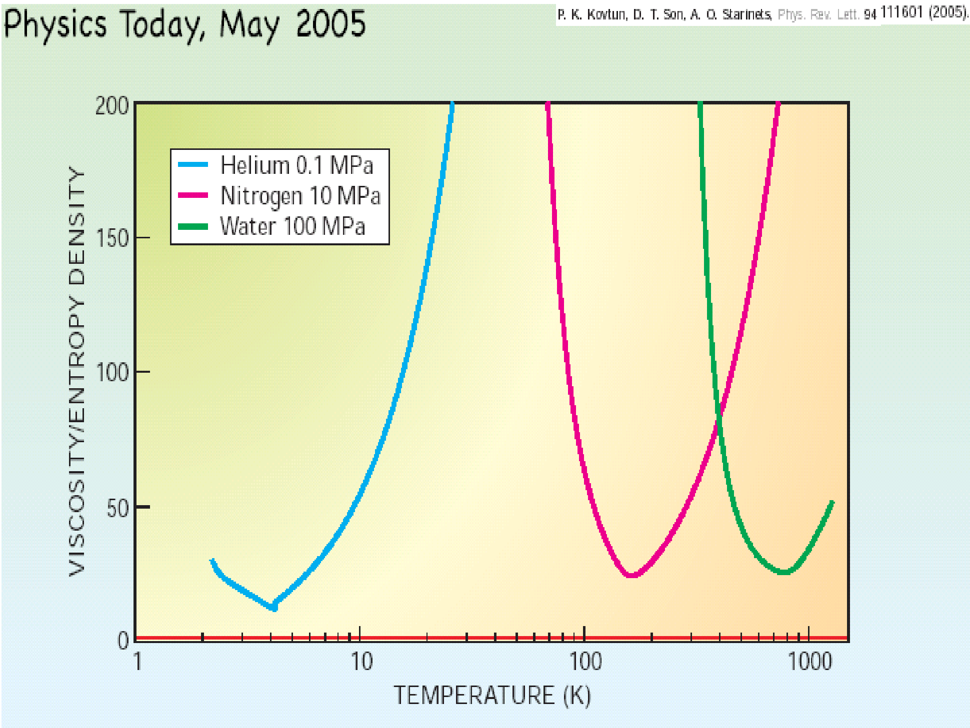
Small value of specific viscosity over entropy ***η/s***

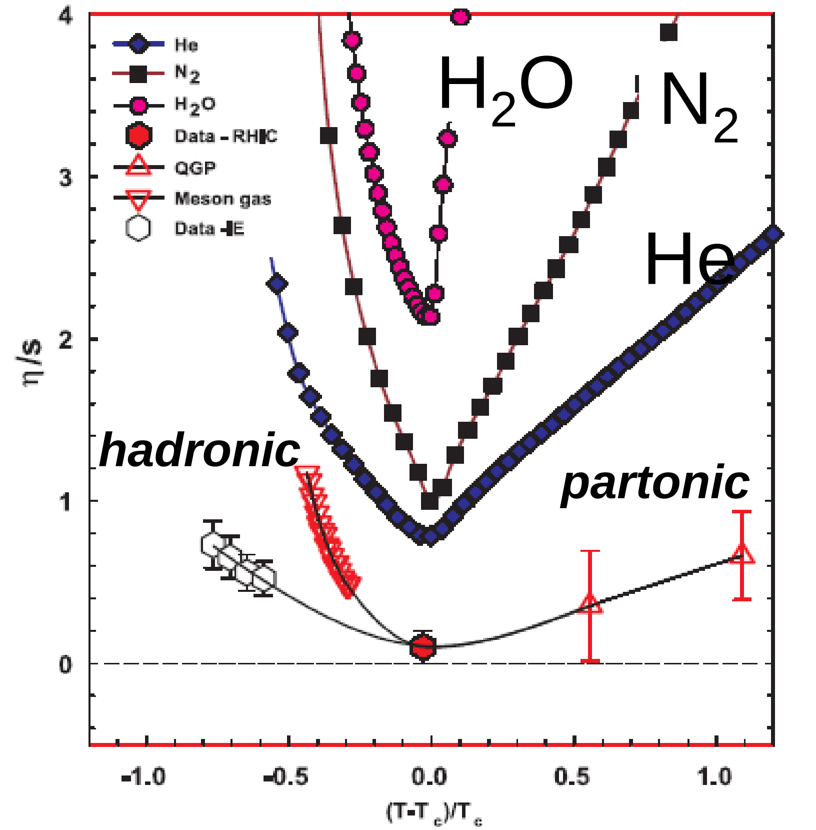
Model uncertainty dominated by initial eccentricity ε

Model: Song *et al. arXiv:1011.2783*



Viscosity and the Perfect Fluid





1) ***η/s ≥ 1/4π***

Caption: The viscosity to entropy ratio versus a reduced temperature.

2) ***η/s***(QCD matter) < ***η/s***(QED matter)

Lacey et al. PRL **98**:092301(07)
hep-lat/0406009
hep-ph/0604138

Summary and outlook

(1) Parton energy loss - ***QCD*** at work

High density matter has been created

(2) Collectivity -

Hydrodynamic Description of Bulk Particle Properties – v_2 and Spectra Shape – Successful.

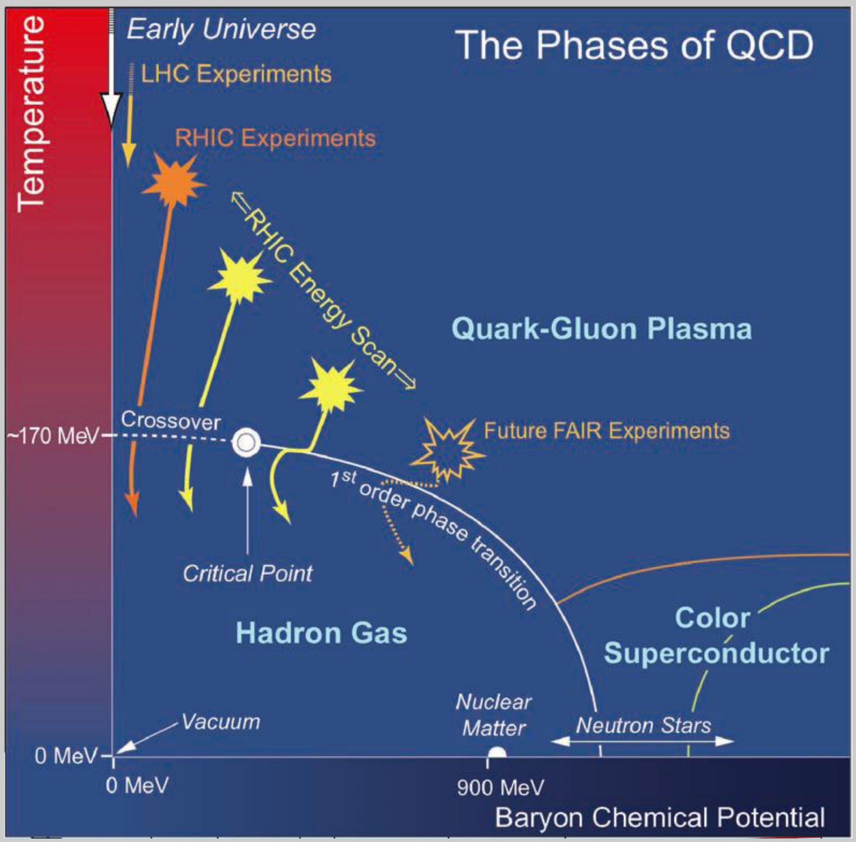
Constituent Quark scaling work for v_2 and R_{AA} (R_{CP})

3) The matter behavior like a ***quantum liquid*** with small ***η/s***

Perfect Liquid (sQGP) has been found at RHIC

Search for QCD cretical point and phase boundary

QCD相结构的研究



Study QCD Phase Structure

- Signals for onset of sQGP
- Signals for phase boundary
- Signals for critical point

2000 – 2012: RHIC、LHC
（1）椭圆流组分夸克的标度性
（2）大横动量粒子的能量损失

强耦合夸克胶子等离子体(sQGP)产生，其物理性质类似于粘滞系数与熵密度之比接近于零的理想液体。

在μ_B=0附近的相变是平滑过渡

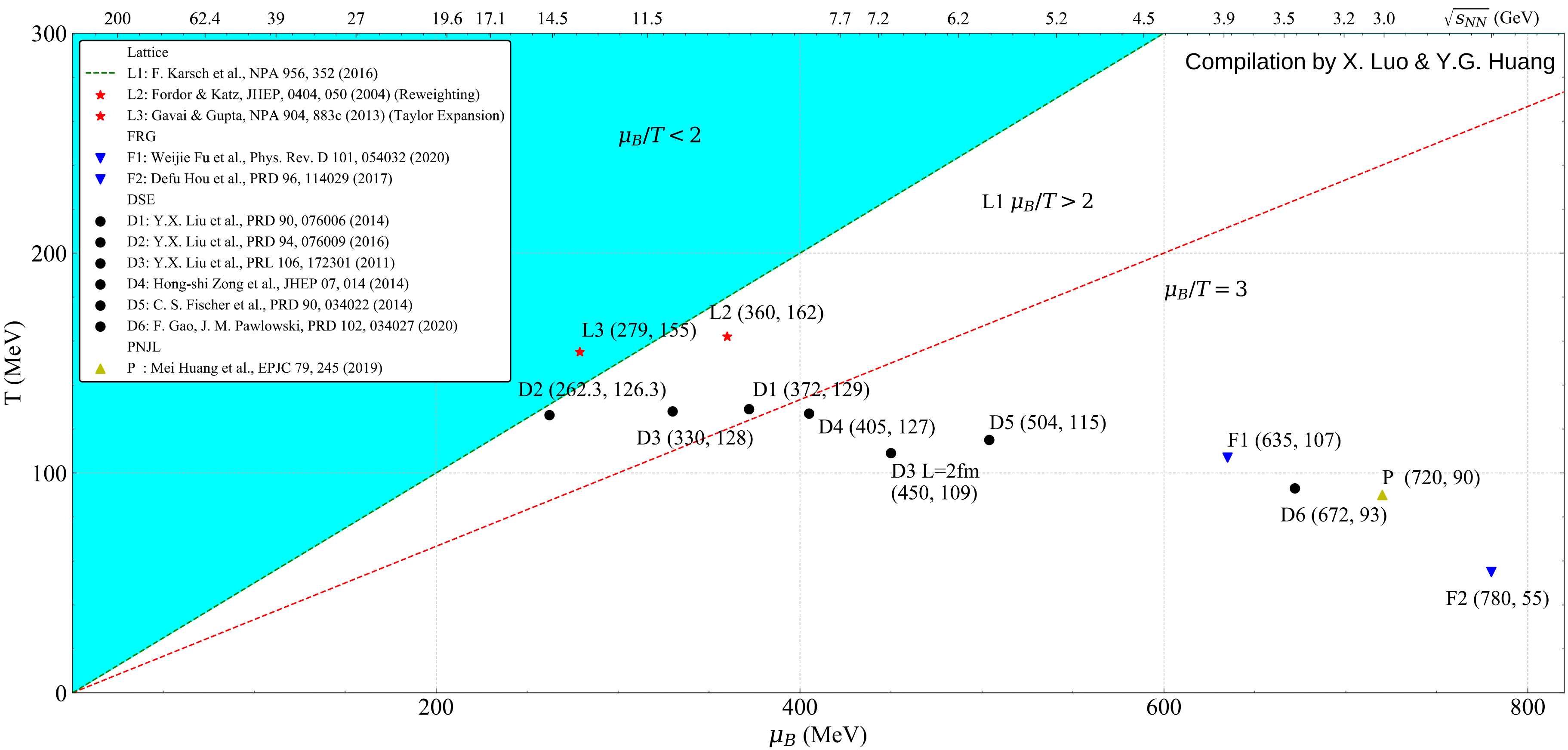
重离子碰撞的研究任务：

1）寻找QCD临界点和相边界
2）研究极端条件下sQGP的性质
3） 研究高能重离子碰撞中的新现象

QCD临界点的寻找和状态方程的研究已成为国际研究的一个热点

临界点位置：理论模型计算

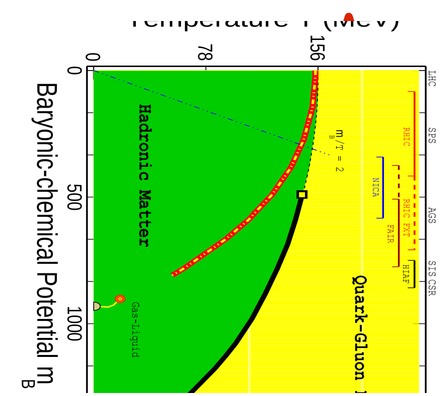
Preliminary collection from Lattice, DSE, FRG and PNJL (2004-2020)

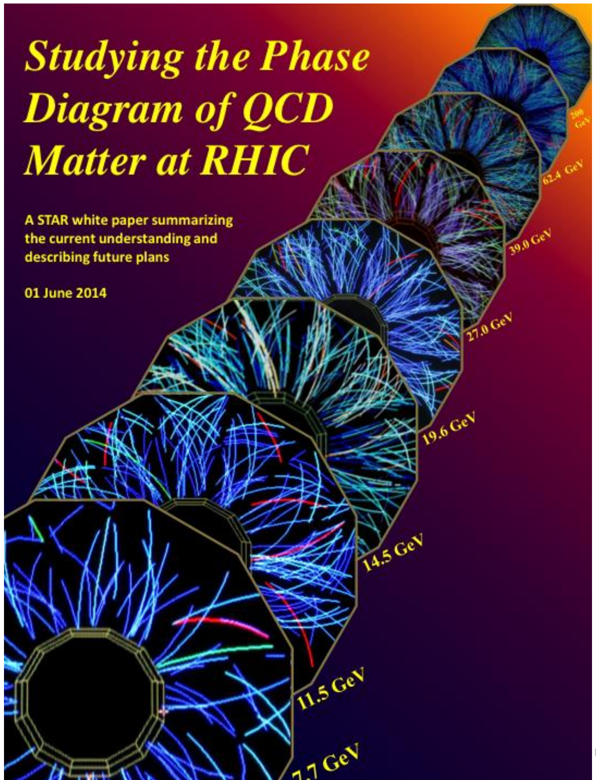


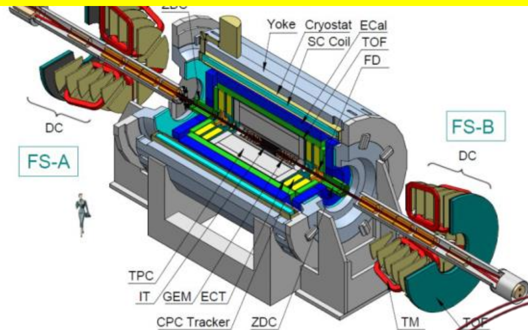
理论上确定QCD相变临界点的位置有较大的不确定性。

寻找QCD临界点

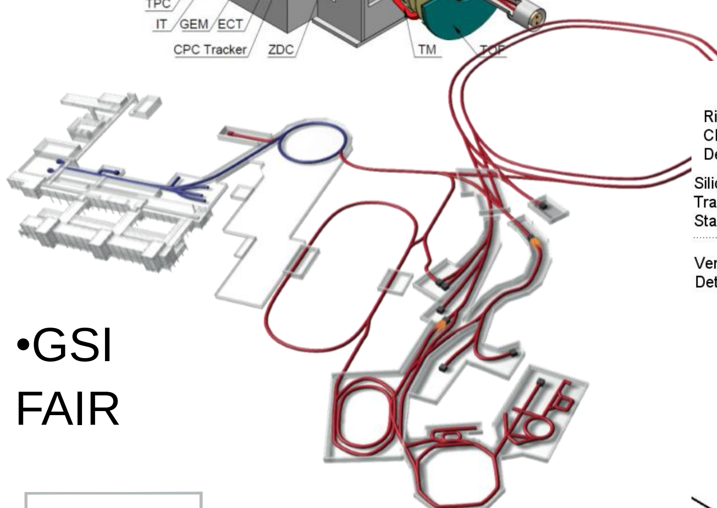
- — 美国RHIC: 2019－2021年能量扫描 < 20GeV
- — 德国FAIR: 计划2025年开始新加速器 < 10GeV





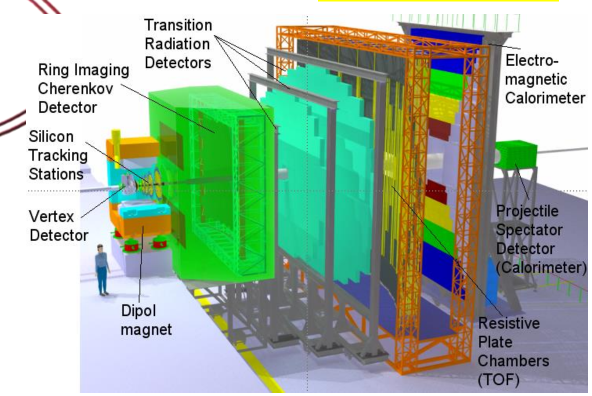


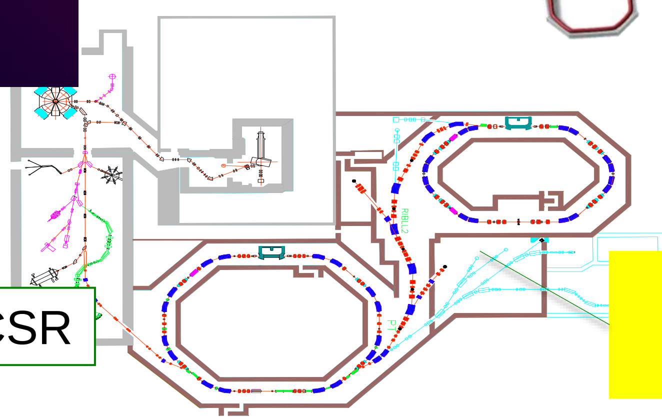
•NICA 科技部国际专项



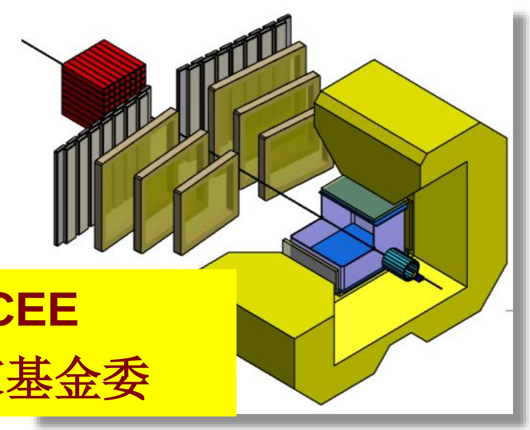
•GSI
FAIR

CBM 973





•HIRFL-CSR



•CEE
•国家基金委

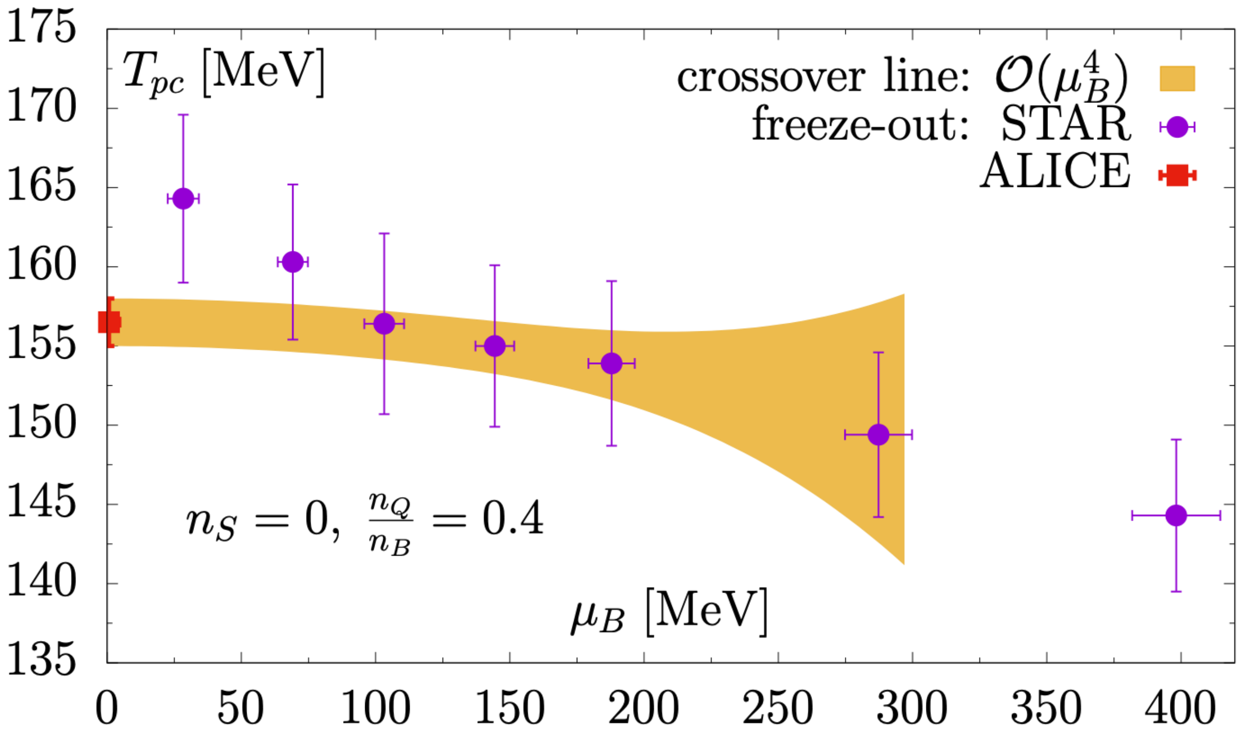
Thanks !

From SPS, RHIC to the LHC

	SPS	RHIC	LHC	
$\sqrt{s_{NN}}$ (GeV)	17	200	5500	
dN/dy	500	850	1500-4000	
τ^0_{QGP} (fm/c)	1	0.2	0.1	
T/T_c	1.1	1.9	3-4	Hotter
ε (GeV/fm^3)	3	5	15-60	Denser
τ_{QGP} (fm/c)	≤2	2-4	≥6	Longer
τ_f (fm/c)	~10	20-30	30-40	
V_f(fm^3)	few 10^3	few 10^4	Few 10^5	Bigger

QCD meets Experiment

Chiral crossover line: $$T_{pc}(\mu_B) = T_{pc}(0)\left(1 - \kappa_2\left(\frac{\mu_B}{T}\right)^2 - \kappa_4\left(\frac{\mu_B}{T}\right)^4\right)$$



ALICE data point:

$T_f = 156.5(1.5)$ MeV

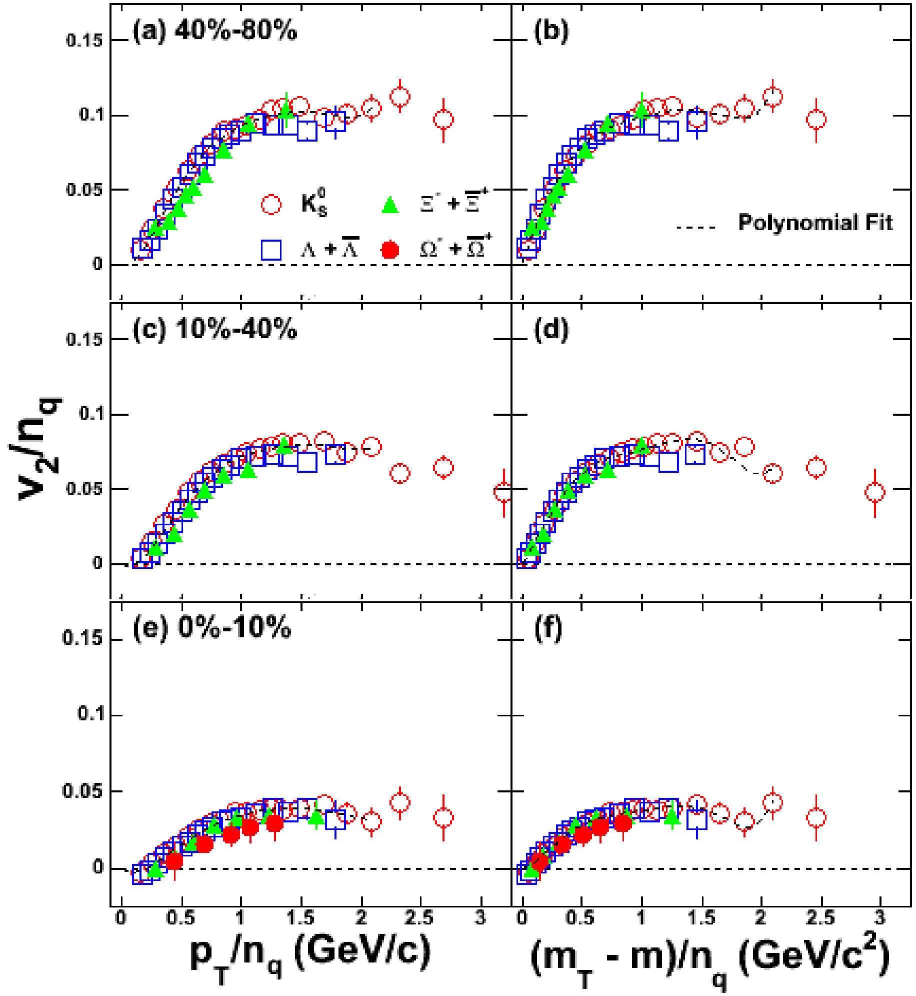
Andronic et al,
Nature 561 (7723) (2018) 321

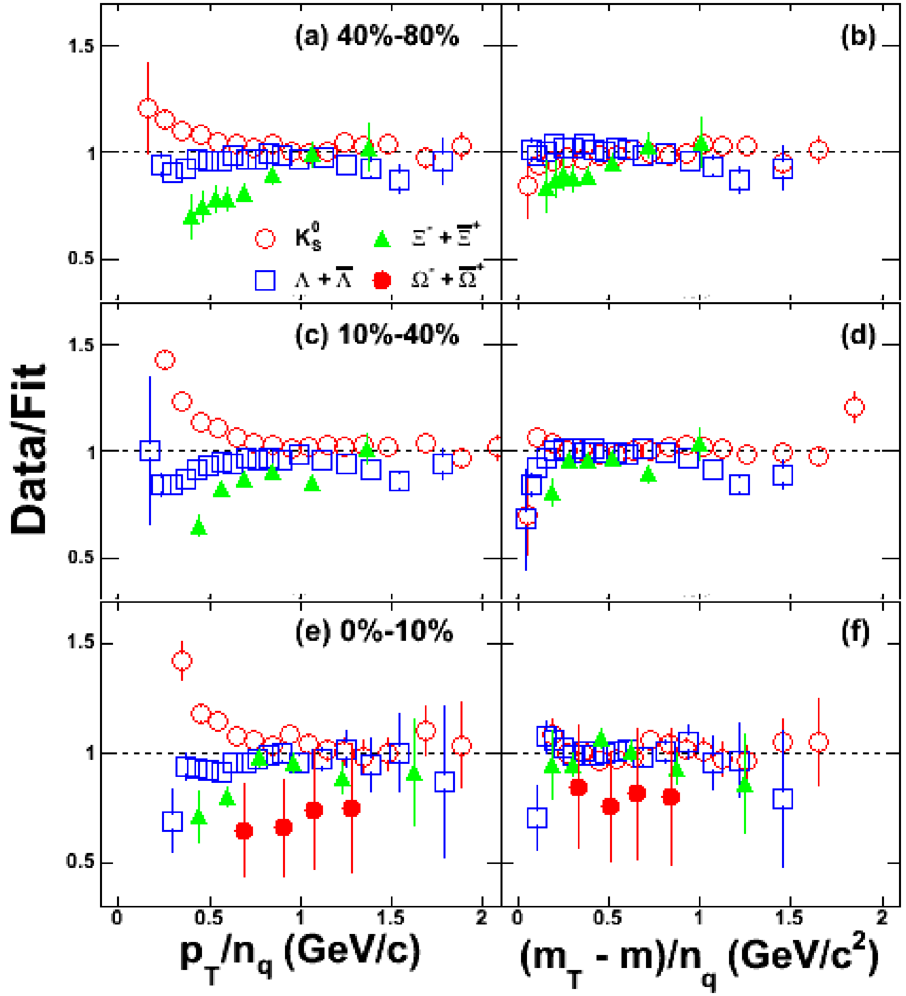
STAR data points:

Adamczyk et al.,
Phys. Rev. C 96 (4) (2017) 044904

A. Bazavov, H.T. Ding, P. Hegde et al. [HotQCD], Phys. Lett. B795 (2019) 15
Consistent results from Wuppertal-Budapest, PRL125 (2020) 052001

Centrality Dependence of NQ Scaling





➢ m_T -n_q scaling is observed at all centrality bins.

强子谱的统计描述

描述强子谱的 Rolf Hagedorn (CERN) 的强相互作用理论

R Hagedorn: Statistical thermodynamics of strong interactions at high energies 1965 Nuovo Cim. Suppl. 3 147

Thermodynamics fire-ball , statistical-thermodynamical

$$N(T) \sim \int_0^{\infty} \rho(m)\, e^{-\frac{m}{T}} \mathrm{d}m$$

$\rho(m)\,\mathrm{d}m$ be the hadronic mass spectrum,

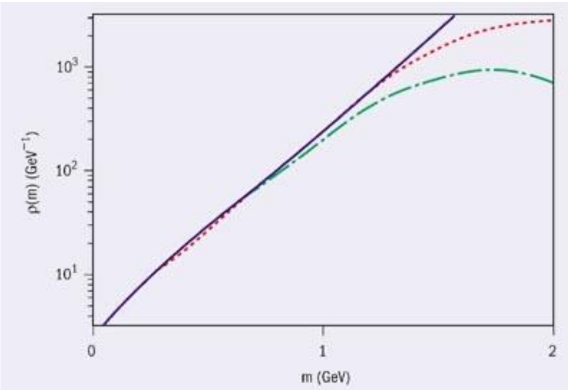
number of created particles with mass m will be proportional to exp[-m/T].

- spectrum of hadrons from “bootstrap equation”:

$$\rho(m) \sim m^{-\frac{5}{2}} e^{\frac{m}{T_H}}$$

Spectrum of hadron masses

- controlled by "Hagedorn temperature", T_H ~ 150-160 MeV



green: states known in 1967

red: states known by mid-1990's

blue: expected spectrum for T_H = 158 MeV

still holds: very similar results from lattice QCD

A Majumder, B Müller, PRL 105:252002,2010

$$lnZ(T,V) \approx V\left[\frac{T}{2\pi}\right]^{3/2}\int \frac{dm}{m^{3/2}}\, e^{-\left[\frac{m}{T}-\frac{m}{T_H}\right]} \leftarrow$$ divergesforT→T_H

T_H would then be the maximum possible temperature!

1975, Cabibbo and Parisi: "quark liberation" at high T

Volume 59B, number 1 PHYSICS LETTERS 13 October 1975

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. CABIBBO
Istituto di Fisica, Universitá di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy

G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

Received 9 June 1975

The exponentially increasing spectrum proposed by Hagedorn is not necessarily connected with a limiting temperature, but it is present in any system which undergoes a second order phase transition. We suggest that the "observed" exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confine

由Hagedorn建议的指数增加的谱不一定与极限温度有关，但它存在于任何经历第二阶相变的系统中. 我们建议"观测到的"指数谱与存在真空中夸克不禁闭的不同相相关。

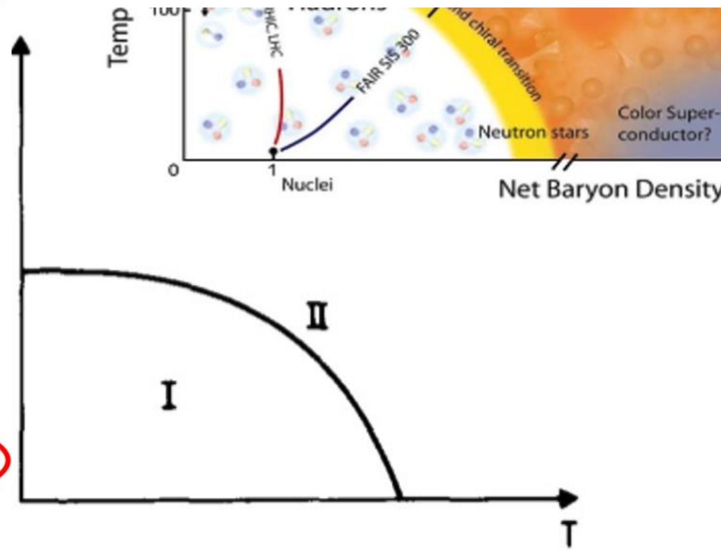
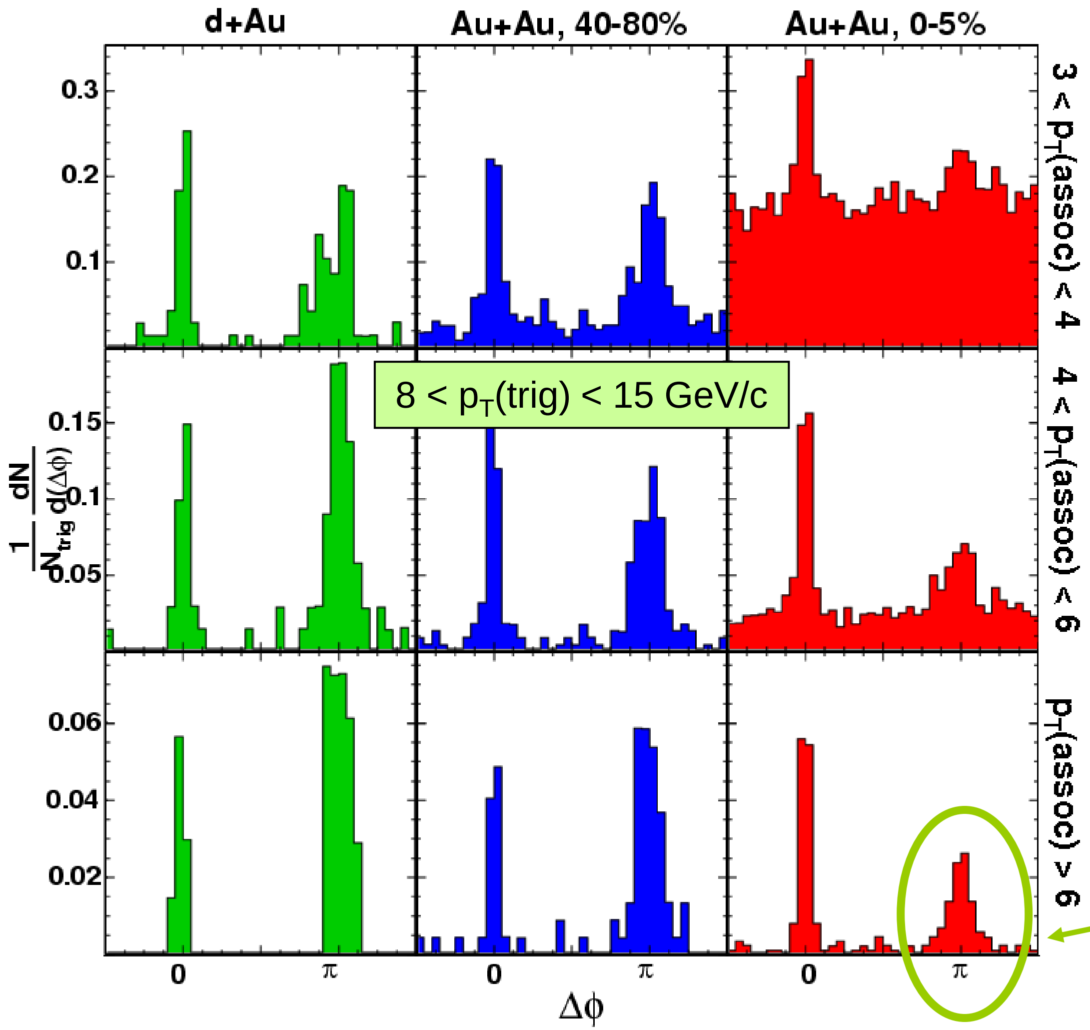
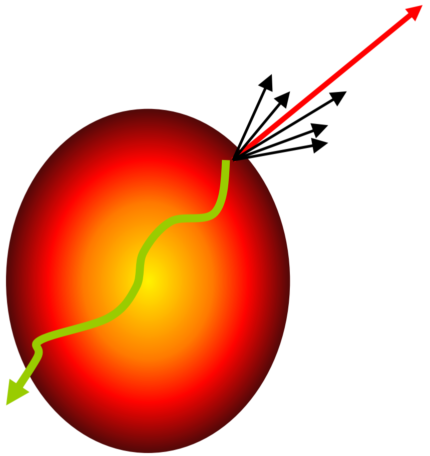


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

T_H not maximum attainable, simply: for $T > T_H$ quarks not confined any more

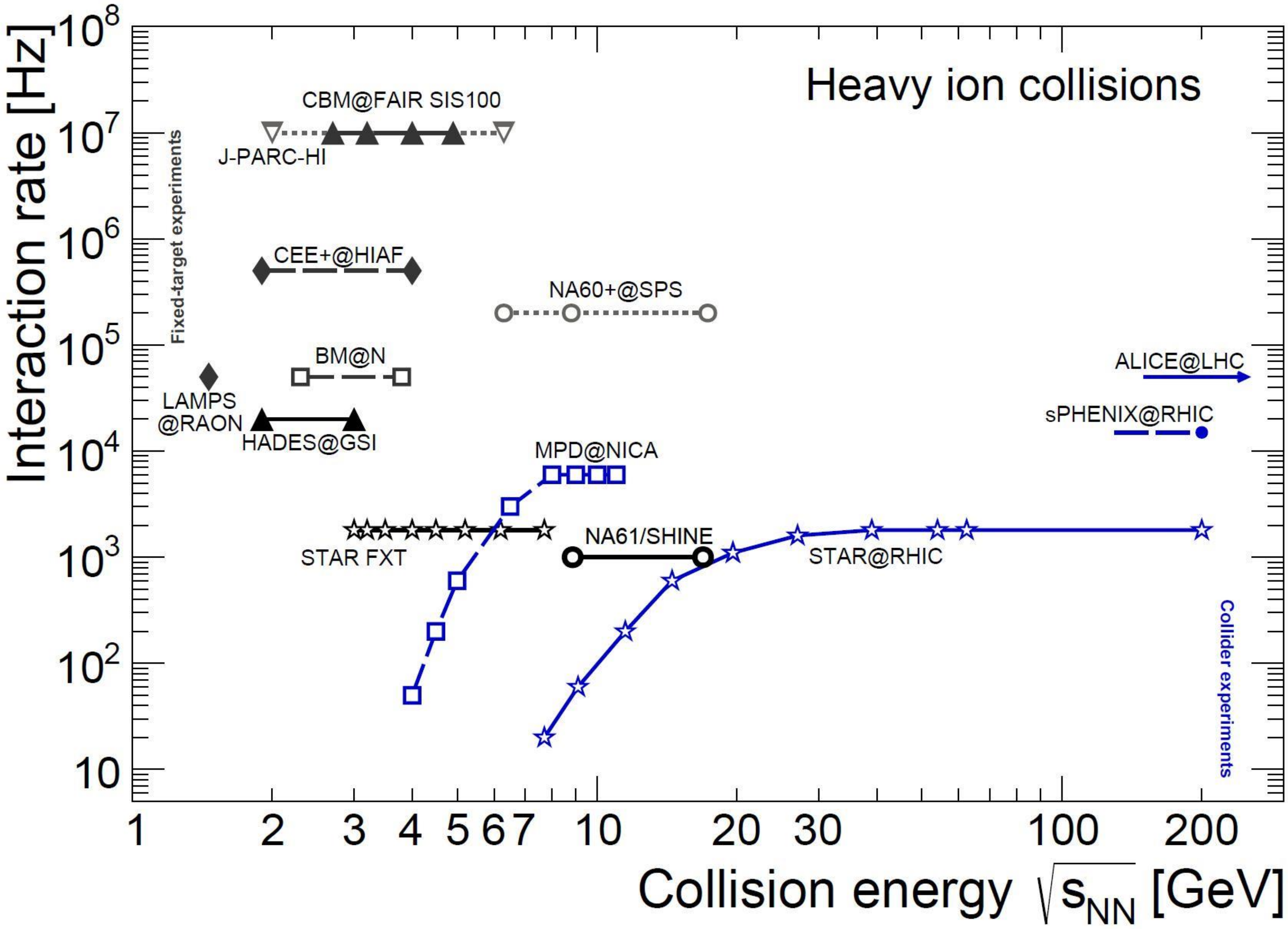
Di-hadron Measurements at Higher p_T





Recoil jet peak emerges above background but at suppressed rate:
⇒ differential measurement of partonic energy loss

国际重离子碰撞实验


Heavy ion collisions
CBM@FAIR SIS100
J-PARC-HI
CEE+@HIAF
NA60+@SPS
BM@N
LAMPS
@RAON
HADES@GSI
MPD@NICA
STAR FXT
NA61/SHINE
STAR@RHIC
ALICE@LHC
sPHENIX@RHIC
Fixed-target experiments
Collider experiments
Interaction rate [Hz]
Collision energy $\sqrt{s_{NN}}$ [GeV]

1975, Collins and Perry: “quark soup” in neutron stars?

VOLUME 34, NUMBER 21 PHYSICAL REVIEW LETTERS 26 MAY 1975

Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England
(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

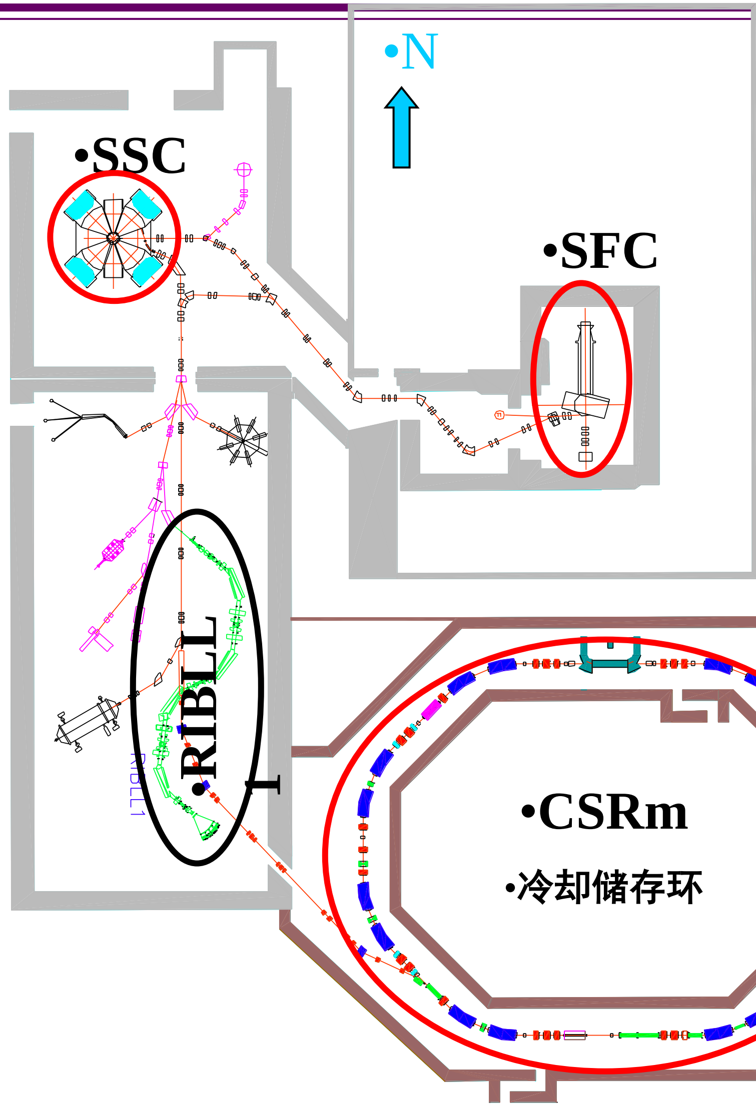
the basic argument is contained in only a few lines...

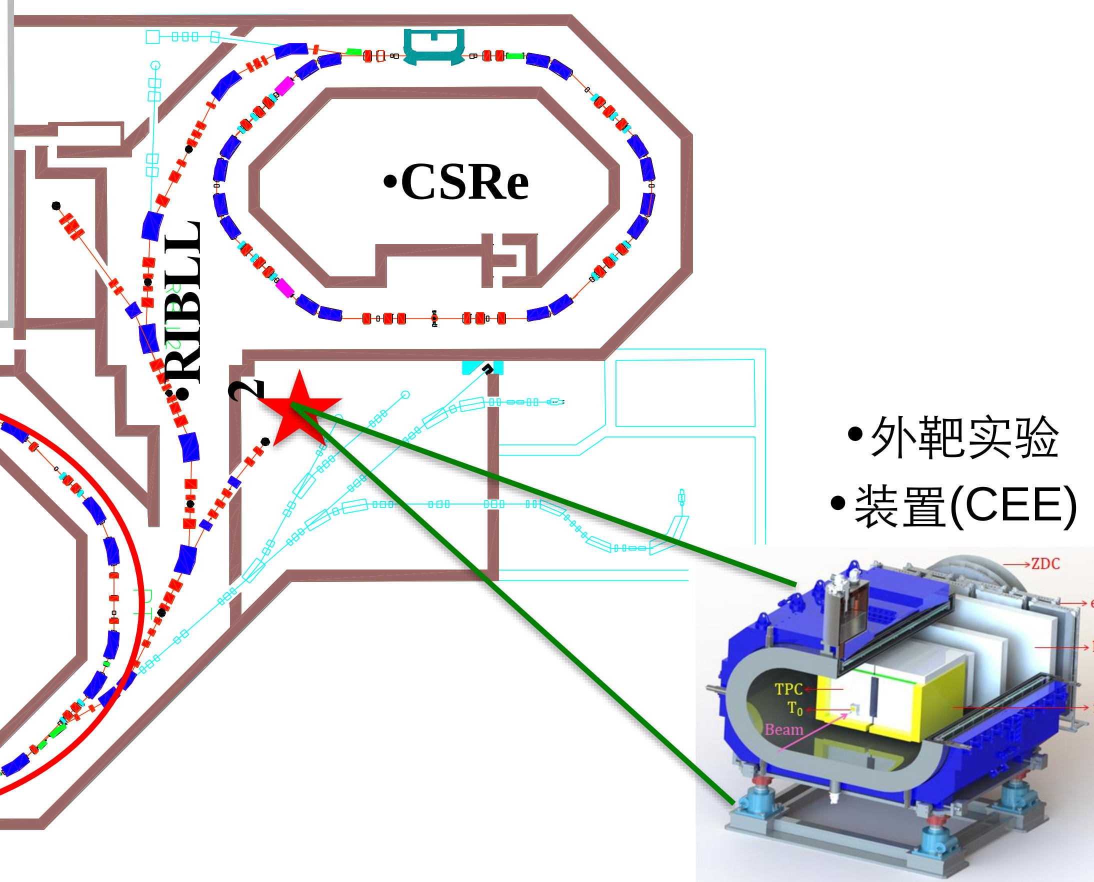
A neutron has a radius[10] of about 0.5–1 fm, and so has a density of about 8×10^{14} g cm^{-3}, whereas the central density of a neutron star[1,2] can be as much as 10^{16}–10^{17} g cm^{-3}. In this case, one must expect the hadrons to overlap, and their individuality to be confused. Therefore, we suggest that matter at such high densities is a quark soup.

中子的半径约0.5~1fm,密度约 8x10^{14}gcm^{-3}, 中子星的中心约 10^{16}~10^{17}gcm^{-3}.在这种情况下,强子重叠，它们的个性被混淆，我们认为如此高密度的物质是夸克汤

兰州重离子加速器冷却储存环(HIRFL-CSR）

- **SFC:** ≤ 10 AMeV (H.I.)
- **SSC:** ≤ 100 AMeV (H.I.)
- **CSRm:** ≤ 1000 AMeV (H.I.)



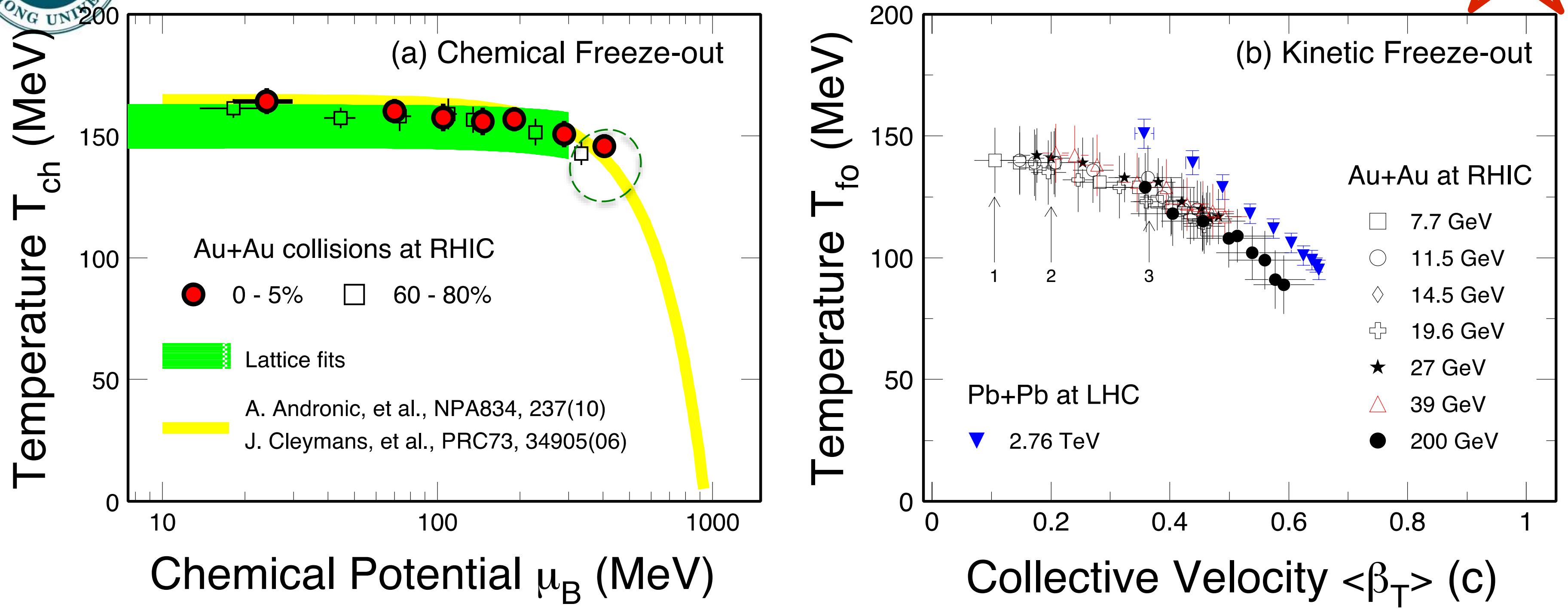


Frank Wilczek:

“In the quest for evidence of the quark-gluon plasma, there are two levels to which one might aspire. At the first level, one might hope to observe phenomena that are very difficult to explain from a hadronic perspective but have a simple qualitative explanation based on quarks and gluons.

But there is a second, more rigorous level that remains a challenge for the future. Using fundamental aspects of QCD theory, one can make quantitative predictions for the emission of various kinds of “hard” radiation from the quark gluon plasma. We will not have done justice to the concept of weakly interacting plasma of quarks and gluons until some of the predictions are confirmed by experiment.”

Bulk Properties at Freeze-outs



Chemical Freeze-out: (GCE)

- Weak temperature dependence
- Centrality dependence μ_B!
- LGT calculations indicate Critical region above μ_B **~ 300 MeV?**

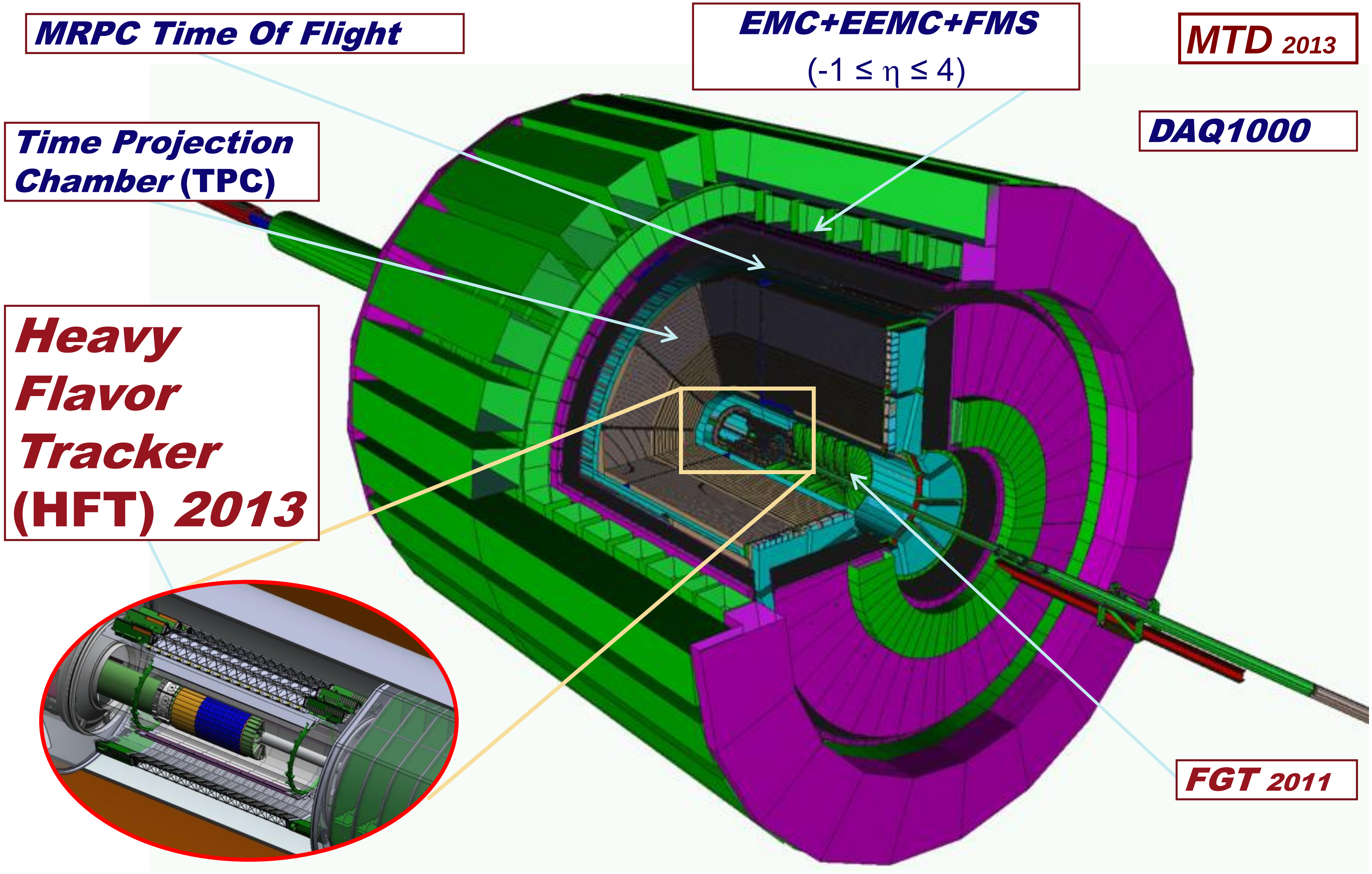
Kinetic Freeze-out:

- Central collisions => lower value of T_{fo} and larger collectivity β_T

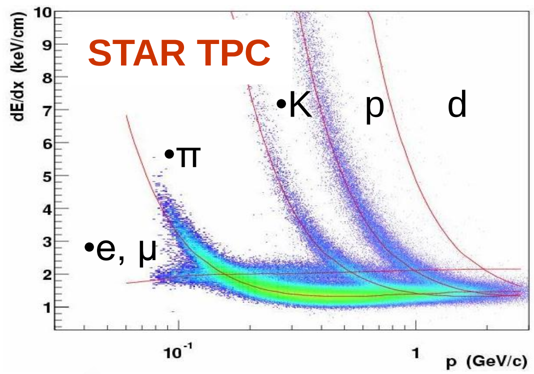
- **Stronger collectivity at higher energy, even for peripheral collisions**

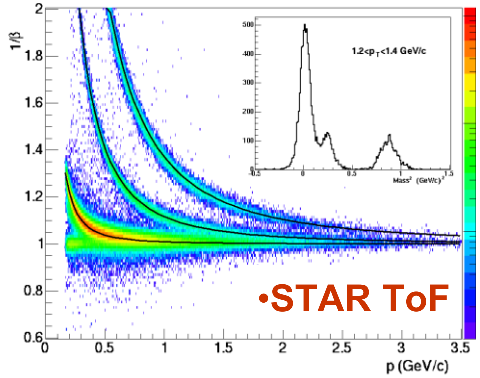
- ALICE: B.Abelev et al., PRL109, 252301(12); PRC88, 044910(2013).
- STAR: J. Adams, et al., NPA757, 102(05); X.L. Zhu, NPA931, c1098(14); L. Kumar, NPA931, c1114(14)
- S. Mukherjee: Private communications. August, 2012

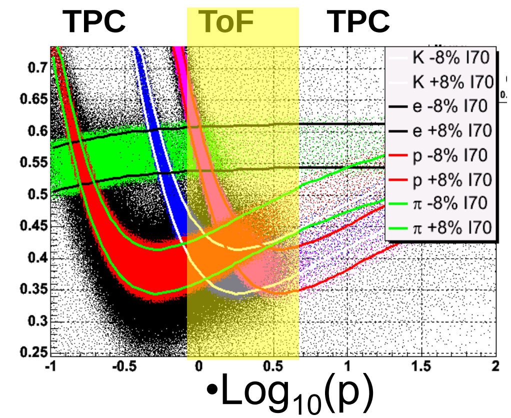
STAR Detectors *Fast and Full azimuthal particle identification*

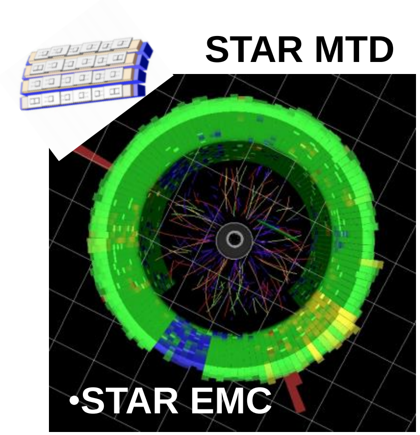


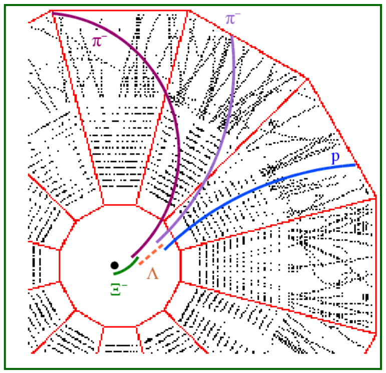
Particle Identification at STAR

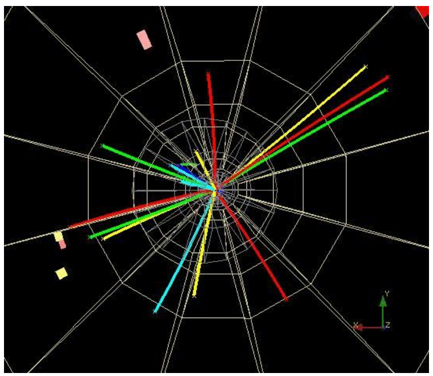


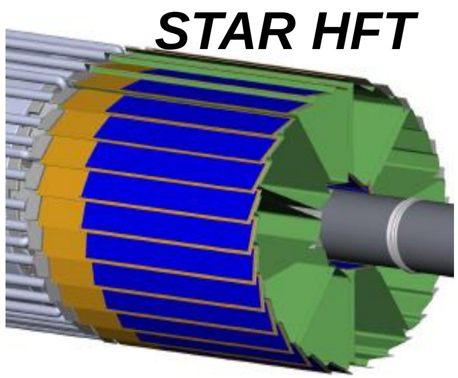












Neutral particles

Strange hyperons Hadrons

Jets

Heavy Quark

1975, Cabibbo and Parisi: “quark liberation” at high T

Volume 59B, number 1 PHYSICS LETTERS 13 October 1975

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

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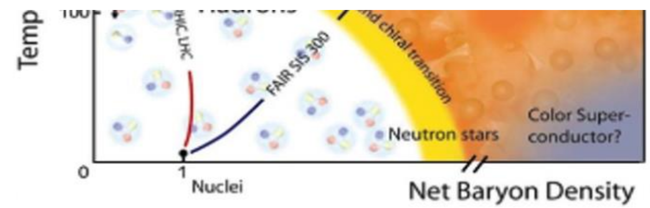
Received 9 June 1975

The exponentially increasing spectrum proposed by Hagedorn is not necessarily connected with a limiting temperature, but it is present in any system which undergoes a second order phase transition. We suggest that the “observed” exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confine

由Hagedorn建议的指数增加的谱不一定与极限温度有关，但它存在于任何经历第二阶相变的系统中. 我们建议“观测到的”指数谱与存在真空中夸克不禁闭的不同相相关。



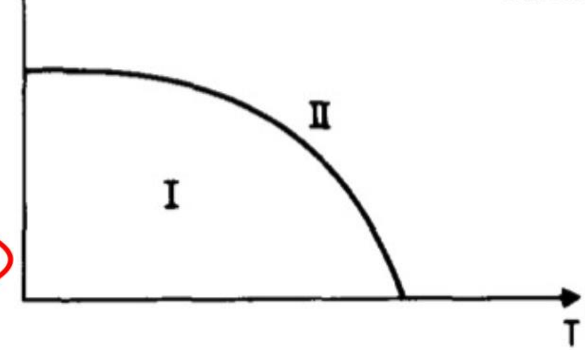
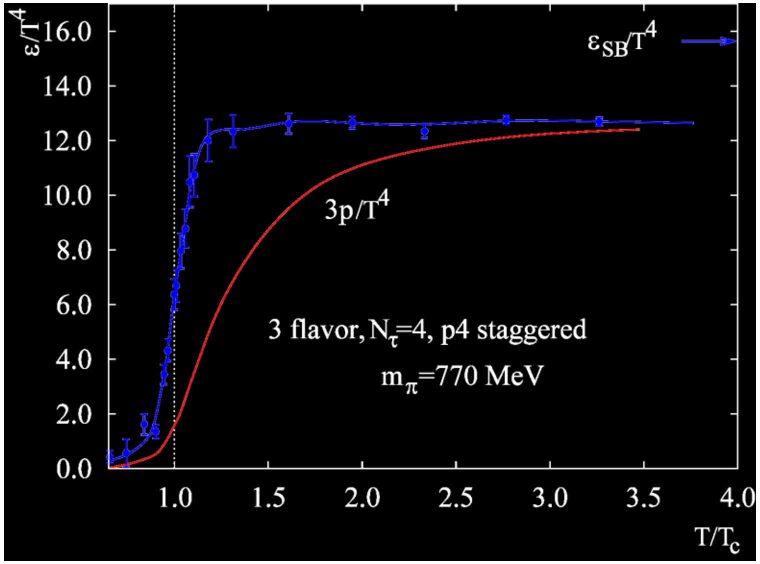


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

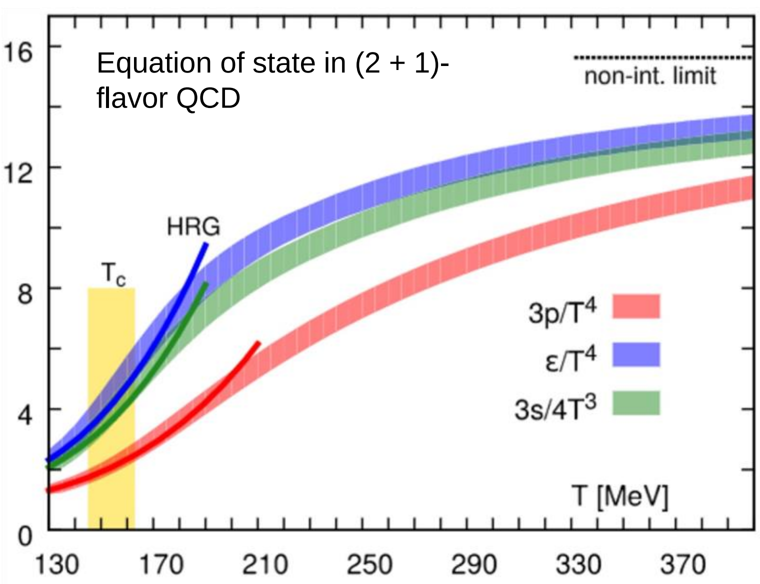
T_H , simply: for $T > T_H$ quarks not confined any more

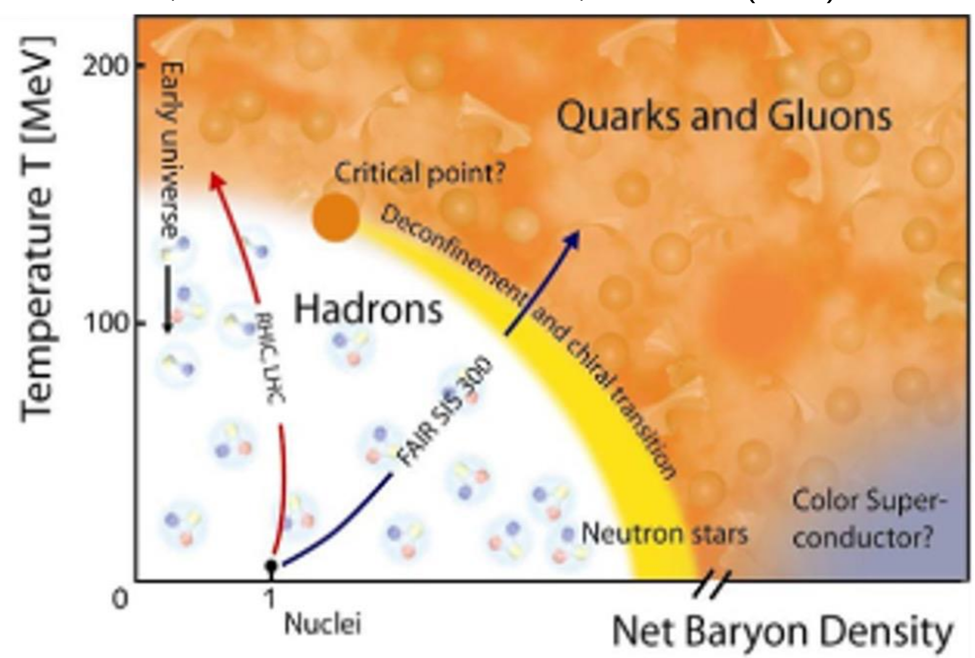
Lattice QCD



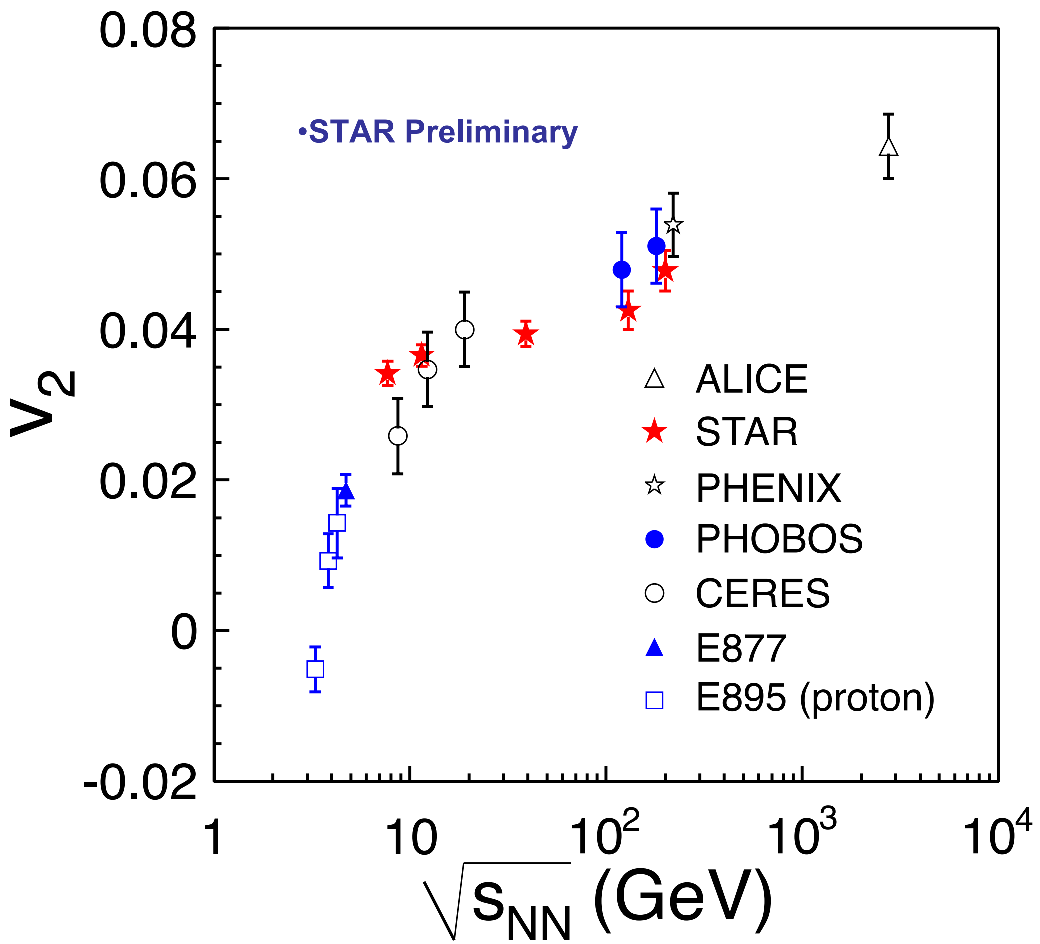
- perturbation theory not applicable
  - lattice QCD calculate bulk properties
- at the critical temperature a strong increase in degrees of freedom
- not an ideal gas!
  - residual interactions
- At phase transition d*p*/dε decreases rapidly!!
- T_c ~ 170 MeV, $\varepsilon_C = 0.6$ GeV/fm^3

F. Karsch, E. Laermann and A. Peikert, PLB 478 (2000) 447





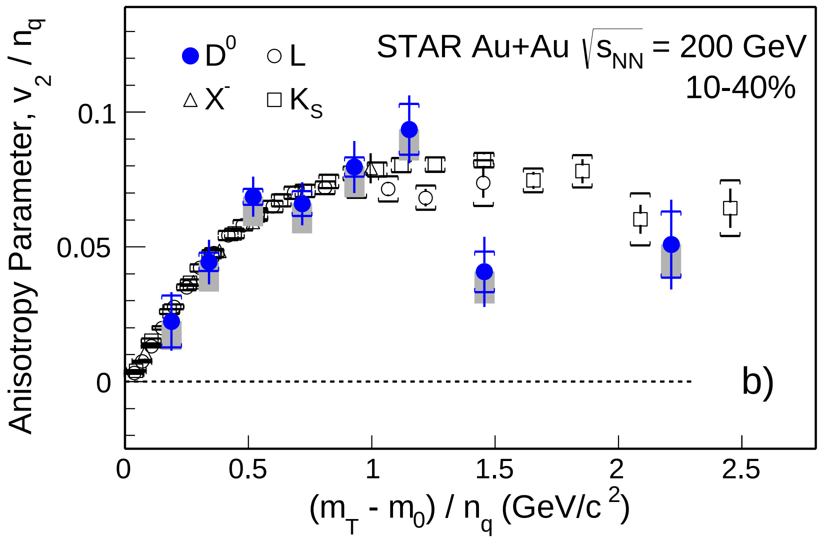
Energy Dependence

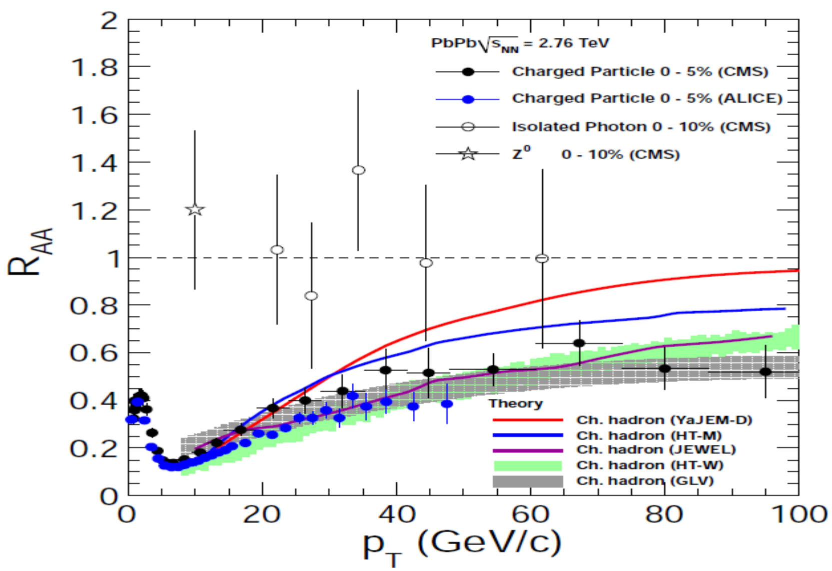


- STAR, ALICE: $v_2\{4\}$ results
  Centrality: 20-30%
- An increasing trend is observed for p_T integrated v_2 from AGS to LHC

•ALICE: Phys. Rev. Lett. 105, 252302 (2010); PHENIX: Phys. Rev.Lett. 98, 162301 (2007).
•PHOBOS: Phys. Rev.Lett. 98, 242302 (2007). CERES: Nucl. Phys. A 698, 253c (2002).
•E877: Nucl. Phys. A 638, 3c(1998). E895: Phys. Rev. Lett. 83, 1295 (1999).
•STAR 130 and 200 GeV: Phys. Rev. C 66,873 034904 (2002); Phys. Rev. C 72,790 014904 (2005); QM2012,Nucl. Phys. A904-905(2013)895C=909C

QCD相变临界点的寻找





2000 – 2012: RHIC、LHC

（1）椭圆流组分夸克的标度性

（2）大横动量粒子的能量损失

强耦合夸克胶子等离子体(sQGP)产生，其物理性质类似于粘滞系数与熵密度之比接近于零的理想液体。

在μ_B=0附近的相变是平滑过渡

重离子碰撞的研究任务：

1）寻找QCD临界点和相边界

2）研究极端条件下sQGP的性质

QCD临界点的寻找和状态方程的研究已成为国际研究热点