高能重离子碰撞实验
---QCD相结构研究

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

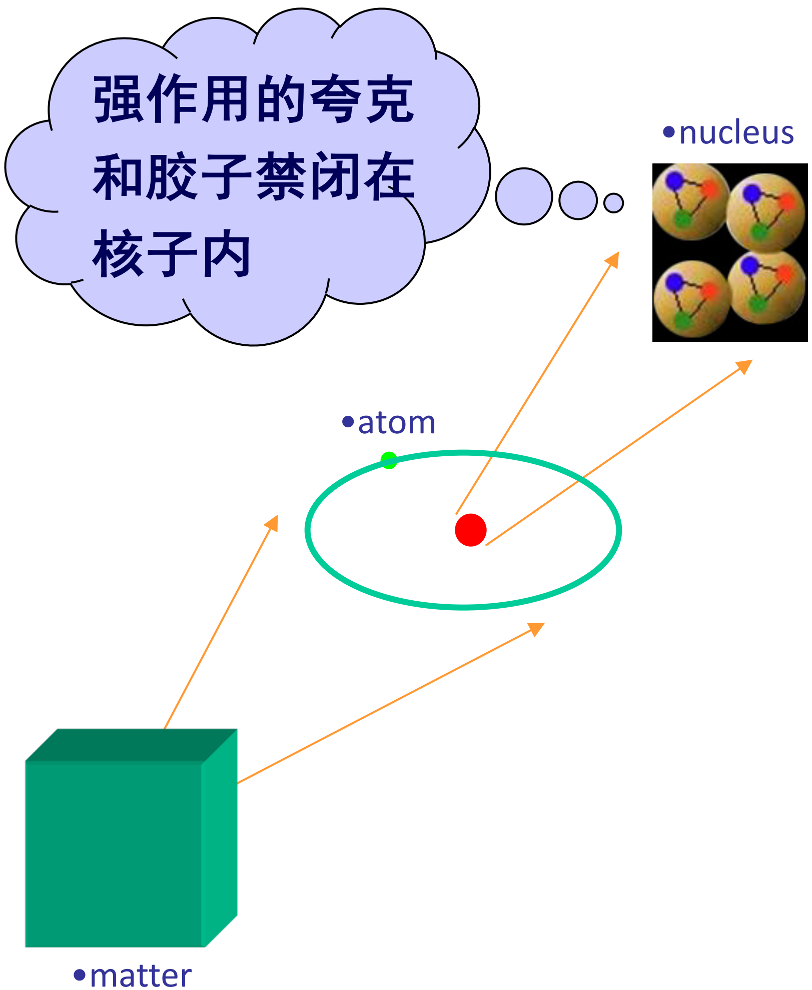
2024年**8**月**9-12**日 复旦

Outline

- Introduction
- Perfect Liquid at RHIC
- Criticality
- Summary and Outlook

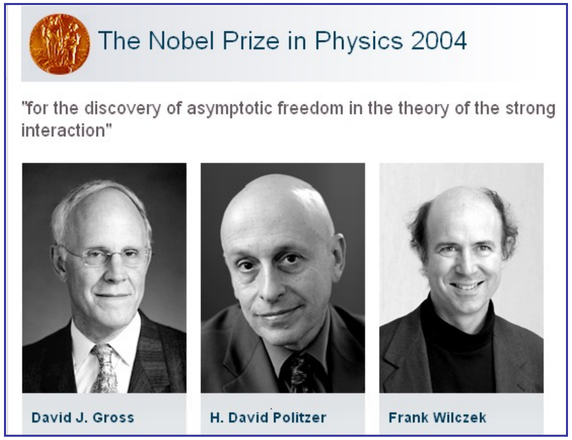
Two Puzzles of Modern Physics

-- T.D.Lee

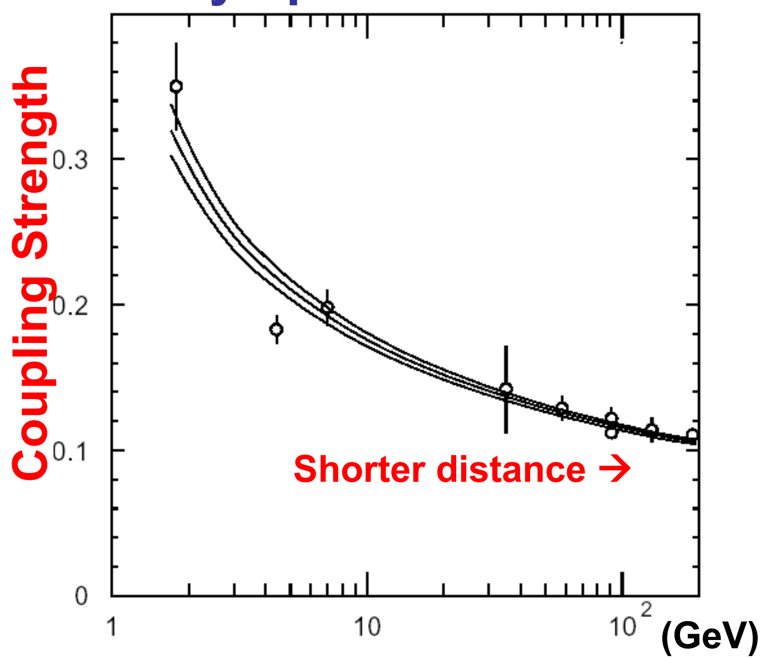


- **Missing Symmetry – all present theories are based on symmetry, but most symmetry quantum numbers are NOT conserved.**
- **Unseen Quarks – all hadrons are made of quarks, yet NO individual quark has been observed.**

Theory of strong interaction : Quantum Chromodynamics (QCD)



Asymptotic Freedom



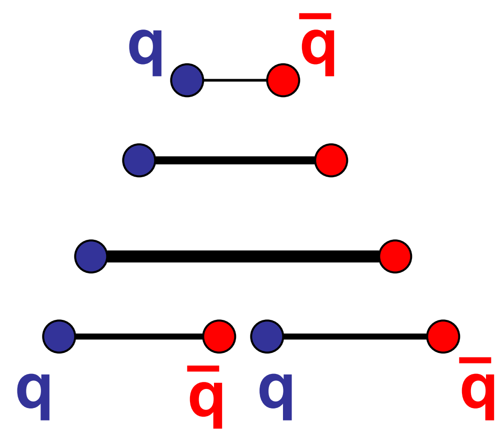
Quark Confinement:

庄子天下篇 ~ 300 B.C.

一尺之棰，日取其半，万世不竭

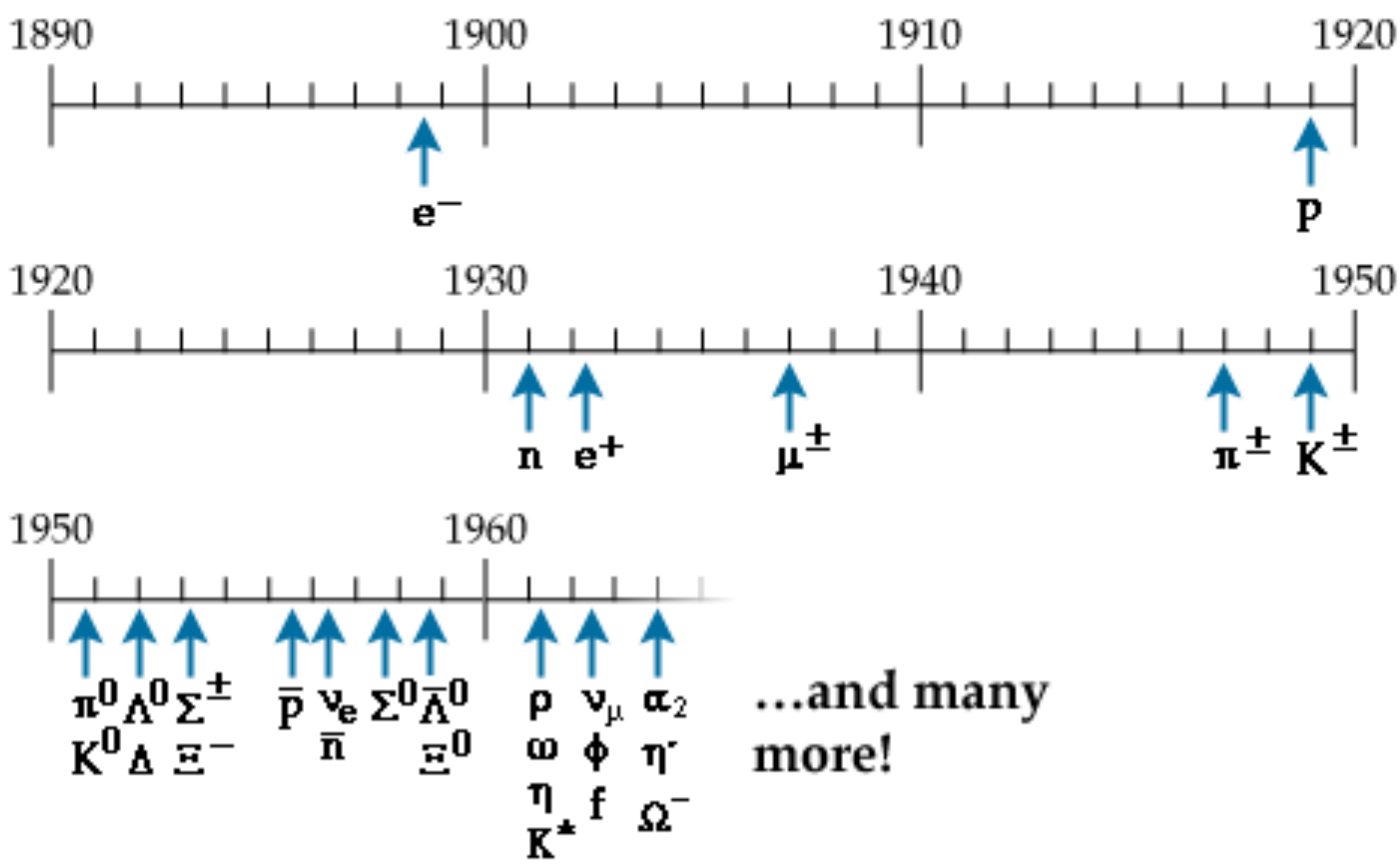
Take half from a foot long stick each day,
You will never exhaust it in million years.

QCD

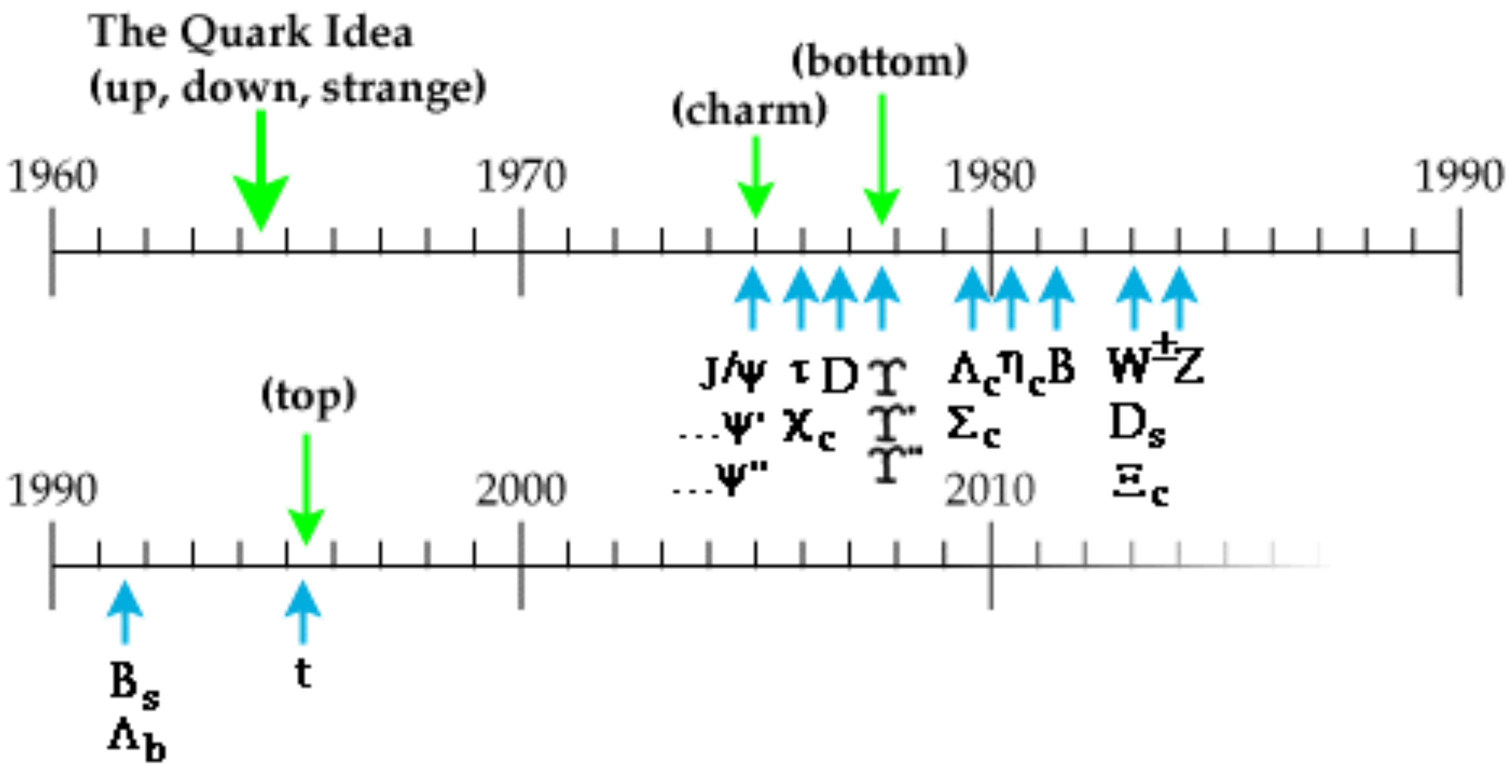


Quark pairs can be produced from vacuum
No free quark can be observed

Particles discovered 1898 - 1964



Particles discovered 1964 - present:



强子谱的统计描述

- ~百种强子， 所有的强子地位都是平等的

- 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

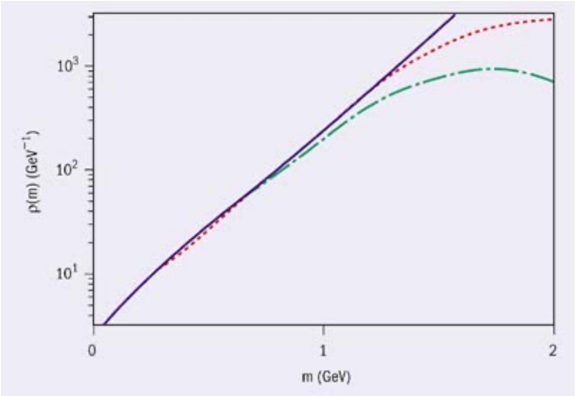
$$N(T) \sim \int_0^\infty \rho(m)\, e^{-\frac{m}{T}} \mathrm{d}m$$

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

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

Spectrum of hadron masses

- spectrum of hadrons from "bootstrap equation": $\rho(m) \sim m^{-\frac{5}{2}} e^{\frac{m}{T_H}}$
  - exponential growth of number of hadrons at higher and higher 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

- btw, still holds: very similar results from lattice QCD
  - A Majumder, B Müller, PRL 105:252002,2010
  - that's why bootstrap theory worked well for hadron interactions!

(the idea was very deep, even if the picture was not the correct fundamental one!)

Hagedorn temperature: a limiting value?

- partition function for a system of non-interacting pions:

$$lnZ(T,V) = \frac{VTm_0^2}{2\pi^2} K_2\left(\frac{m_0}{T}\right)$$

- interactions as resonance formation:
  - interacting system of pions ↔ non-interacting gas of all possible resonances

$$lnZ(T,V) = \sum_i \frac{VTm_i^2}{2\pi^2} \rho(m_i) K_2\left(\frac{m_i}{T}\right) \approx \frac{VT}{2\pi^2} \int dm m^2\ \rho(m) K_2\left(\frac{m}{T}\right)$$

- inserting Hagedorn's spectrum:

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

  - energy pumped into such a system, goes to creating heavier and heavier resonances
  - asymptotically reaching T_H

T_H would then be the maximum possible temperature!

... but Quarks enter the scene...

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。

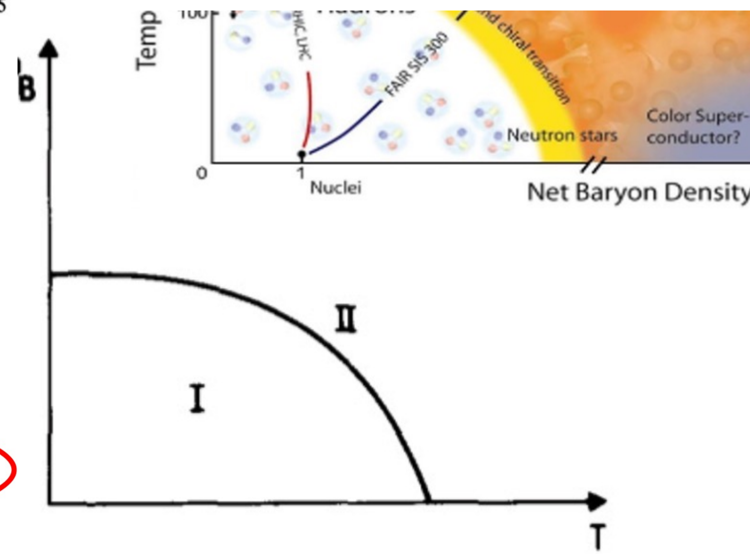


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is th density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

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

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”

QGP 命名

It was quickly realized that asymptotic freedom would lead to deconfined quarks and gluons at high densities and/or pressures:

- *Superdense Matter: Neutrons or Asymptotically Free Quarks?,* J.C. Collins and M.J. Perry, Phys. Rev. Lett. 34, 1353 (1975).

- “We suggest that matter at such high densities is a quark soup.”

Hot Quark Soup,

L. Susskind, submitted to Phys. Rev. D (1978...)
available as http://slac.stanford.edu/pubs/slacpubs/2000/slac-pub-2070.pdf .

- “At high temperatures a transition to a plasma-like phase occurs.”

QGP 命名

1980

Shuryak publishes first “review” of thermal QCD-and coins a phrase:

“Because of the apparent analogy with similar phenomena in atomic physics, we may call this phase of matter the QCD (or quark-gluon) plasma.”

由于与原子物理学中的类似现象明显相似，我们可以将物质的这一阶段称为QCD (或夸克-胶子)等离子体。

QGP

1. Introduction

1.1. Preface

It is widely believed that the fundamental theory of strong interactions is the so called quantum chromodynamics (QCD), a theory of colored quarks interacting via massless vector fields, the gluons. This theory not only provides a general understanding of hadronic phenomenology and a good quantitative description of small distance phenomena, but it mostly wins our hearts by the remarkable simplicity of its foundations, so similar in spirit to quantum electrodynamics (QED).

The properties of superdense matter were always of interest for physicists. Now, relying upon QCD, we can say much more about them. When the *energy* density ε exceeds some typical hadronic value ($\sim 1\ \mathrm{GeV/fm^3}$), matter no longer consists of separate hadrons (protons, neutrons, etc.), but of their fundamental constituents, quarks and gluons. Because of the apparent analogy with similar phenomena in atomic physics we may call this phase of matter the QCD (or quark-gluon) plasma. Due to large similarity between QCD and QED the new theory benefits from the methods previously elaborated for QED plasma made of electrons and photons.

There exist important nonperturbative effects, which result in qualitative differences between QCD and QED. This is seen already from the fact, that quarks and gluons are absent in the physical spectrum of the theory. Many attempts have been made to explain this phenomenon (the so-called color confinement). They have revealed many important effects, but still do not provide a complete solution to the problem. Still missing is an understanding of the large scale fluctuations of the gauge field. It is very important that in superdense matter such fluctuations are suppressed and, in the $\varepsilon \to \infty$ limit, only perturbative corrections survive. While being unable to control the vacuum properties, we may calculate those for superdense matter.

The QCD plasma phase is separated from usual matter by some phase transitions, in which a major role is played by the nonperturbative effects mentioned above. As far as they are not too large, they can be taken into account and so we may somehow approach the phase transition region from the plasma side.

The natural objects at such energy density are hadrons and the core of neutron stars. Such conditions were present in the early Universe and can be created in the laboratory by means of high energy collisions of hadrons and nuclei. These applications are discussed in the present work.

Let us also express our hopes, that the importance of the theory discussed here goes beyond these particular applications. The macroscopic approach, or the problem of infinite and homogeneous matter (or field) is the simplest one, being therefore a good framework for discussing the most difficult questions. One good example of the usefulness of such an approach is the recent explanation of hadronic “bags” as being due to instanton suppression inside hadrons [5.16, 5.17].

The author expresses his sincere apologies to those colleagues whose works are not properly presented in this review. Its topic is too vast and the theory now moves ahead at high speed. One of main restrictions is the principle to only discuss the consequences of QCD and not to go into more model-dependent conceptions. There exist also the natural tendency to discuss ideas more familar to the author. Anyway, I have tried to compensate for this by a very extensive and self-explaining reference list, so that the reader may judge by himself.

I am much indepted to many people who have contributed to this review by helpful discussions and criticism, in particular to E.B. Bogomolny, V.F. Dmitriev, E.L. Feynberg, A.D. Linde, A.B. Migdal, I.B. Khriplovitch, A.M. Polyakov, M.A. Shifman, A.I. Vainshtein, V.I. Zakharov and O.V. Zhirov.

电磁等离子体

固态、液态、气态，**物质第四态** 等离子体态

原子当被加热到足够高的温度或其他原因，外层电子摆脱原子核的束缚成为自由电子，电子离开原子核，这个过程就叫做“电离”

电磁等离子体：正离子和电子的密度大致相等的电离气体

- 高温等离子体：高度电离，通过加热高度电离的等离子体,离子温度和电子温度都很高
- 低温等离子体：轻度电离，外加电压达到击穿电压时，气体分子被电离，离子温度一般远低于电子温度，如荧光灯、霓虹灯

夸克胶子等离子体

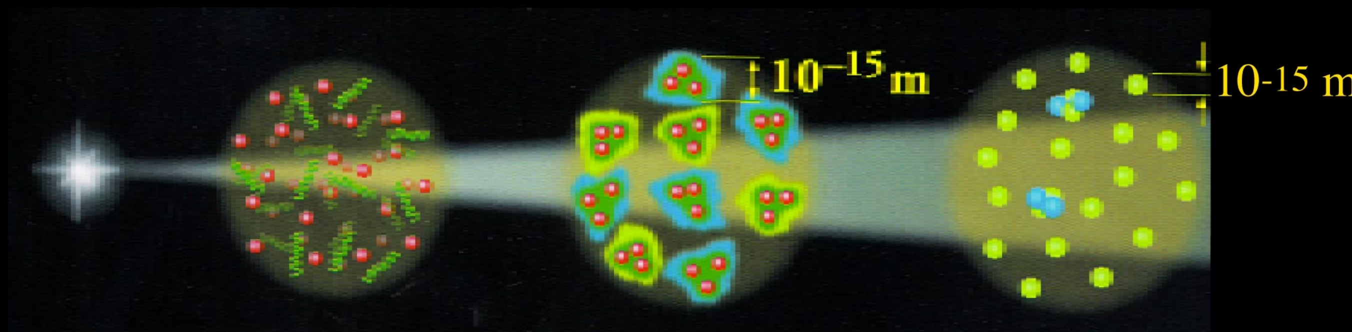
由夸克和胶子组成的等离子体。

夸克、胶子：　组成物质的最基础单元

Temperature, MeV ~ 1.16 x 10^{10} K

10^{-6} second after the Big Bang T~10^{13} K

History of the Universe

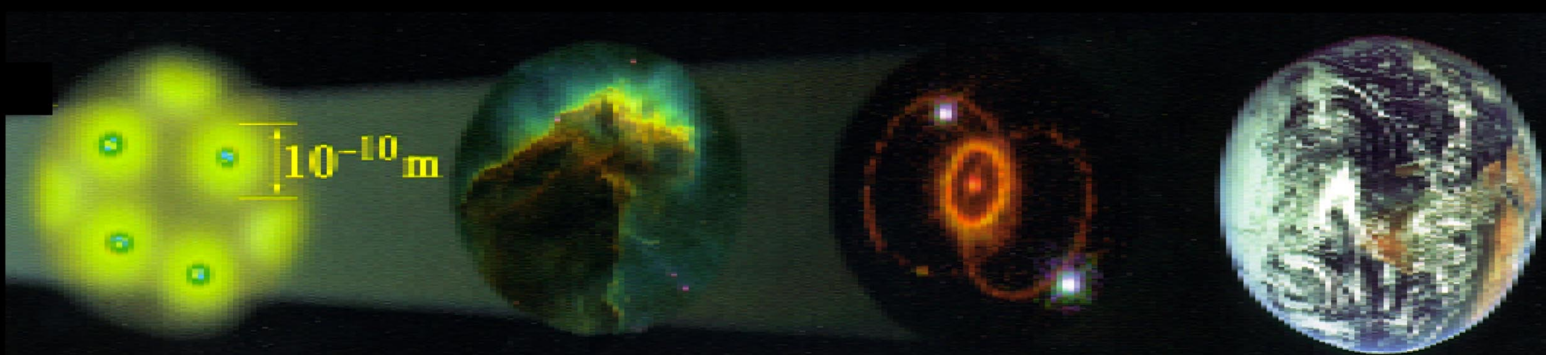


Big Bang

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

What Temperature Is Required for Deconfinement?

For massless non-interacting *bosons* :

Number density $$n(T) = \frac{1.202}{\pi^2} T^3 \approx \left(\frac{T}{2}\right)^3$$

Energy density $$\varepsilon(T) = \frac{\pi^2}{30} T^4$$

Pressure $$P(T) = \frac{1}{3}\varepsilon(T) = \frac{\pi^2}{90} T^4$$

Counting degrees of freedom

Equation of State and degrees of freedom

ideal Gas:

$$P = \frac{1}{3}\varepsilon = g\frac{\pi^2}{90}T^4$$

$$\frac{\varepsilon}{T^4} = g\frac{\pi^2}{30}$$

- Energy density for g massless degrees of freedom

$$\frac{\varepsilon}{T^4} = 3\cdot\frac{\pi^2}{30}$$

- Hadronic matter (T< 150 MeV, π^+,π^- and π^0) ~80% of all particles are pions

$$\frac{\varepsilon}{T^4} = \left\{2_{\text{helicity}}\cdot 8_{\text{gluons}} + \frac{7}{8}\cdot 2_{\text{flavors}}\cdot 2_{\text{quark/anti-quark}}\cdot 2_{\text{spin}}\cdot 3_{\text{color}}\right\}\cdot\frac{\pi^2}{30}$$

$$\frac{\varepsilon}{T^4} = 37\cdot\frac{\pi^2}{30}$$

- Quark Gluon Plasma (T>200 MeV)
- ε_{QGP}=2.5 GeV/fm^3 for T = 200 MeV

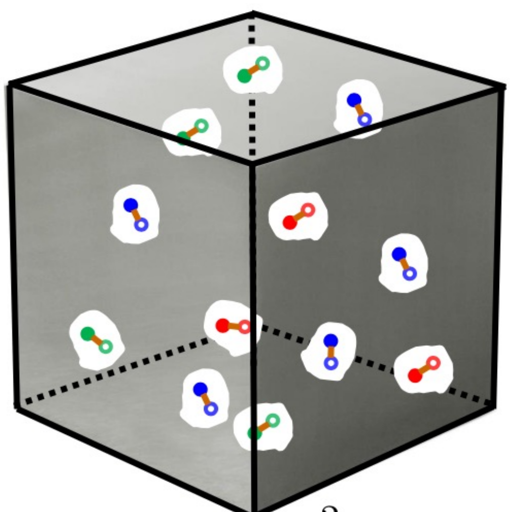
$ndf_{QGP} \sim 10 \times ndf_{Hadrons}$

QCD phase transition temperature

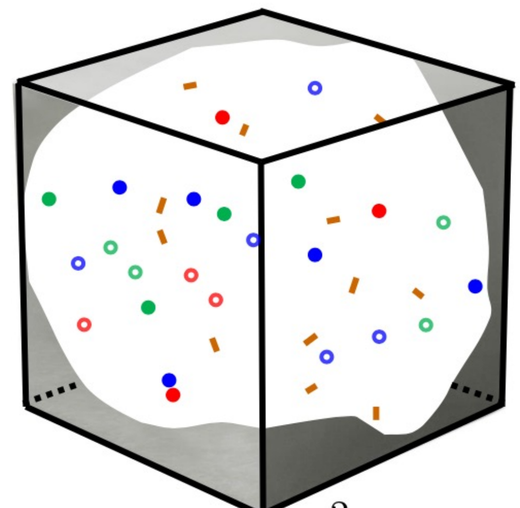
confinement due to bag pressure B (from the QCD vacuum)

$B^{1/4} \sim 200$ MeV

deconfinement when thermal pressure is larger than bag pressure



$$P_\pi(T) = 3\,\frac{\pi^2}{90}\,T^4$$



$$P_{QGP}(T) = g\,\frac{\pi^2}{90}\,T^4 - B$$

$$g \sim 37\text{–}47.5$$

QCD Phase Transition Temperature

STAR

Ideal gas of quark-gluon system in thermal equilibrium:

Pion Gas | Quark Gluon Plasma

$$P = g_H \frac{\pi^2}{90} T^4 \quad \overset{\text{at phase transition}}{=} \quad P = g_{QGP} \frac{\pi^2}{90} T^4 - B$$

$$g_H = 3, \qquad g_{QGP} = \frac{7}{8}(g_q + g_{\bar{q}}) + g_g = \frac{7}{8} N_c N_s N_f \times 2 + (N_c^2 - 1) N_s = 37$$

B: "bag" constant. $B^{1/4}$ ~ 200 MeV estimated from 3-quark proton radius

$$T_c = \left(B \frac{90}{\pi^2 \Delta g}\right)^{1/4} \sim 144 \text{ MeV}$$

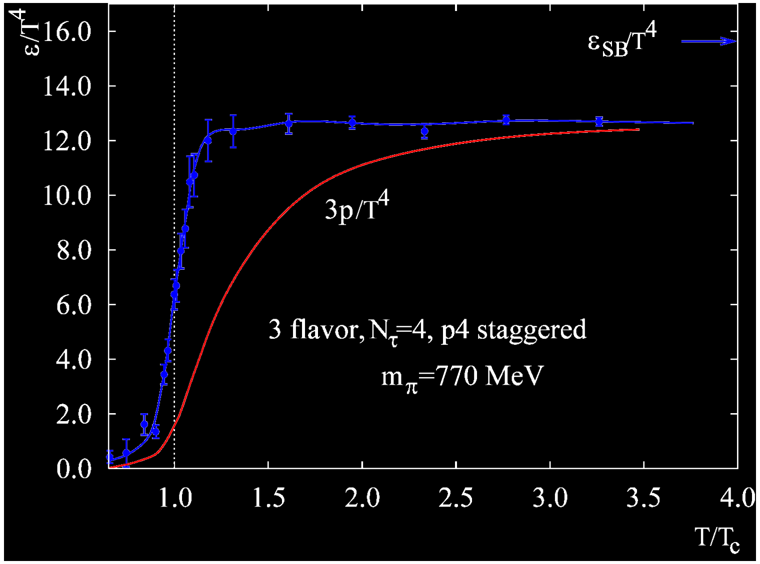
Hadron side

- ☐ Pions hardly massless relative to 140 MeV
- ☐ Ignores exponential growth at higher T
- ☐ Ignores (strong!) interactions

QGP side

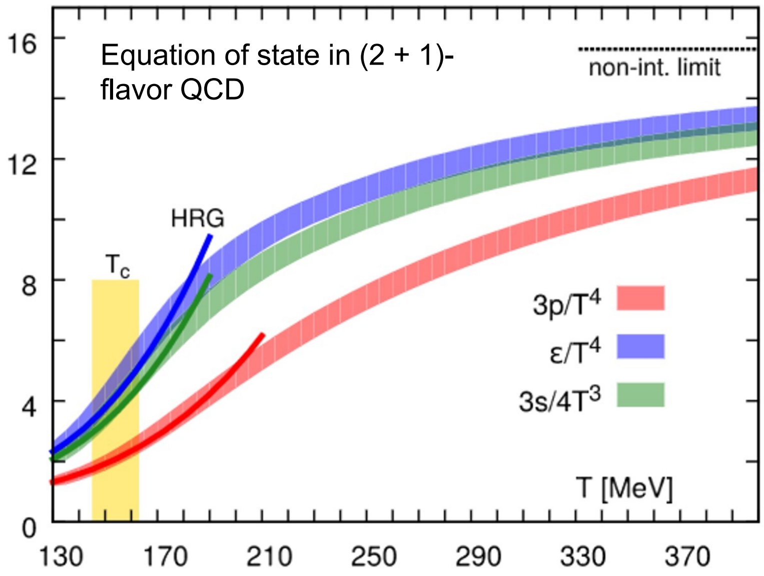
- ☐ Strange quark neither massless nor massive
- ☐ Bag constant stand-in for QCD vacuum fluctuations
- ☐ Ignores (strong!) interactions

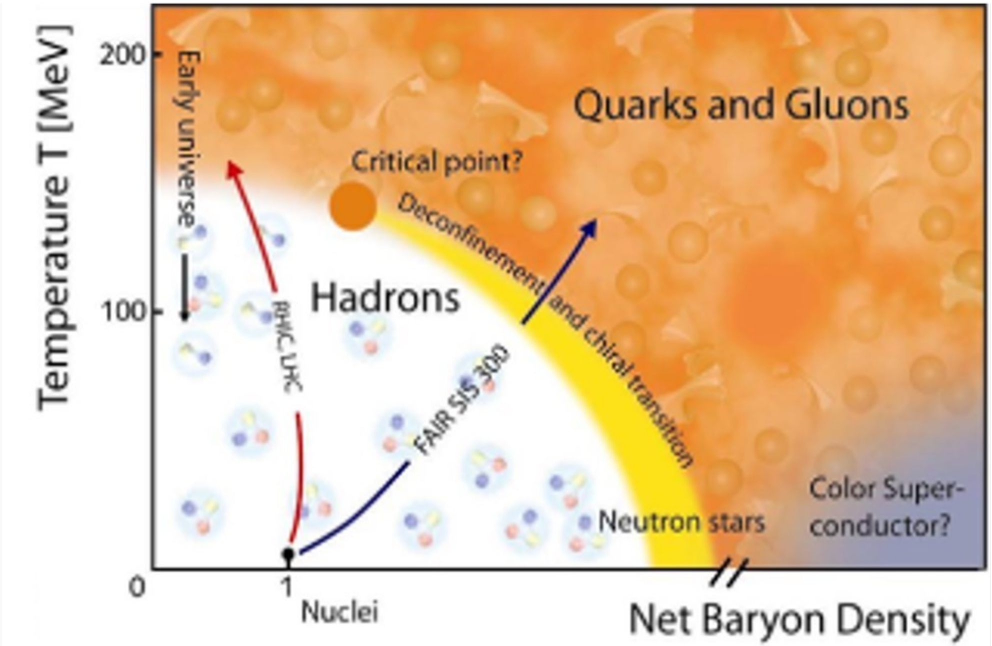
Lattice QCD



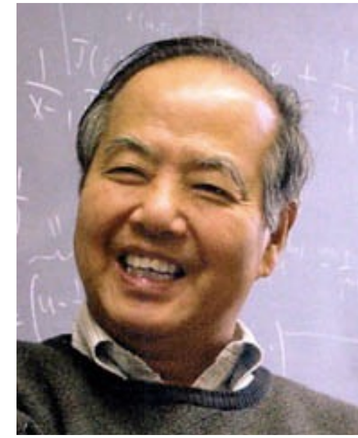
- perturbation theory not applicable
  - lattice QCD calculate bulk properties
- at the critical temperature a strong increase in degrees of freedom
- not an ideal gas!
  - residual interactions
- At phase transition d*p*/dε decreases rapidly!!
- T_c ~ 170 MeV, ε_C = 0.6 GeV/fm^3

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





How to Address the Problem?



T.D. Lee

The confinement:

Quarks are the basic building blocks of matter.

No free quarks are seen, confined within hadron:

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

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

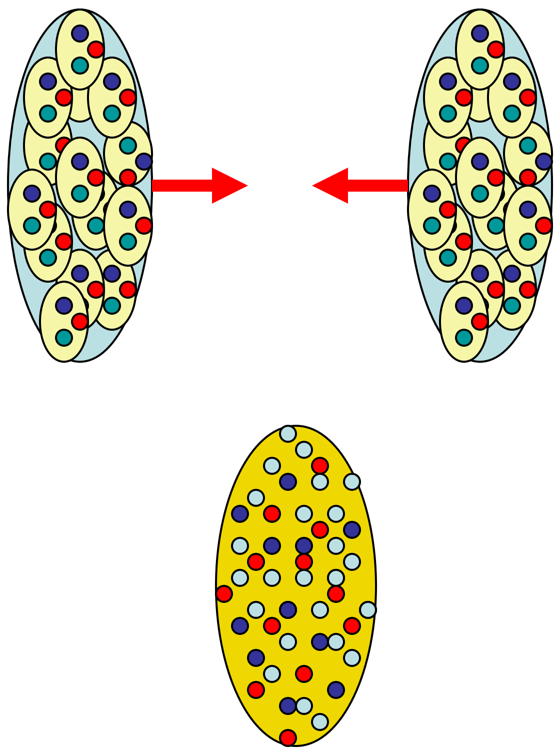
New form of ***matter with partonic degrees of freedom***

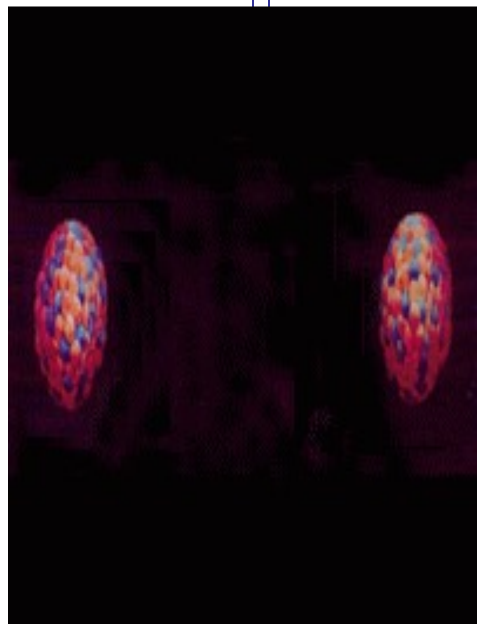
QCD Phase Structure

- 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:

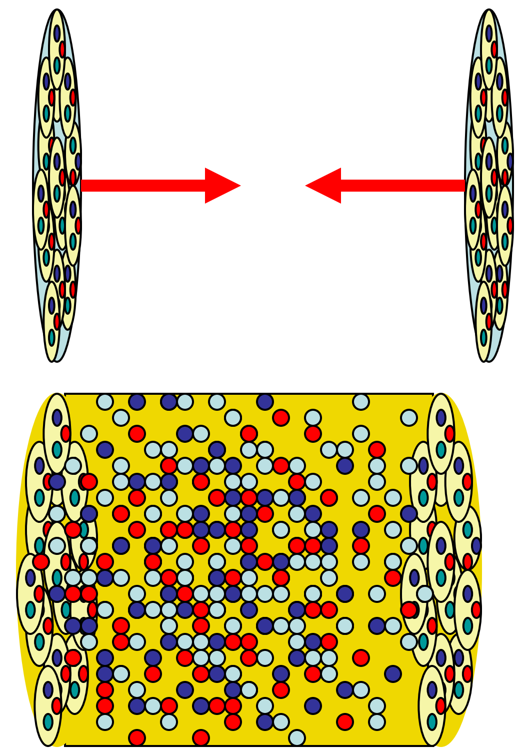




Deconfinement

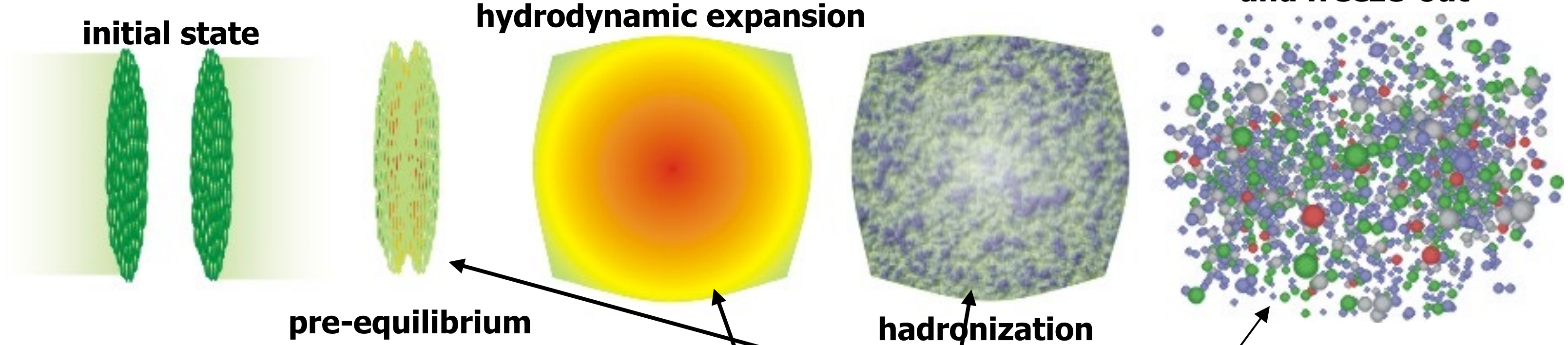
High Baryon Density
-- low energy heavy ion collisions
-- neutron star→quark star

Vacuum Heating:



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

Why Heavy Ion Collisions



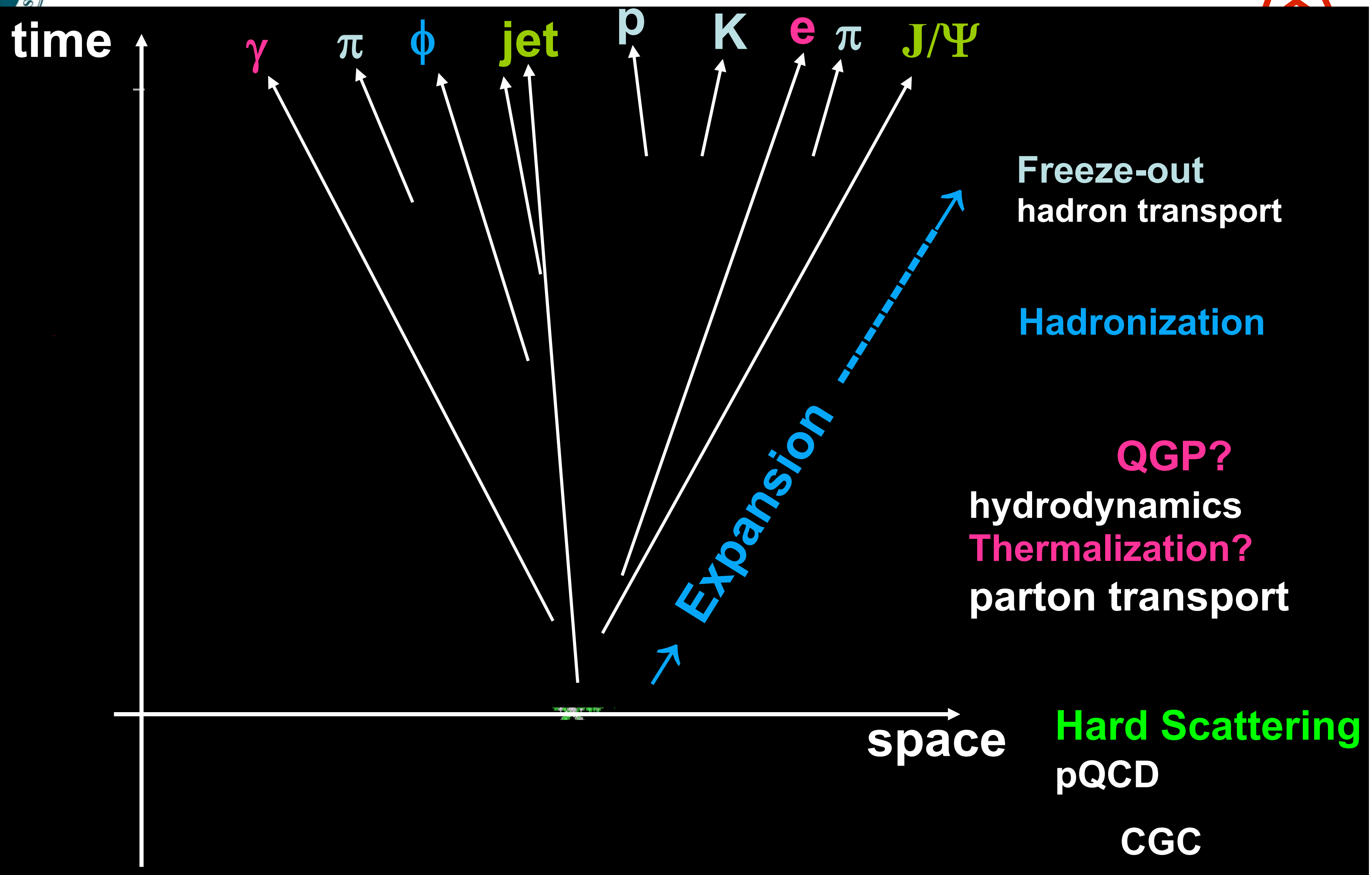
Pre-equilibrium parton hard scattering.

QGP thermal and Expansion Stage: 1-10fm/c
Collective expansion, Parton energy loss et al.,
Hadronization: Recombination and coalescence.

Freeze out Stage: ~10-15fm/c
Chemical freeze out: Inelastic scatt. cease.
Kinetic freeze out: Elastic scatt. cease.

Experimental probes:
1) ***Penetrating probes:*** "jets" **Energy loss**
2) ***Bulk probes*** **:**Elliptic flow**, radial flow**
3) ***Fluctuation*:**

Schematic Time Evolution

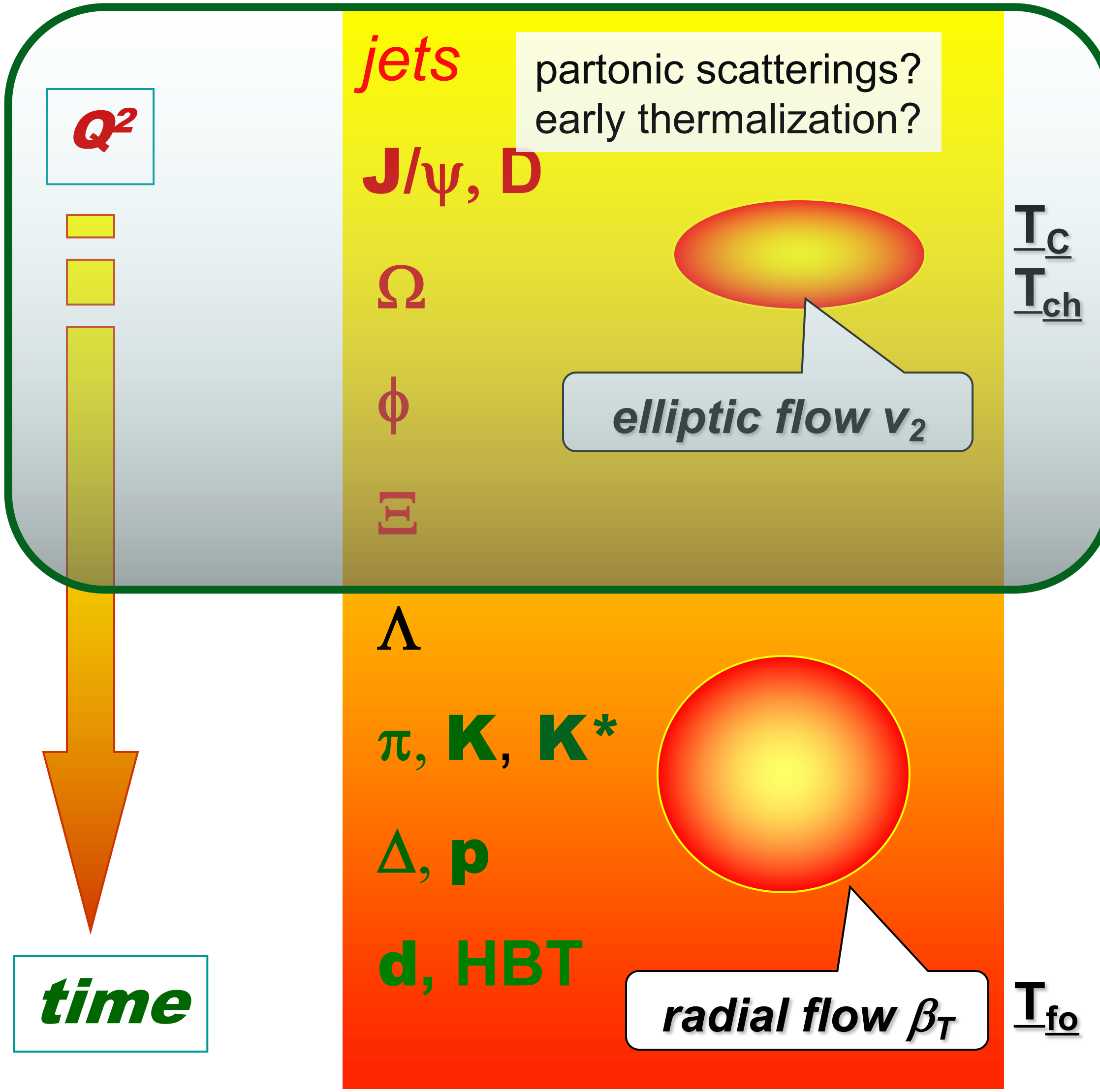


High-energy Nuclear Collisions

Initial Condition
- initial scatterings
- baryon transfer
- E_T production
- parton dof

System Evolves
- parton interaction
- parton/hadron expansion

Bulk Freeze-out
- hadron dof
- interactions stop



早期 QGP 的寻找

how to access this physics experimentally? high-energy nuclear collisions!

- since the 70's nuclear physicists were already colliding heavy ions
  - •Coulomb barrier, shock waves...
  - •UNILAC (GSI), Super-Hilac and Bevalac (Berkeley), Synchrophasotron (Dubna)

nuclear collisions could provide the conditions for QGP formation

to reach Tc higher-energy accelerators were needed **ultrarelativistic** AA collisions

International conference on **ultrarelativistic** **Nucleus-Nucleus Collisions (QM)**

starting from the mid-80's: high-energy beams of nuclei on fixed target

- at the Alternating Gradient Synchrotron (AGS) BNL

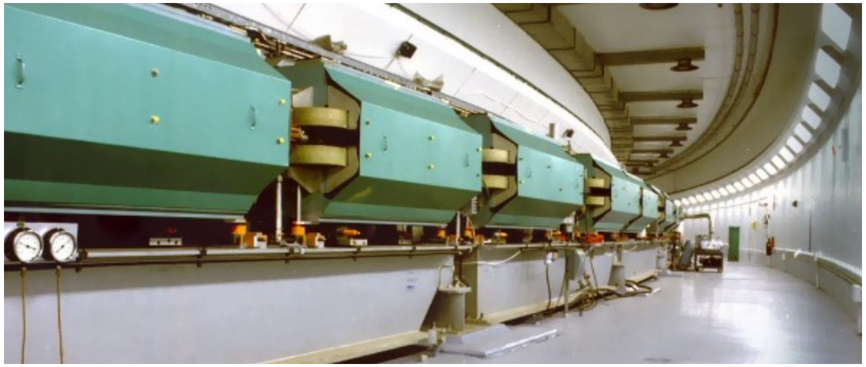
  $\sqrt{s_{NN}} \sim$ 5 GeV , O (1986), Si (1987), Au (1993)

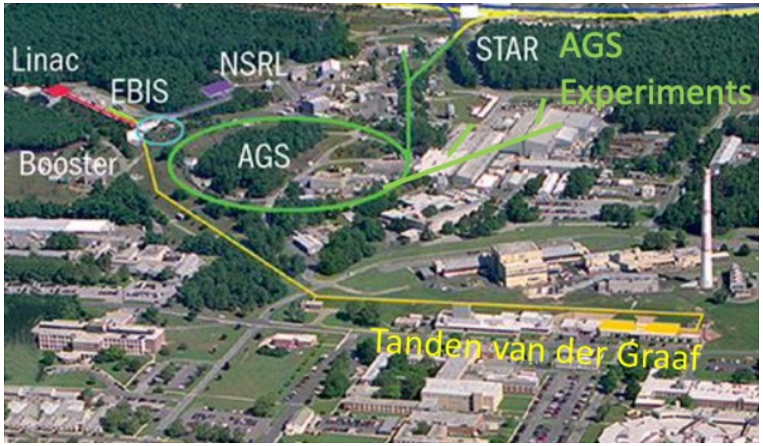
- at the Super-Proton Synchrotron (SPS) at CERN (Geneva)

  $\sqrt{s_{NN}} \sim$ 17 GeV O (1987), S (1987), Pb (1994)

Nuclear beam at experiments at the AGS

- E802/E859/E866/E917: mid-rapidity spectrometer
  - π, K, p, light nuclei, HBT
- E810/E891: Time Projection Chamber
  - K_0,Λ
- E814/E877: spectrometer, TOF, calorimetry
  - π, p, light nuclei, Λ, directed flow, elliptic flow, HBT
- E864: spectrometer, TOF, calorimetry
  - p, light nuclei, strangelet search
- E895/E910: Time Projection Chamber
  - π, p, Λ, directed flow, elliptic flow, HBT





Pb-beam experiments at the SPS (1994 – 2000)

- WA97: silicon pixel telescope spectrometer
  - production of strange and multi-strange particles
- WA98: photon and hadron spectrometer
  - production of photons and hadrons
- NA44: single-arm spectrometer
  - particle spectra, interferometry, particle correlations
- NA45: electron and hadron spectrometer
  - low mass lepton pairs, hadron production
- NA49: large acceptance TPCs
  - particle spectra, strangeness, interferometry, event-by-event , ...
- NA50: muon spectrometer
  - high-mass lepton pairs, J/ψ production
- NA52: focussing spectrometer
  - strangelet search, particle production
- NA57: silicon pixel telescope spectrometer
  - production of strange and multi-strange particles

Two historic signatures

Federico Antinori QM2022

- QGP phase, if existed, would obviously be very short-lived, how to observe it?
  - is there a memory of the passage through the QGP phase?
  - are there "signatures" of the QGP that we can look for in the final state?

two major proposals made in the 80's:

- strangeness enhancement (Johann Rafelski and Berndt Müller)
  - enhanced production of strange quarks in the QGP
  - → enhancement of strange particles in the final state

- J/ψ suppression (Tetsuo Matsui and Helmut Satz)
  - colour field screened at short distances in QGP
  - → suppression of production of tightly-bound quarkonium states

Strangeness enhancement

Strangeness Production in the Quark-Gluon Plasma

Johann Rafelski and Berndt Müller
Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, D-6000 Frankfurt am Main, Germany
(Received 11 January 1982)

Rates are calculated for the processes $gg \to s\bar{s}$ and $u\bar{u}, d\bar{d} \to s\bar{s}$ in highly excited quark-gluon plasma. For temperature $T \gtrsim 160$ MeV the strangeness abundance saturates during the lifetime ($\sim 10^{-23}$ sec) of the plasma created in high-energy nuclear collisions. The chemical equilibration time for gluons and light quarks is found to be less than 10^{-24} sec.

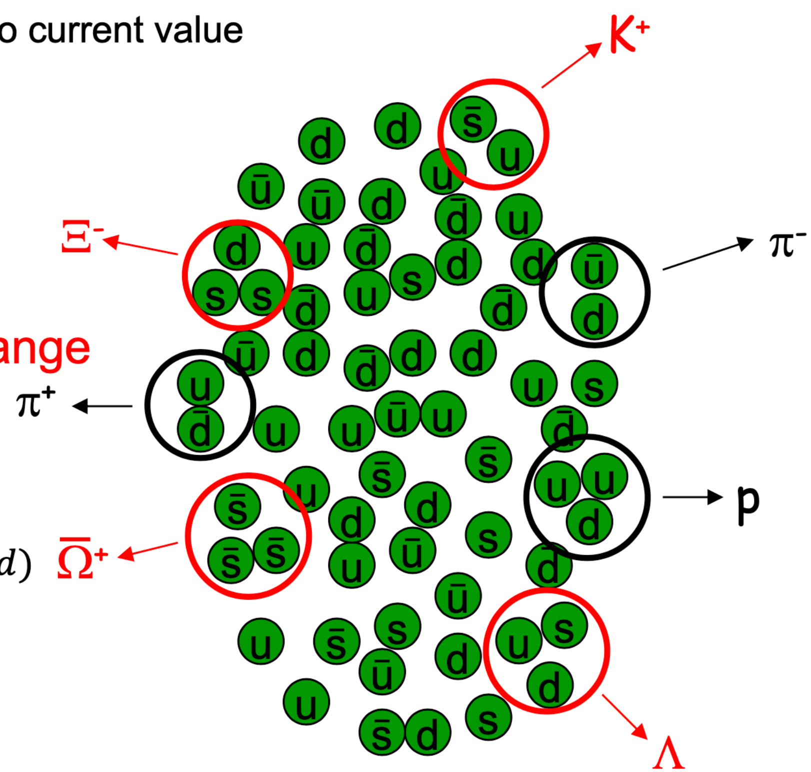
- restoration of χ symmetry -> increased production of s
  - mass of strange quark in QGP expected to go back to current value
    - $m_S \sim 150$ MeV ~ Tc
  - → copious production of $s\bar{s}$ pairs, mostly by gg fusion

    [J Rafelski: Phys. Rep. 88 (1982) 331]

    [J Rafelski and B Müller: Phys. Rev. Lett. 48 (1982) 1066]

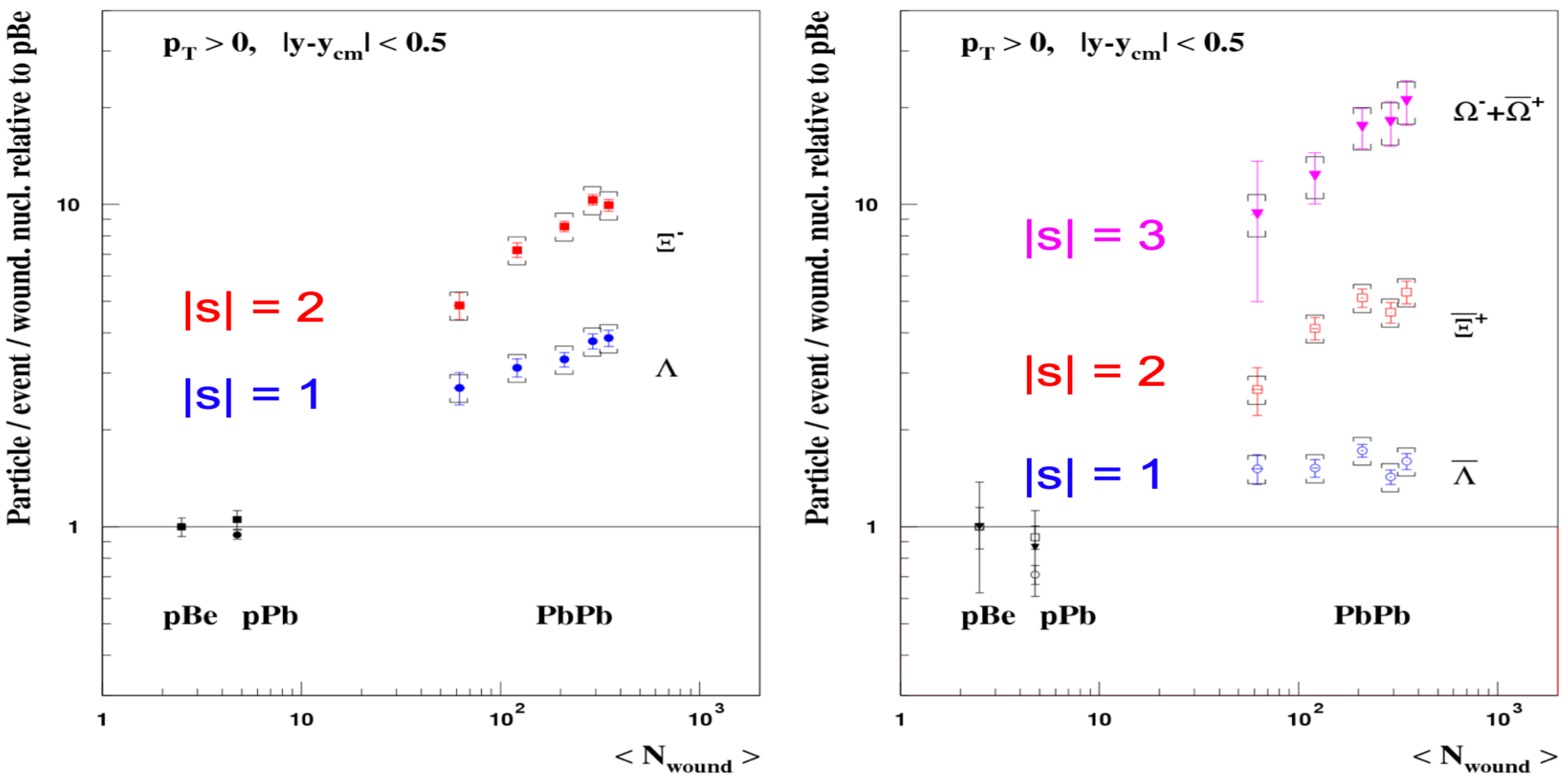
- deconfinement → stronger effect for multi-strange
  - can be built recombining s quarks
  - → strangeness enhancement increasing with strangeness content
  - → expect larger for $\Omega(sss)$ than for $\Xi(ssd)$ than for $\Lambda(sud)$

    [P Koch, B Müller and J Rafelski: Phys. Rep. 142 (1986) 167]



Strangeness enhancement at the SPS

WA97/NA57

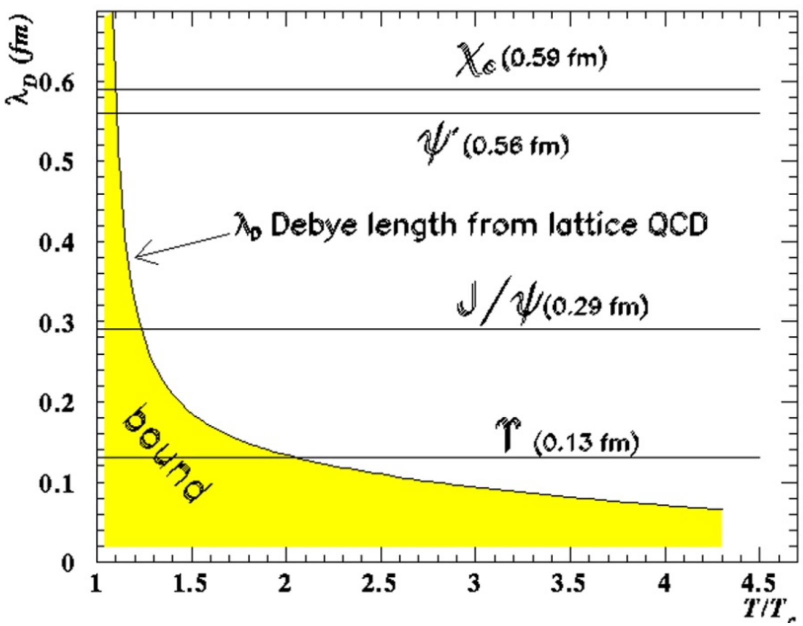


- enhancement relative to p-Be, p-Pb
- increasing with |S|
- up to ~ x 20 for the Ω

Quarkonium suppression

- QGP signature proposed by Matsui and Satz, 1986
- quarkonium: $c\bar{c}$ states , $b\bar{b}$ states
- in the plasma phase the interaction potential is expected to be screened
  - analogous to Debye screening in electromagnetic plasma
  - beyond the Debye screening length λ_D

λ_D depends on T



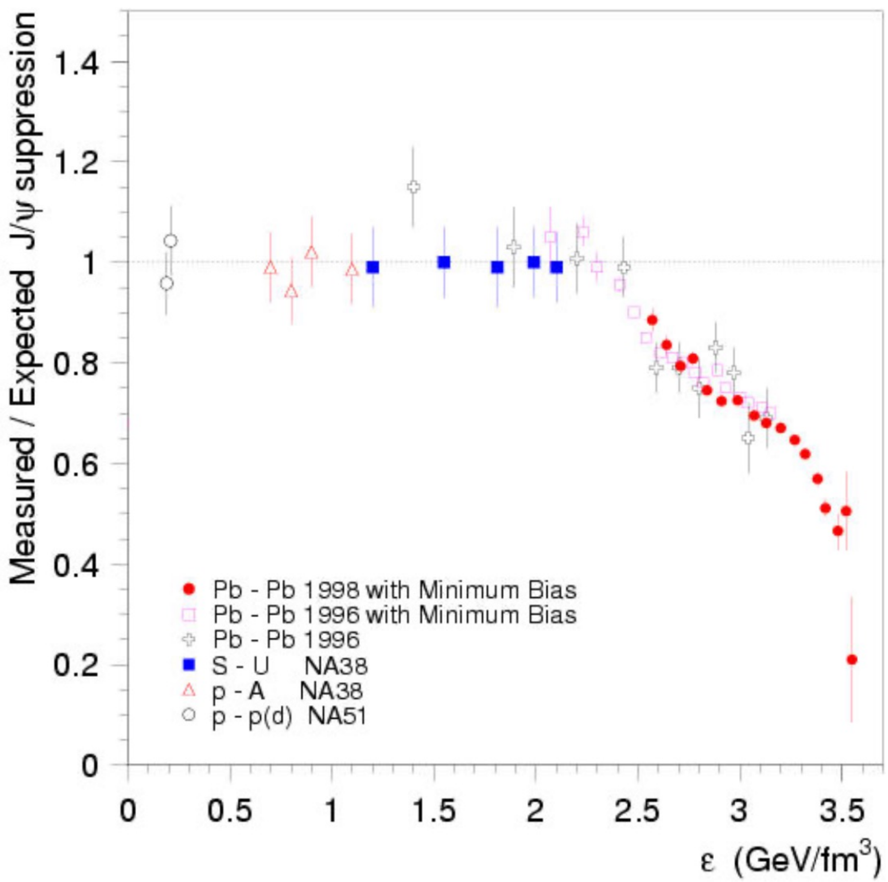
states with radius > λ_D will not bind ♋ suppressed

- J/ψ, ψ', χ' → $c\bar{c}$ states
- Υ → $b\bar{b}$ states

[Digal, Petrecki, Satz PRD 64(2001) 094015]

J/ψ suppression at the SPS

NA50: "anomalous" suppression



- nuclear suppression of J/ψ production
  - due to nuclear absorption effects
  - measured in pA, light ion collisions
  - scaled to Pb-Pb (= 1 in the plot)

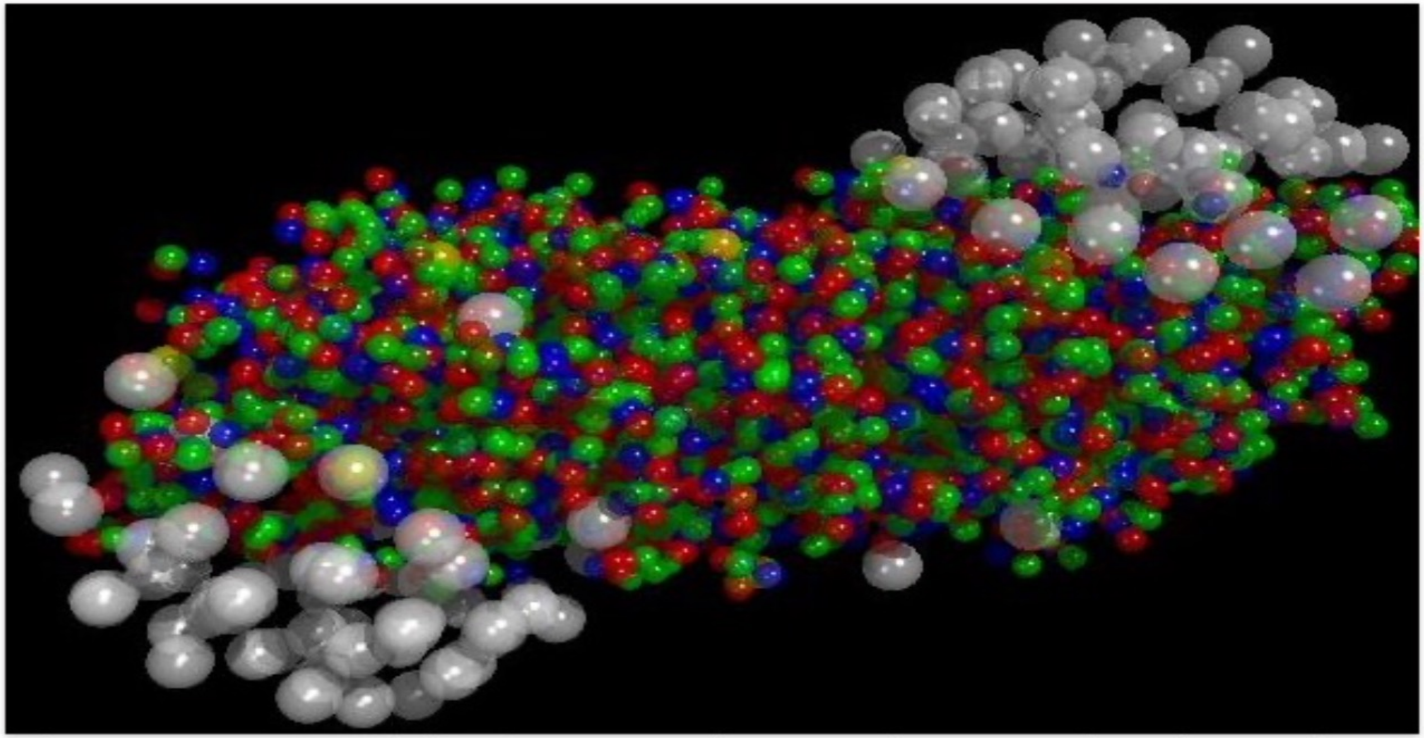
- "anomalous" suppression
  - measured/expected
  - setsinate~2.3GeV/fm^3 (*b*~8fm)

CERN February 2000 announcement

STAR

New State of Matter created at CERN

10 FEBRUARY, 2000

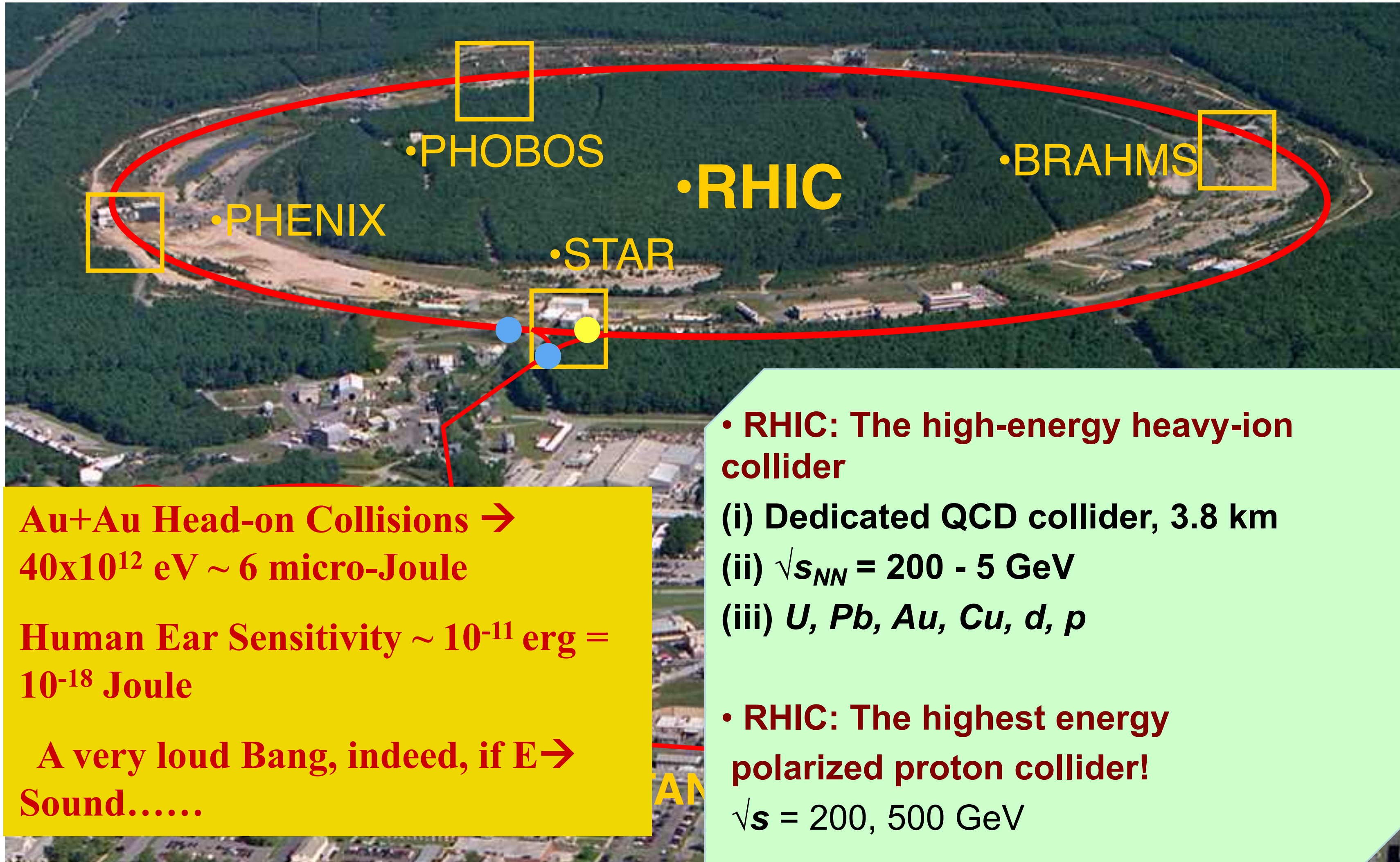


Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN[1]'s Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Luciano Maiani (Director General, CERN)
Summary.

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

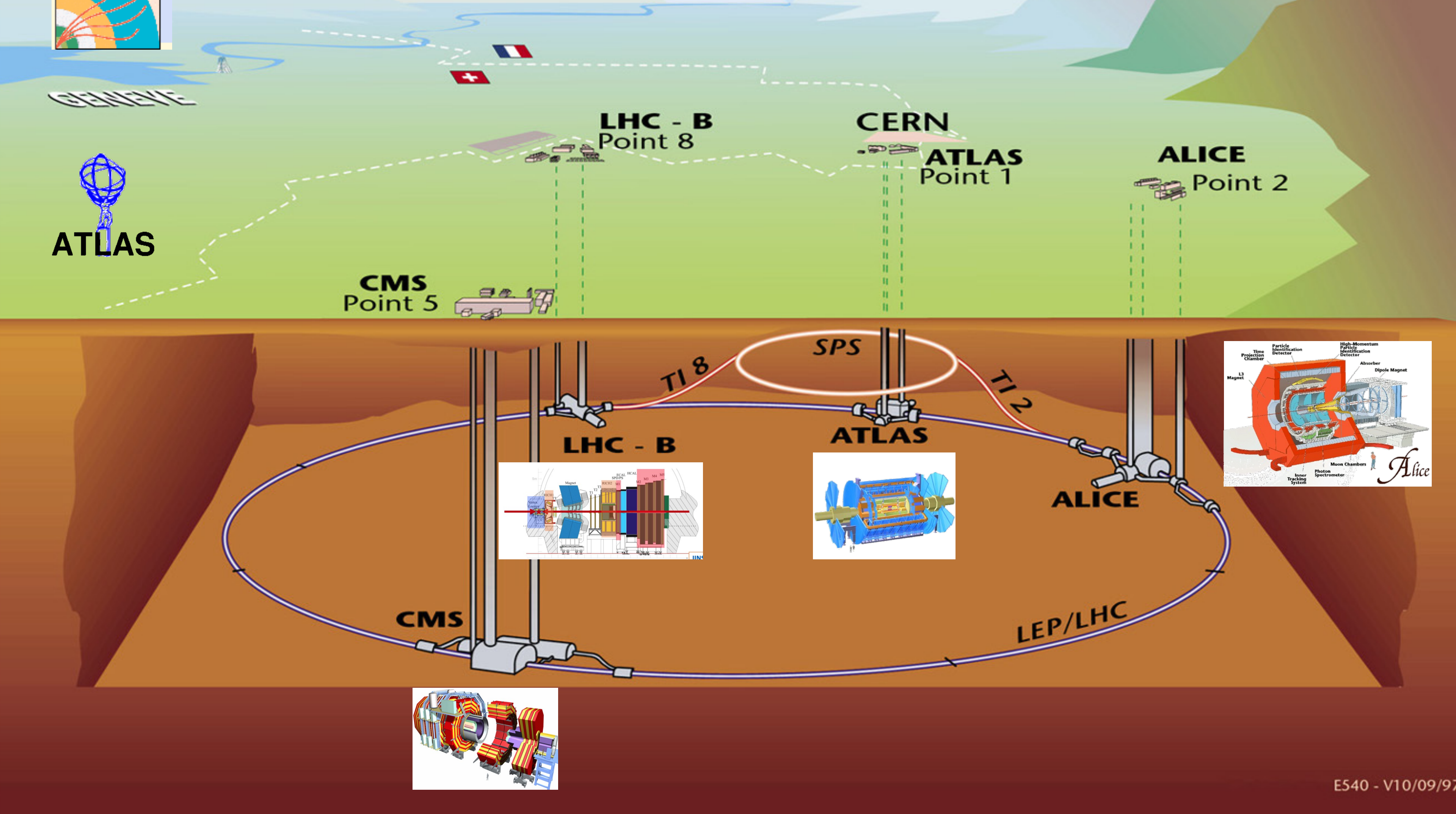
•*Animation M. Lisa*

Overall view of the LHC experiments.

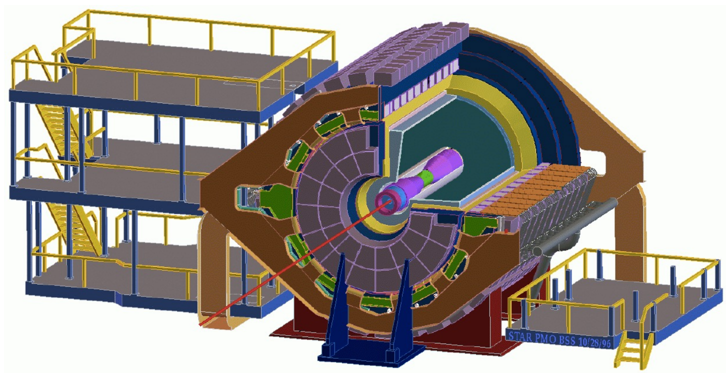
One dedicated HI experiment: ALICE

Two pp experiments with HI program:

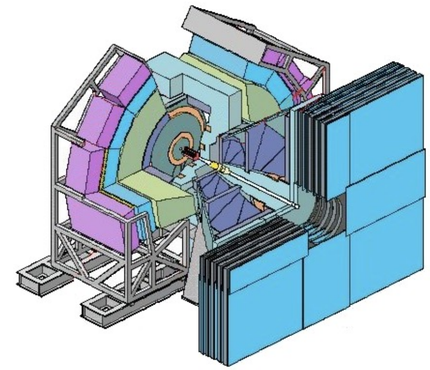
ATLAS and CMS



High-Energy Nuclear Collider Experiments

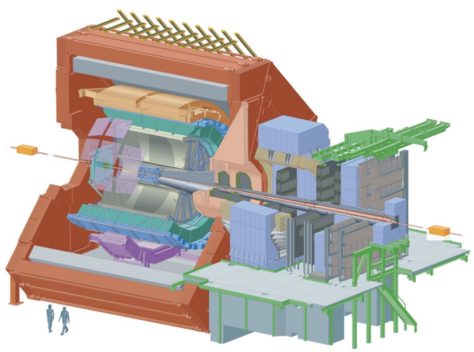


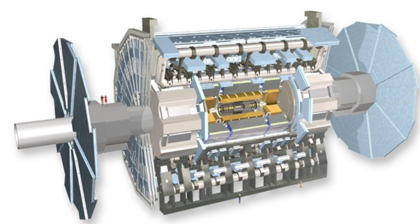
STAR (Solenoidal Tracker At RHIC)



PHENIX (Pioneering High Energy Nuclear Ion Experiment)

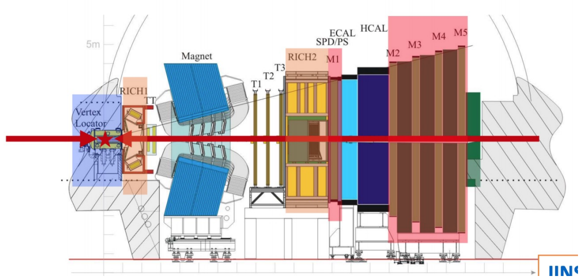
ALICE (A Large Ion Collider Experiment)

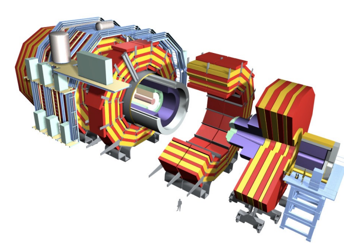




•**ATLAS** (A Toroidal LHC Apparatus)

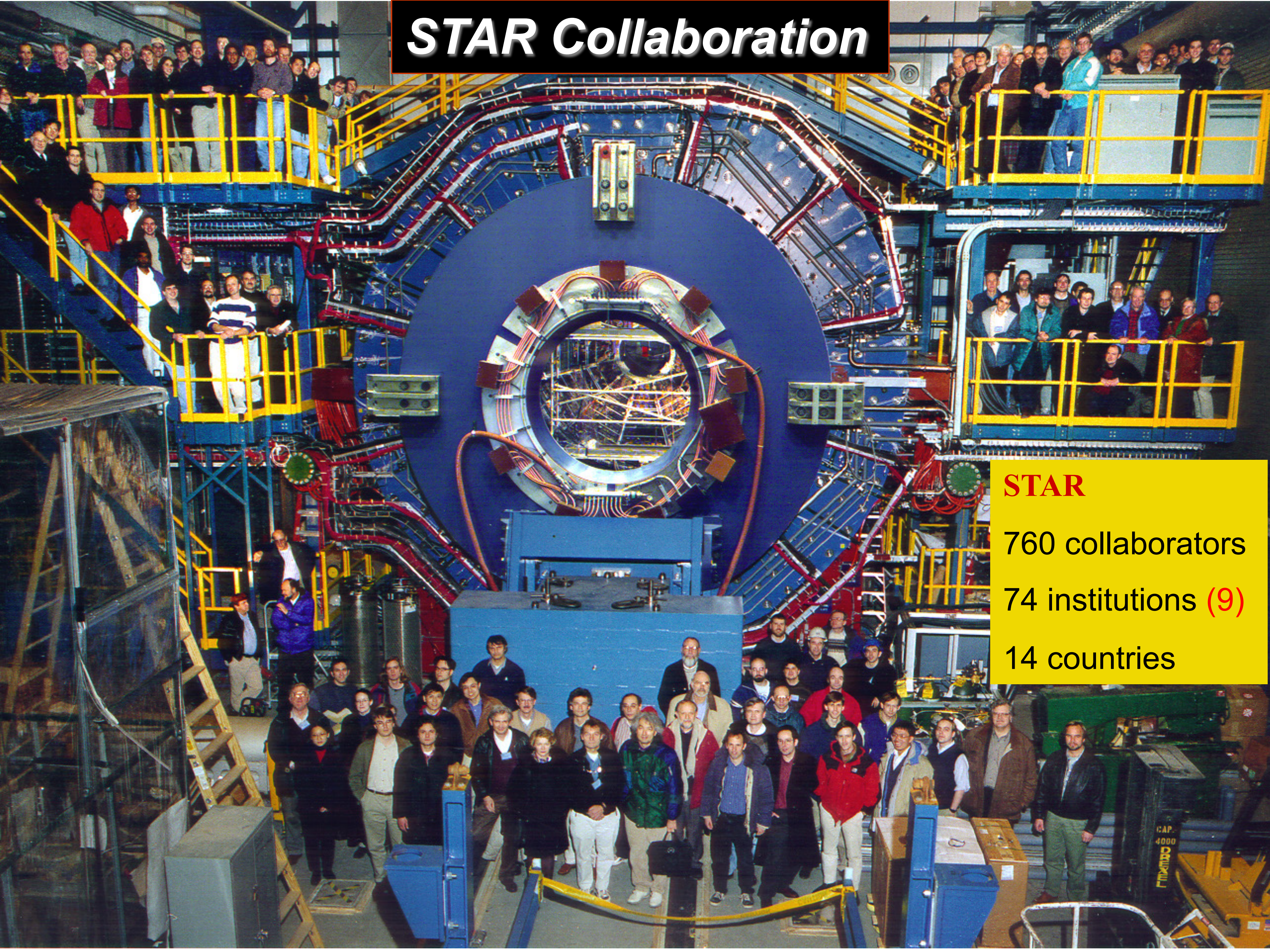
LHCb





CMS (Compact Muon Solenoid)

STAR Collaboration



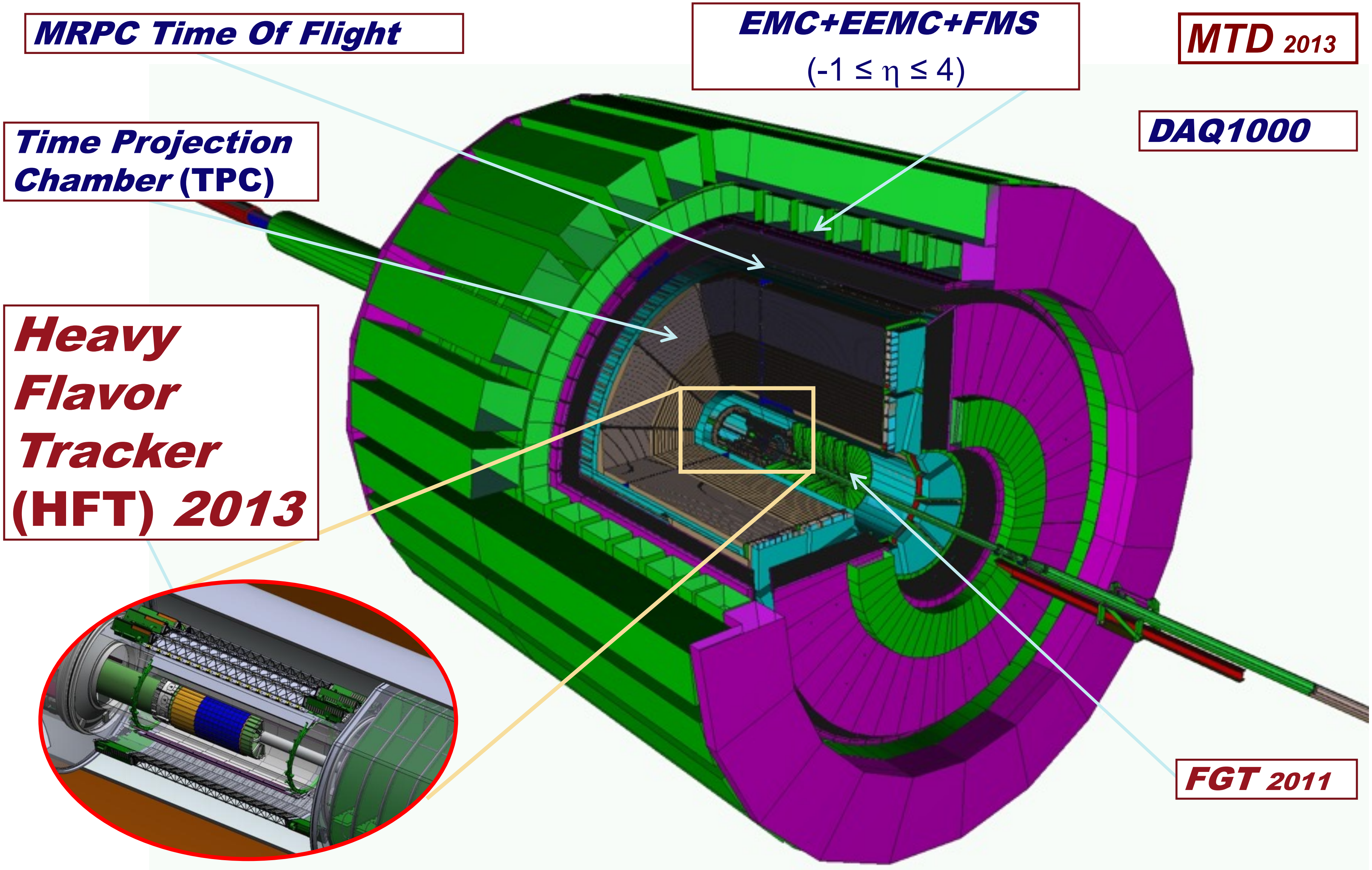
STAR

760 collaborators

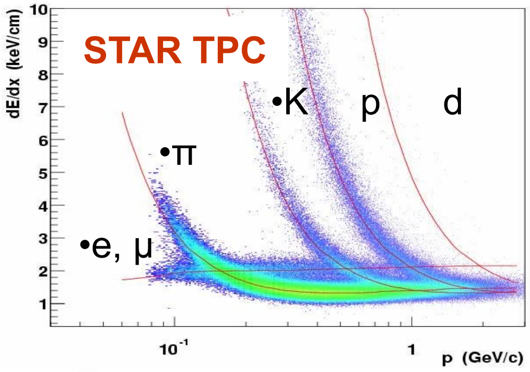
74 institutions (9)

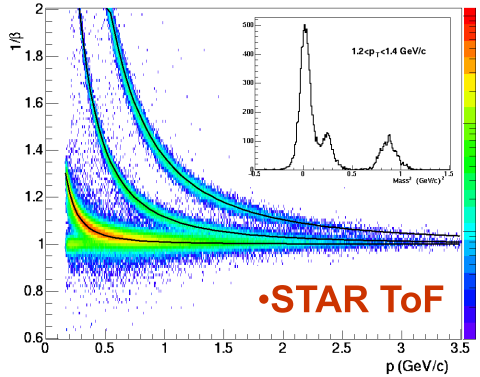
14 countries

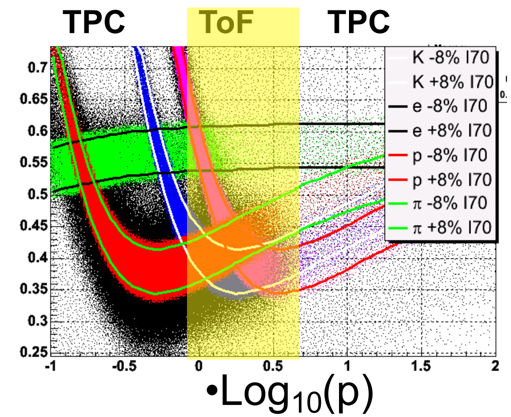
STAR Detectors *Fast and Full azimuthal particle identification*

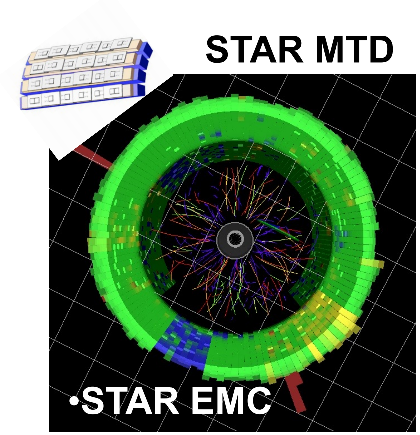


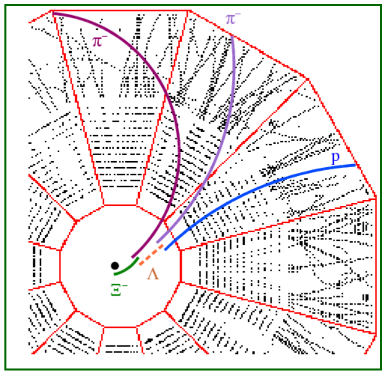
Particle Identification at STAR

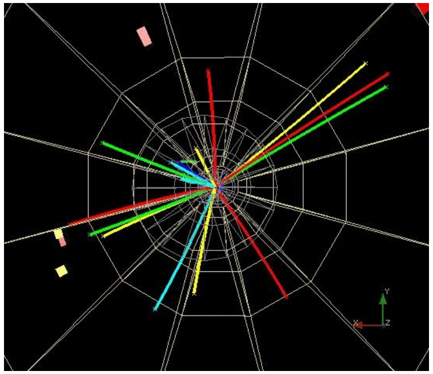


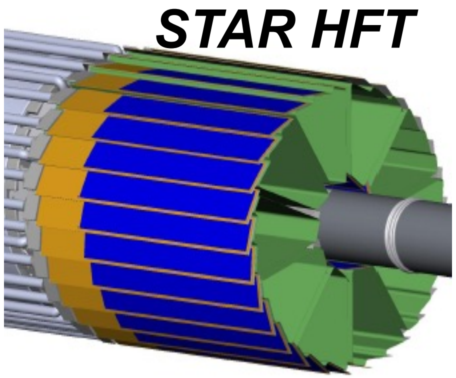












Neutral particles **Strange hyperons Hadrons** **Jets** **Heavy Quark**

Particle Identification

Rest are constructed: Invariant Mass + Decay Topology

V0 decay vertices

$K_s \rightarrow \pi^+ + \pi^-$

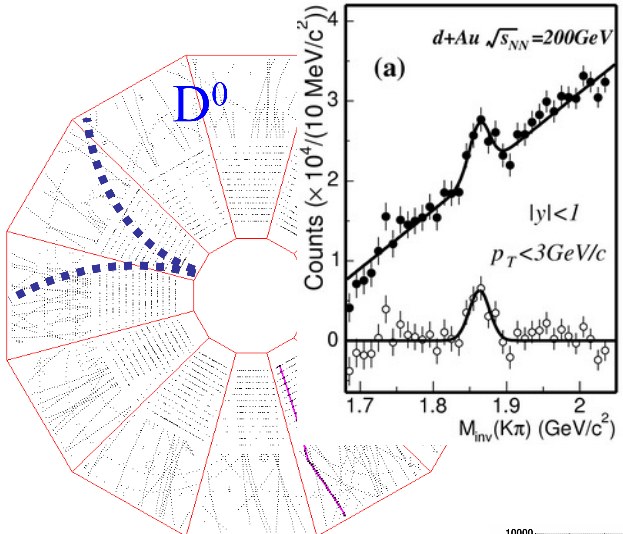
$\Lambda \rightarrow p + \pi^-$

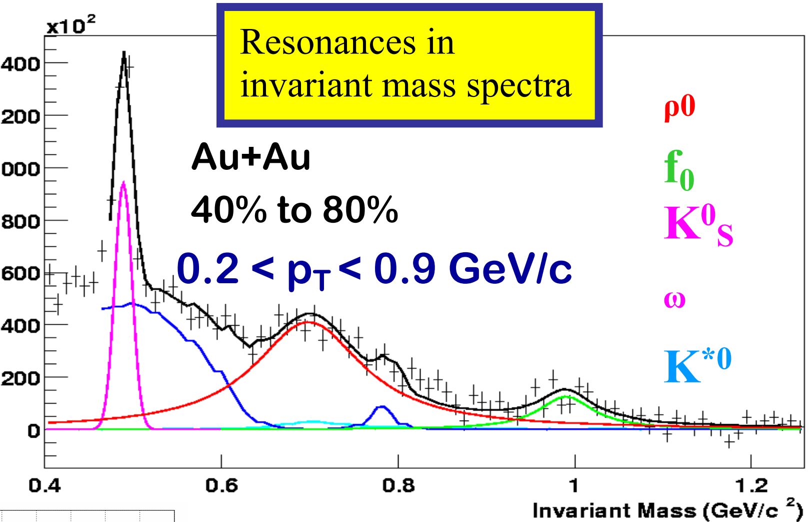
$\bar{\Lambda} \rightarrow \bar{p} + \pi^+$

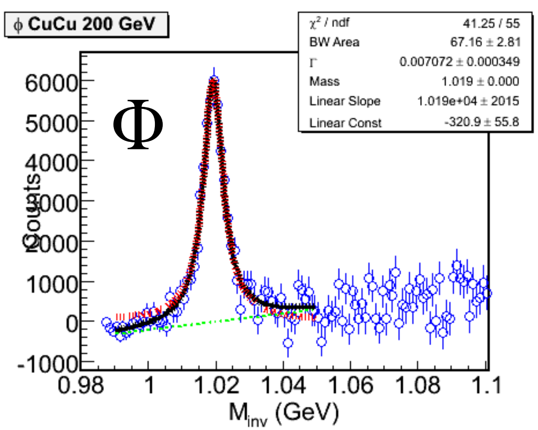
$\Xi^- \rightarrow \Lambda + \pi^-$

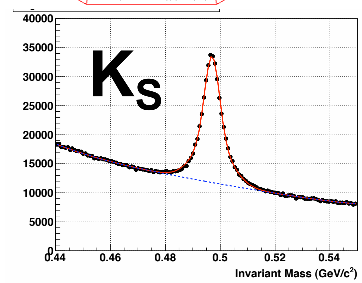
$\Xi^+ \rightarrow \bar{\Lambda} + \pi^+$

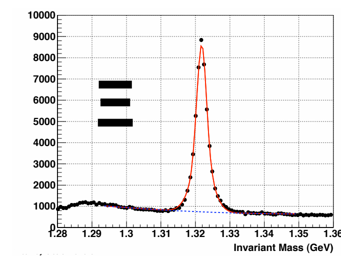
$\Omega \rightarrow \Lambda + K^-$

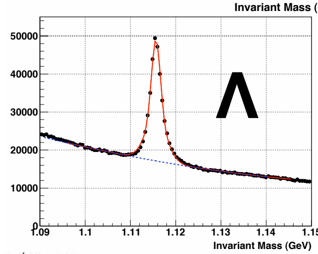


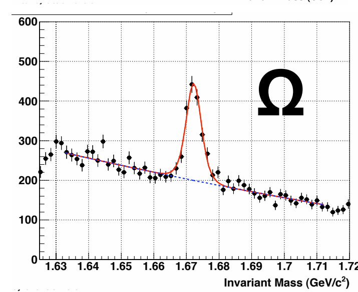




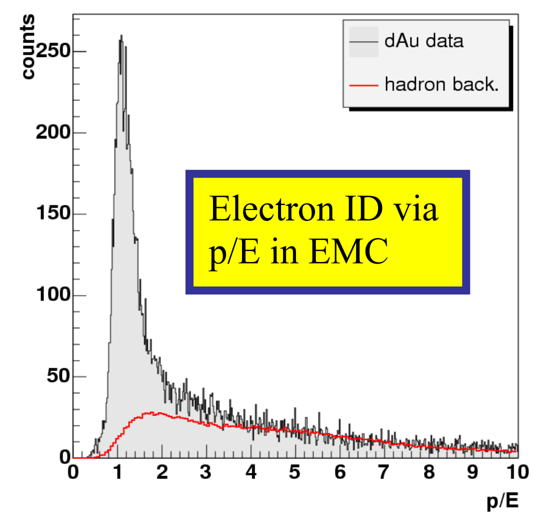






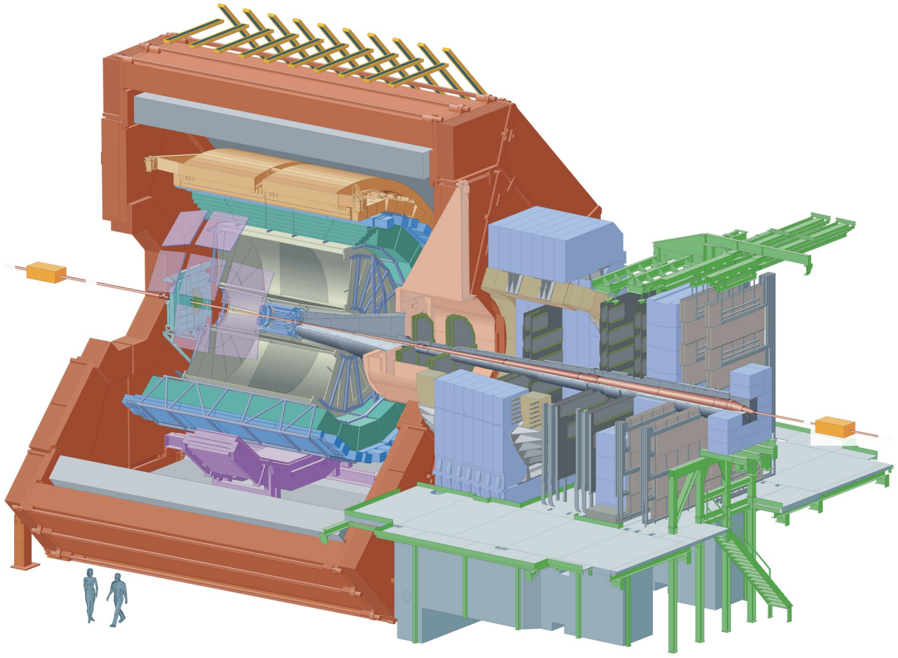


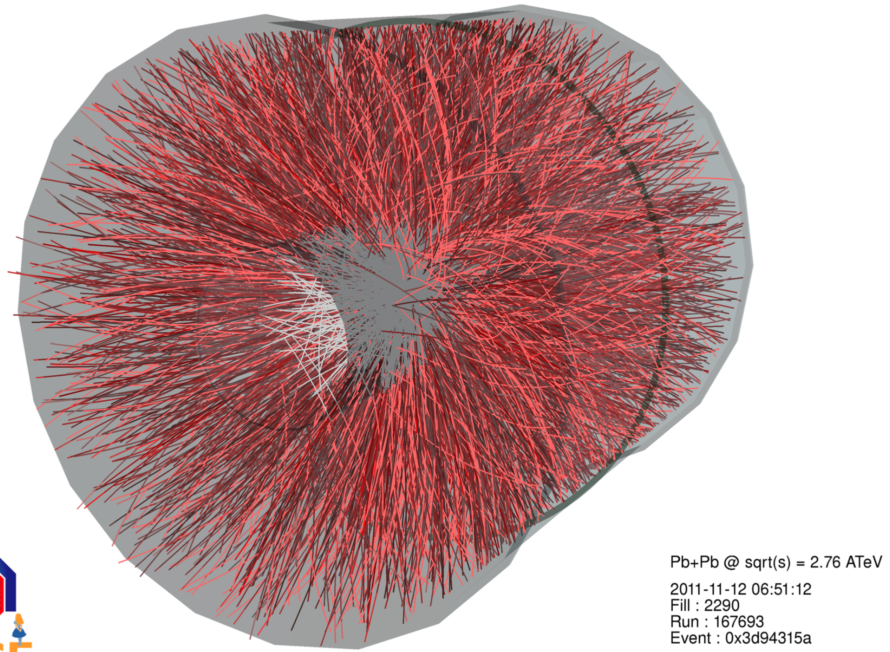
$$M^2 = E^2 - p^2$$



π^0, K^0_s, ρ, ω K^*, Λ, ϕ Ξ Ω, D0 …..

ALICE



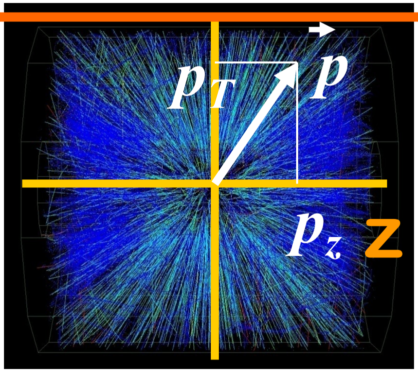

Pb+Pb @ sqrt(s) = 2.76 ATeV
2011-11-12 06:51:12
Fill : 2290
Run : 167693
Event : 0x3d94315a

Frequently used Kinematics Variable and Expression

Relativistic Energy : $E = (p^2 + m_0^2)^{1/2}$

Transverse mass: $m_T \equiv \sqrt{p_T^2 + m^2}$

$P_T = P \sin\theta$



Rapidity:

$$y \equiv \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

$$E = m_T \cosh y$$

$$p_z = m_T \sinh y$$

p=100 GeV/c, y=5.36

p=1380 GeV/c. y=7.99

Pseudo-rapidity :

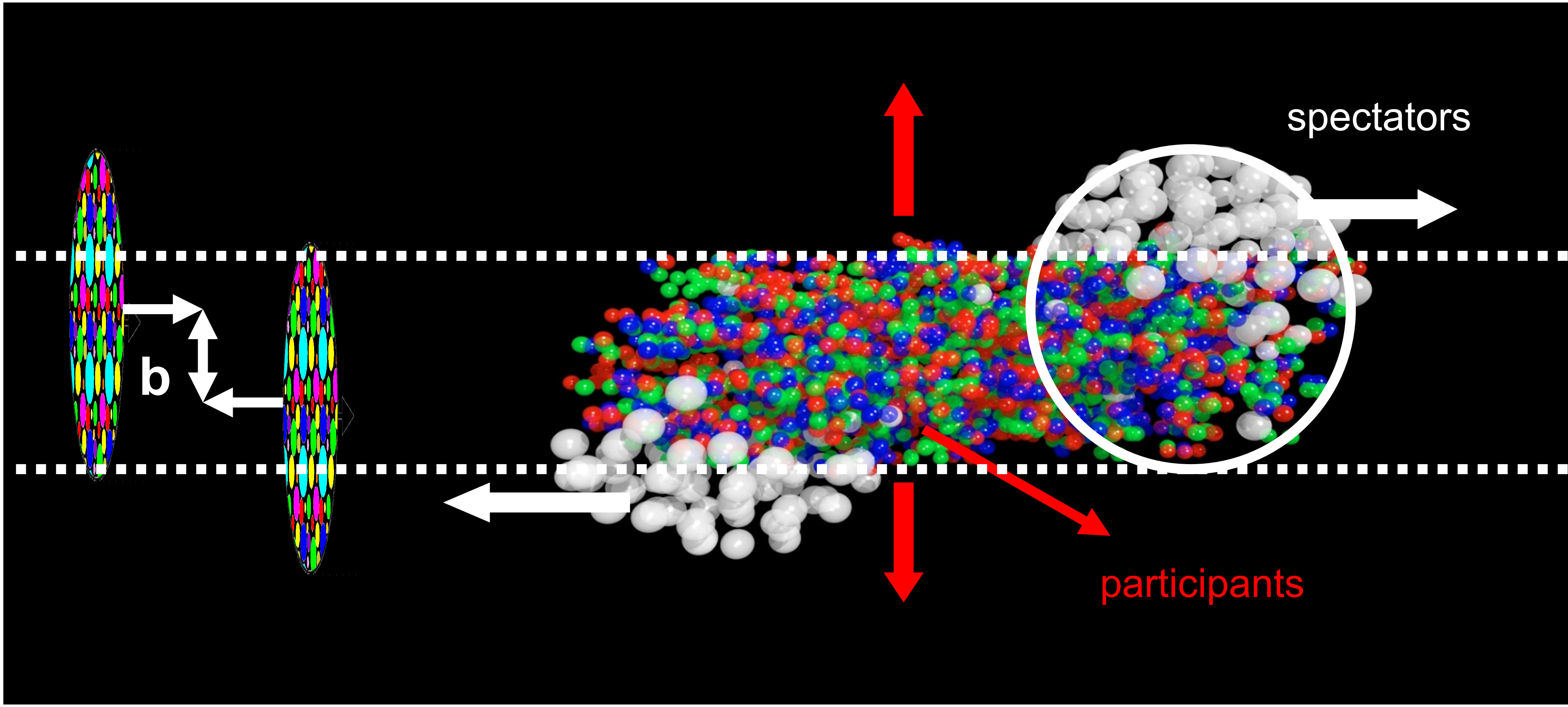
$$\eta = \frac{1}{2}\ln\left(\frac{|\vec{p}|+p_l}{|\vec{p}|-p_l}\right) = -\ln\left(\tan\frac{\theta}{2}\right)$$

$$p = p_T \cosh\eta$$

$$p_z = p_T \sinh\eta$$

$$v \approx c, y \approx \eta; \ \ \eta = 0, \theta = 90°$$

Centrality determination (I)



- Centrality characterized by:
  - N_{part}, $N_{wounded}$: number of nucleons which suffered at least one inelastic nucleon-nucleon collision
  - N_{coll}, N_{bin}: number of inelastic nucleon-nucleon collisions

Glauber Model Calculations

- Nuclear density from Wood-Saxon distribution

$$\rho(r) = \frac{\rho_0 \left(1 + wr^2 / R^2\right)}{1 + e^{(r-R)/a}}$$

Nucleus	A	R	a
Au	197	6.38	0.535
Pb	208	6.68	0.546

- Nucleons travel on straight lines, no deflection after NN collision
- NN collision cross section from measured inelastic cross section in p+p
- NN cross section remains constant independent of how many collisions a nucleon suffered

$\sqrt{S}$ (GeV)	$\sigma_{in,pp}$ (mb)
20	32
200	42
5500	~70

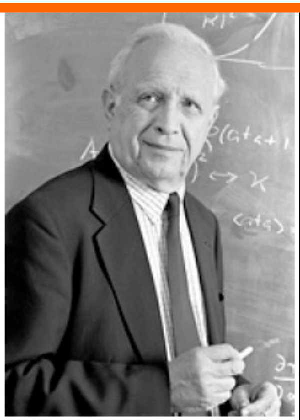
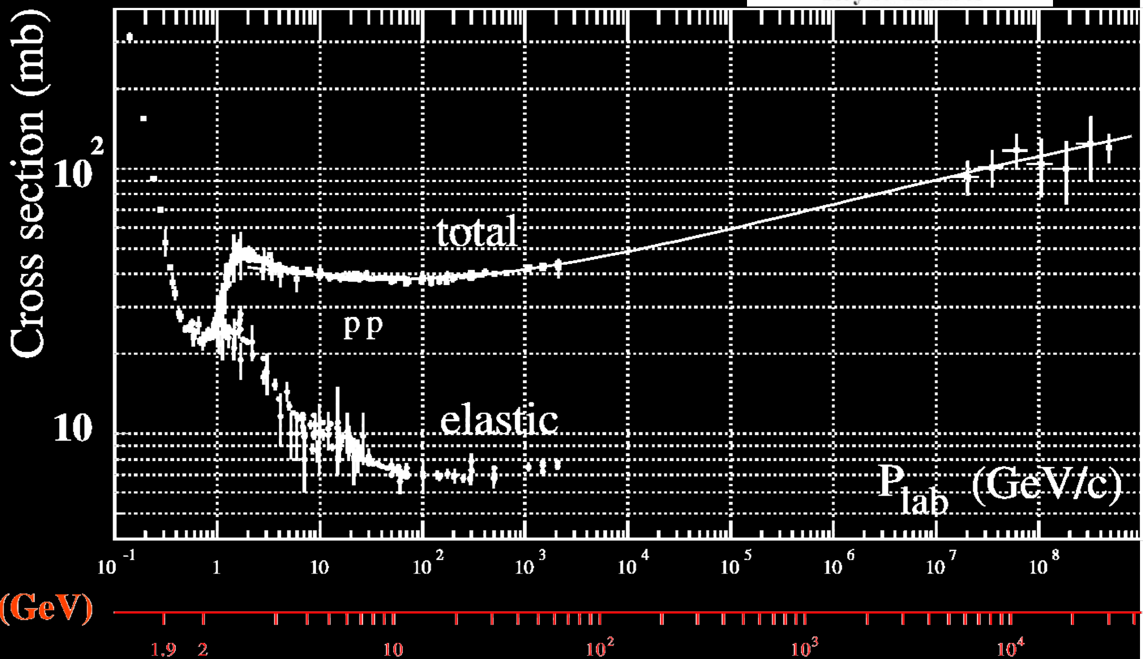


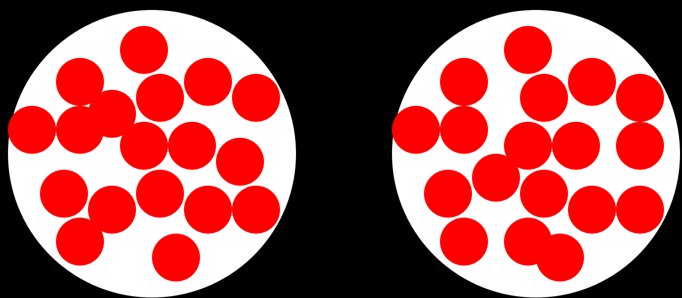
Photo: J.Reed

Roy J. Glauber



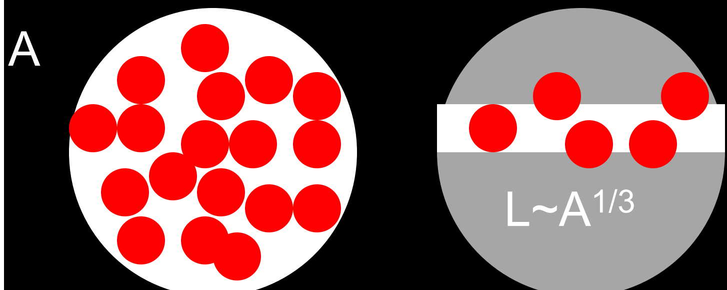
Wounded nucleons and binary collisions

Wounded nucleon scaling

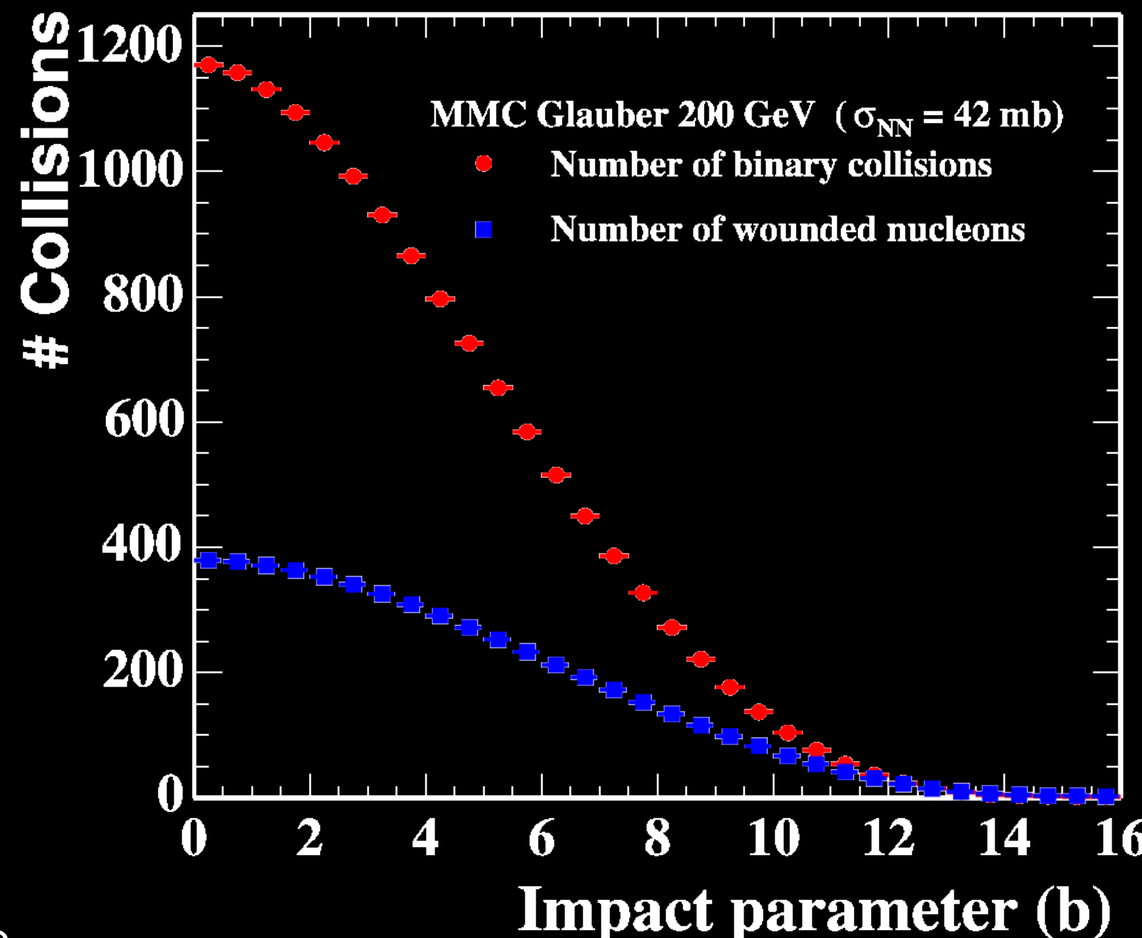


Number of participating nucleons scales with volume ~ 2A

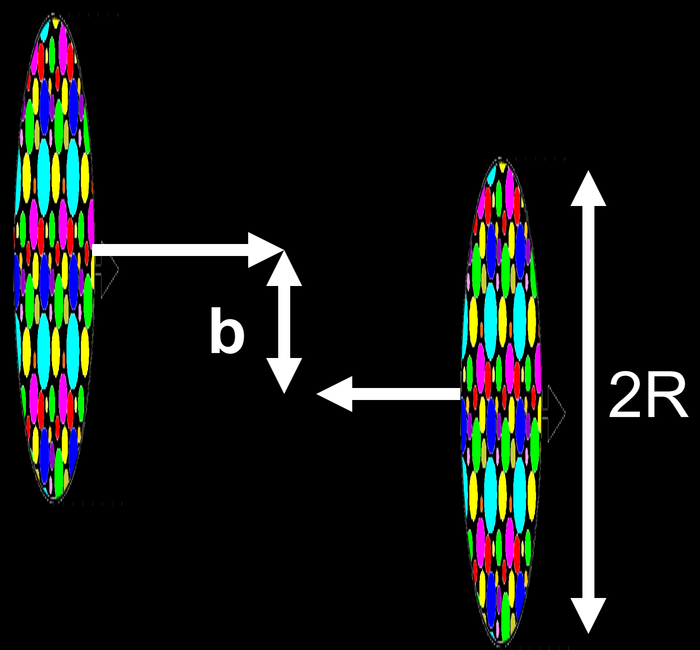
Binary scaling

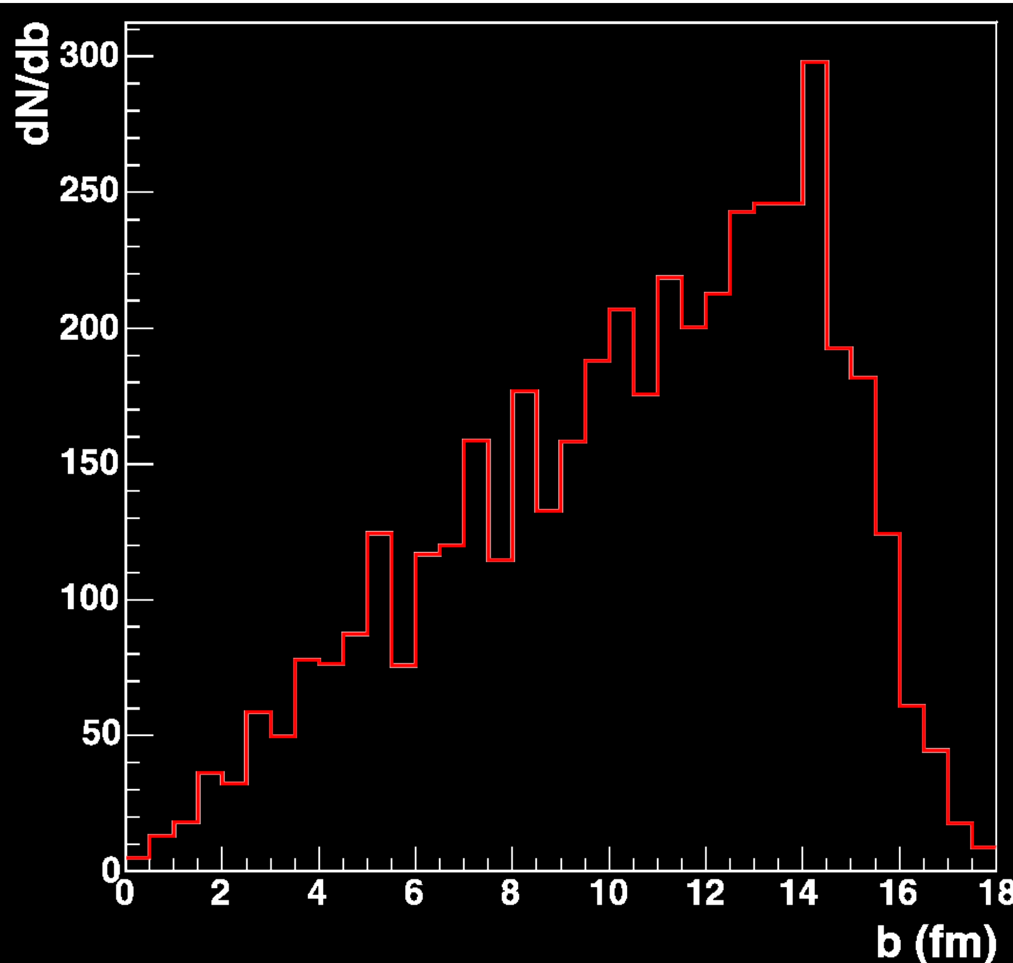


Number of NN collisions, point like, scales with ~ $A^{4/3}$



Impact parameter distribution

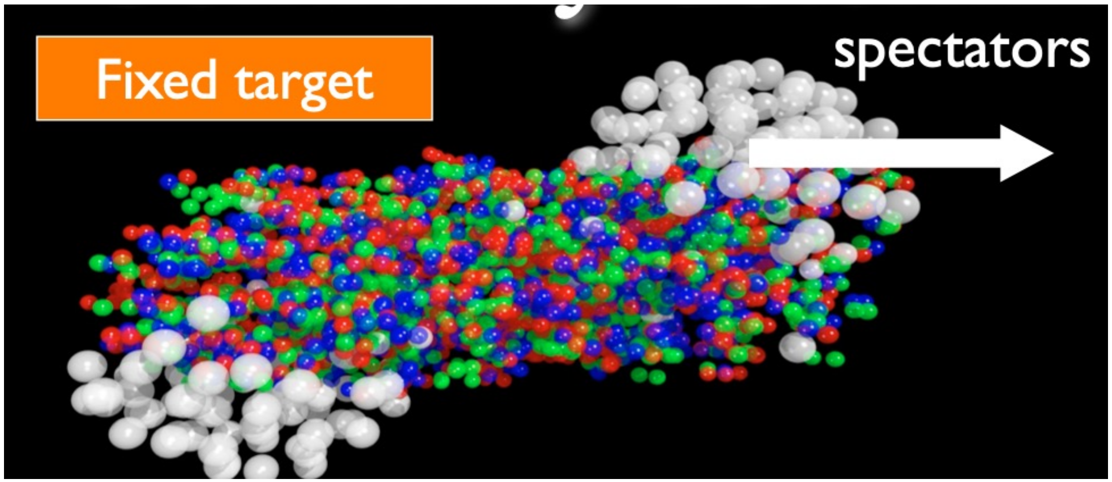




- impact parameter **b**
  - perpendicular to beam direction
  - connects centers of the colliding ions

$$d\sigma = 2\pi b \, db$$

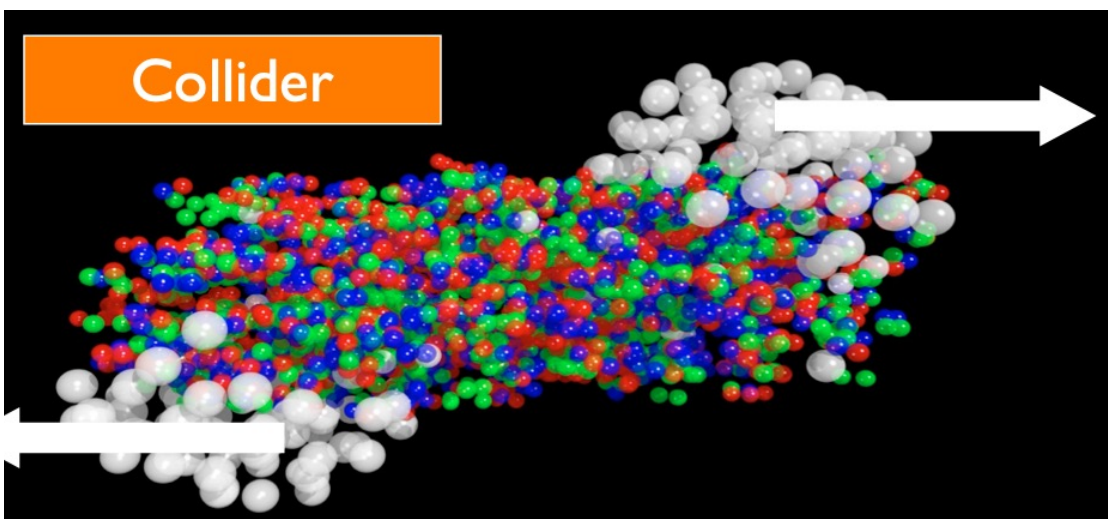
Centrality determination



Zero-Degree-Calorimeter (ZDC) measures energy of all spectator nucleons

$$N_{spec} \approx \frac{E_{ZDC}}{(E_{beam})}/A$$

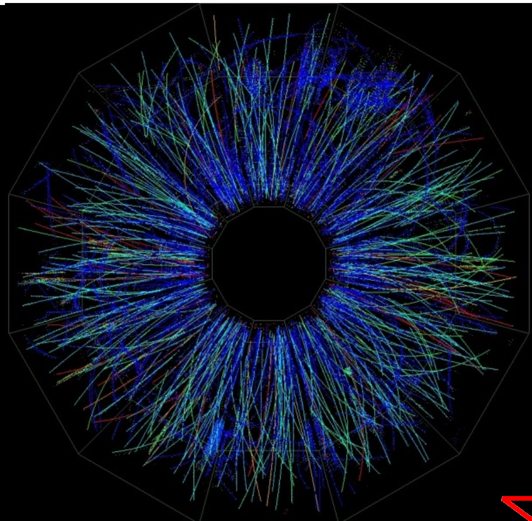
$$N_{part} \approx 2(A - N_{spec})$$



Zero-Degree-Calorimeter (ZDC) measures energy of all unbound spectator nucleons

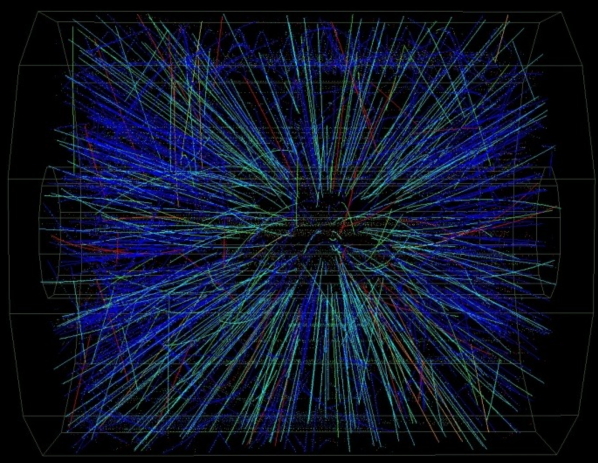
- charged fragments (p, d, and heavier) are deflected by accelerator magnets
- E_{ZDC} small for very central and very peripheral collisions, ambiguous

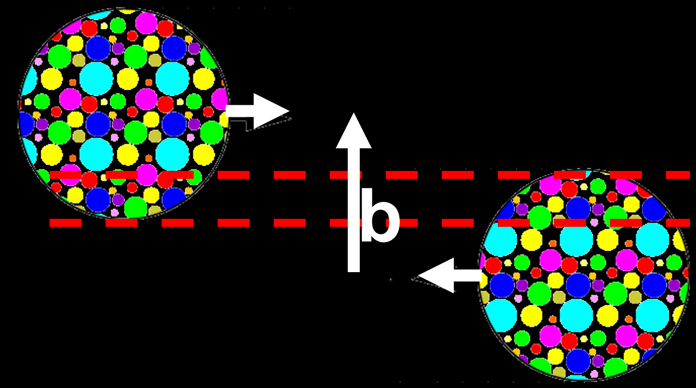
Centrality determination (II)



Peripheral Event

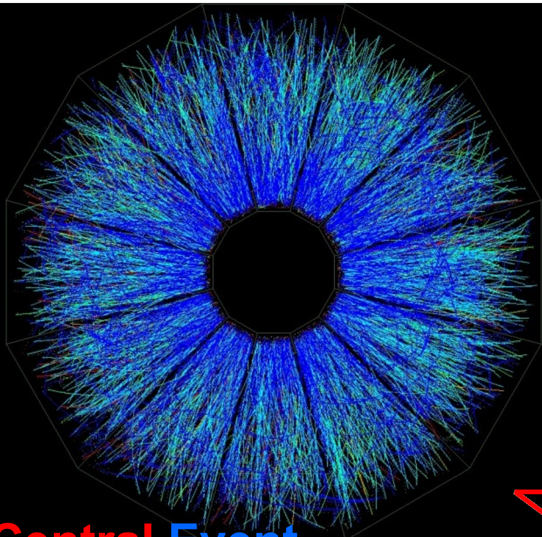
From real-time Level 3 display





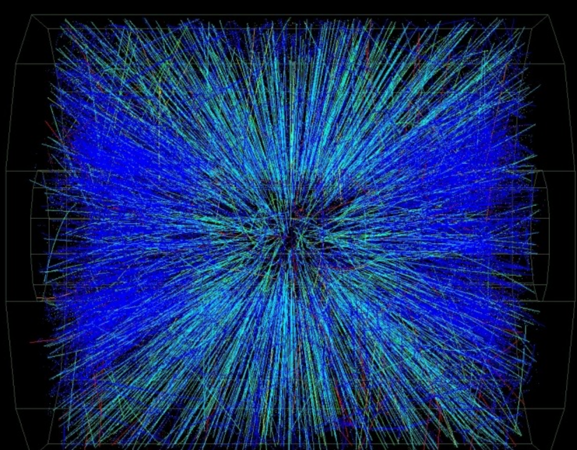
- peripheral collisions, largest fraction cross section
- many spectators
- “few” particles produced

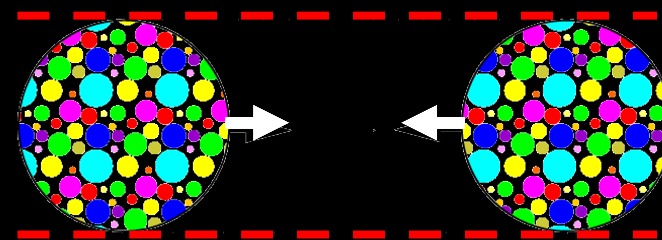
Centrality determination (III)



Central Event

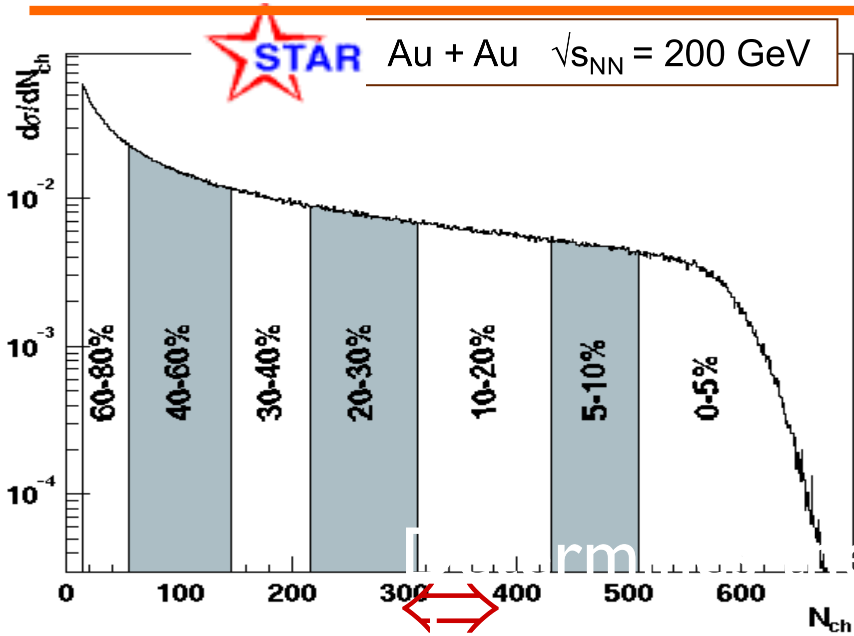
From real-time Level 3 display

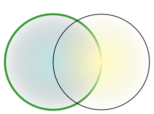


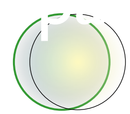


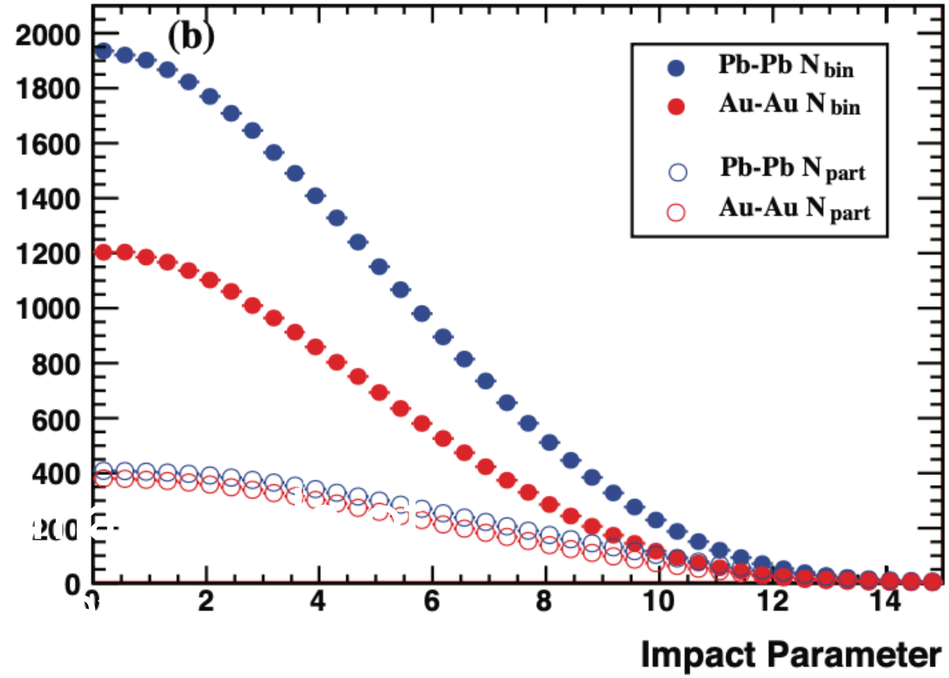
- impact parameter **b** = 0
- central collisions, small cross section
- no spectators
- many particles produced

Collision Geometry









Charged particle multiplicity

⇕

collision centrality

Determines the magnitude of the impact parameter

$\%\sigma_{tot}$	$\langle N_{part}\rangle$	$\langle b\rangle$
0-5	386	2.48
20-30	177	7.85
60-70	25	12.66

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 $\otimes$ Local Thermalization

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.

观察的现象从强子的角度很难解释，但有一个基于夸克和胶子的简单定性解释

Outline

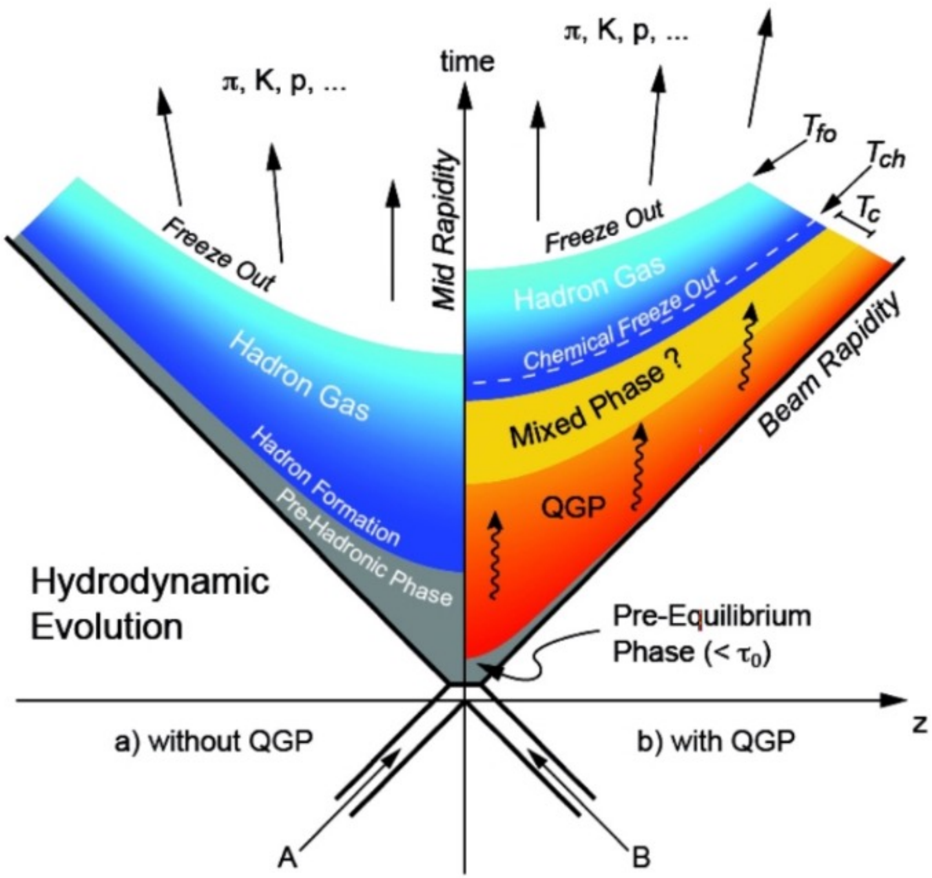
- Introduction
- Perfect Liquid at RHIC

  Energy loss

  Collectivity

  Perfect Liquid
- Criticality
- Summary and Outlook

Heavy Ion Collision Evolution



RHIC 200 GeV collisions:

Two nuclei collide

passage time: $2R/\gamma$ ~ 0.1 fm/c

Pre-equilibrium: < 1 fm/c

QGP evolution: ~ 5-10 fm/c

Hadronization:

Hadron gas evolution:

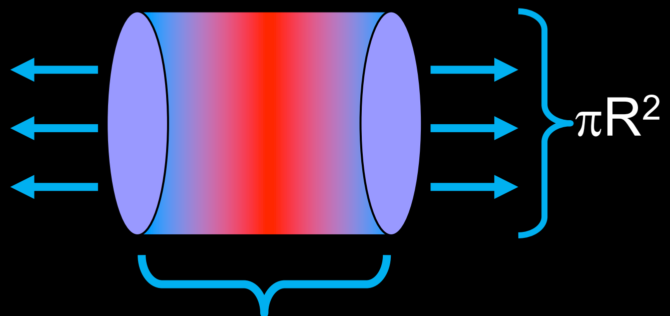
chemical freeze-out

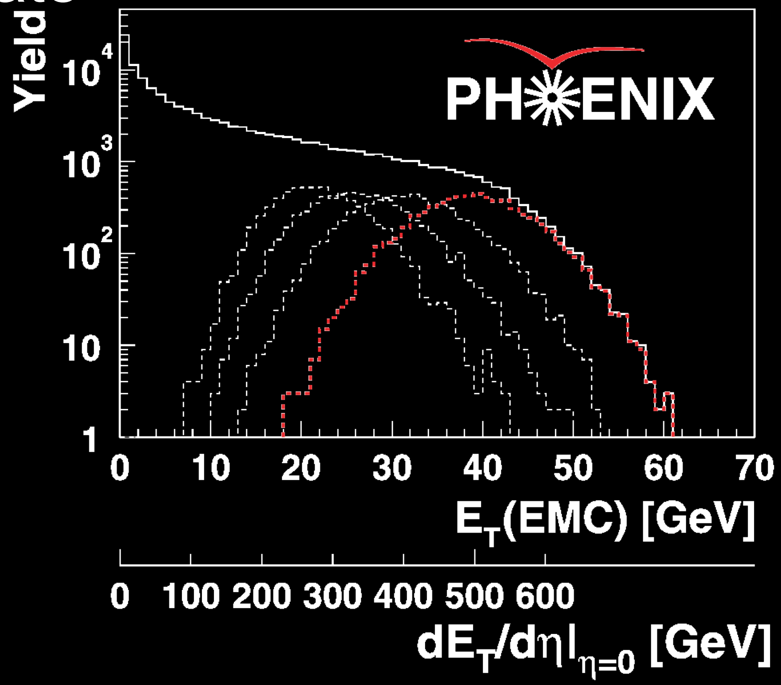
kinetic freeze-out ~ 10-20 fm/c

Transverse Energy and Energy Density

- Bjorken energy density estimate

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





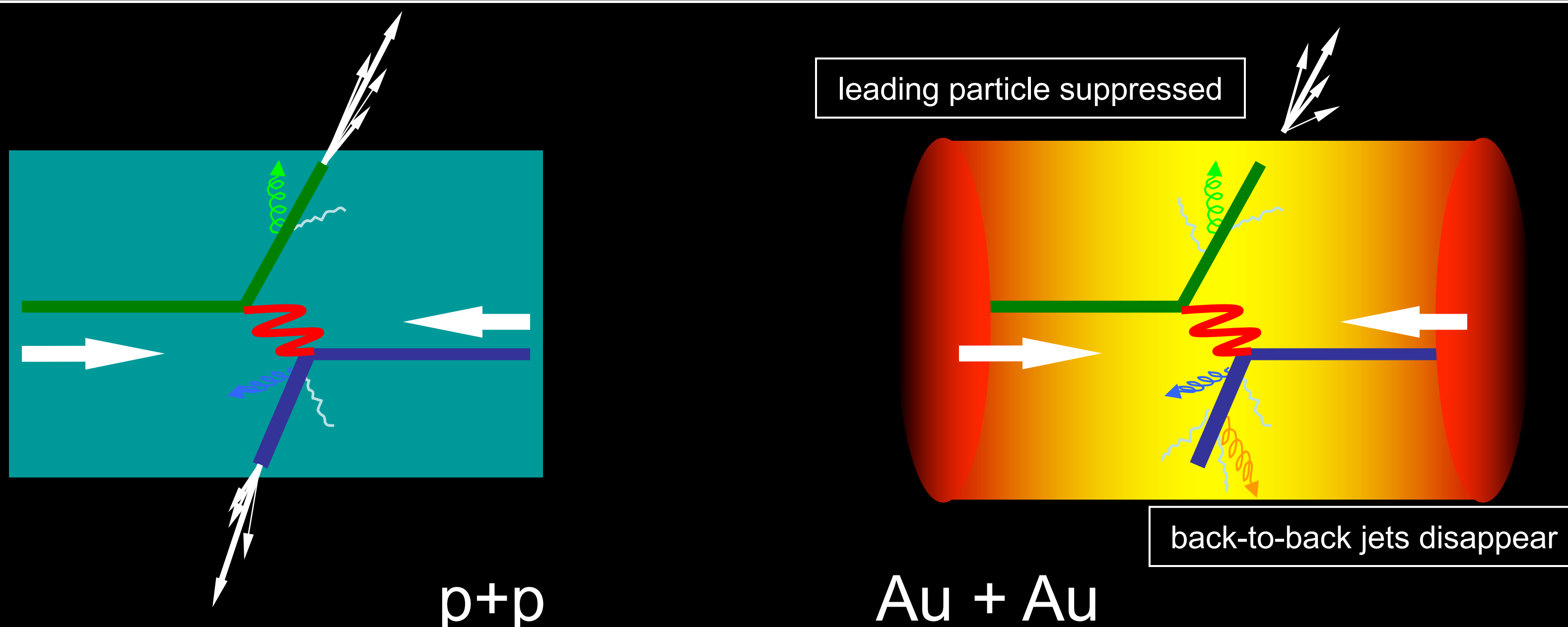
$$\varepsilon_{BJ} = 4.6\,\mathrm{GeV/fm^3}$$

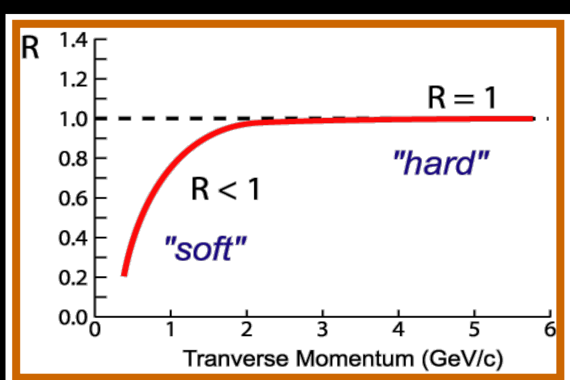
$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\ \mathrm{GeV}$$

- Much larger than the critical energy density !!

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

Energy Loss in A+A Collisions

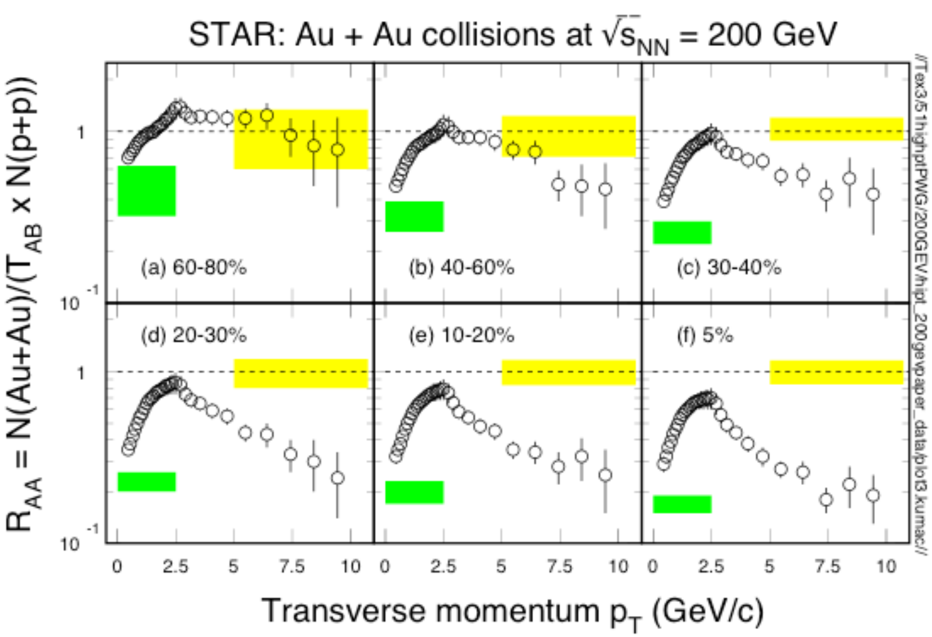


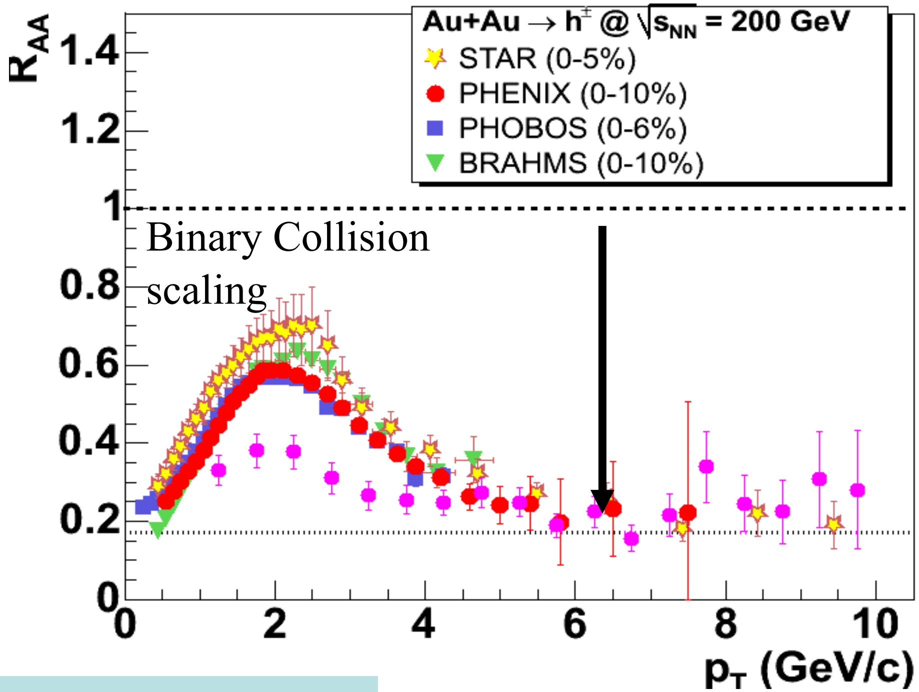


Nuclear Modification Factor:

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

Hadron Suppression at RHIC





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

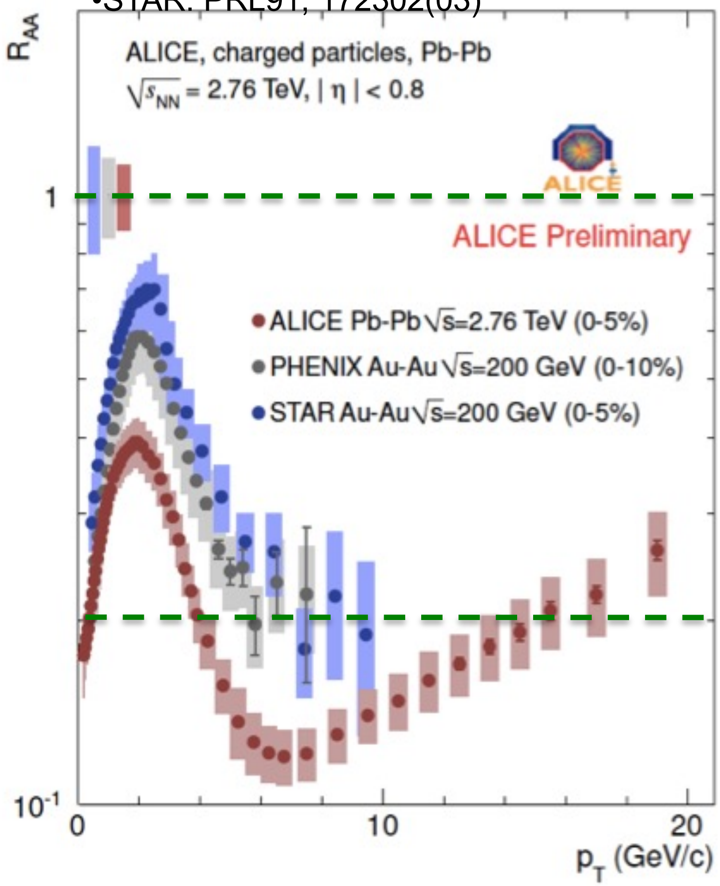
Factor 5 suppression: large effect

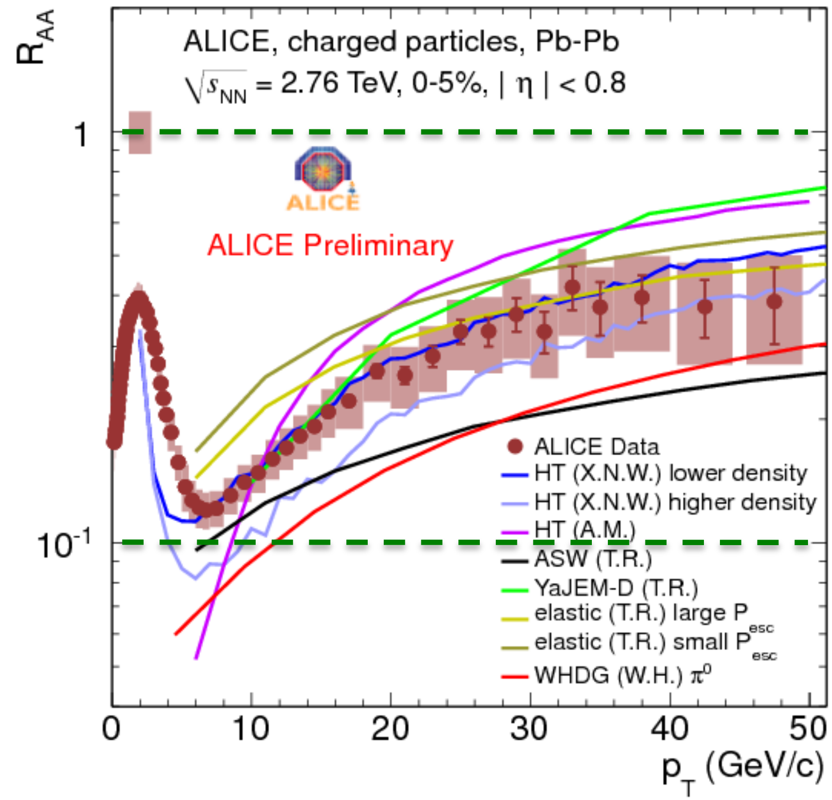
Energy density at RHIC: ε > 5 GeV/fm^3 ~ 30ε_0

Parton energy loss:	Bjorken	1982
("**Jet quenching**")	Gyulassy & Wang	1992

Nuclear Modification Factor

•PHENIX: PRC69, 034910(04)
•STAR: PRL91, 172302(03)



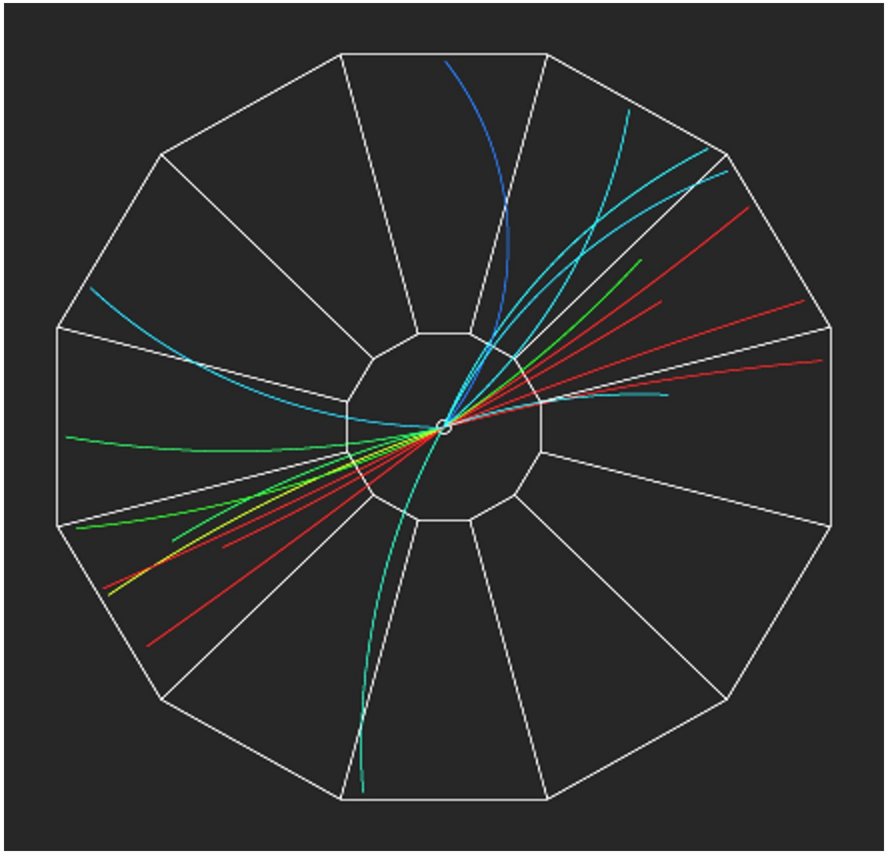


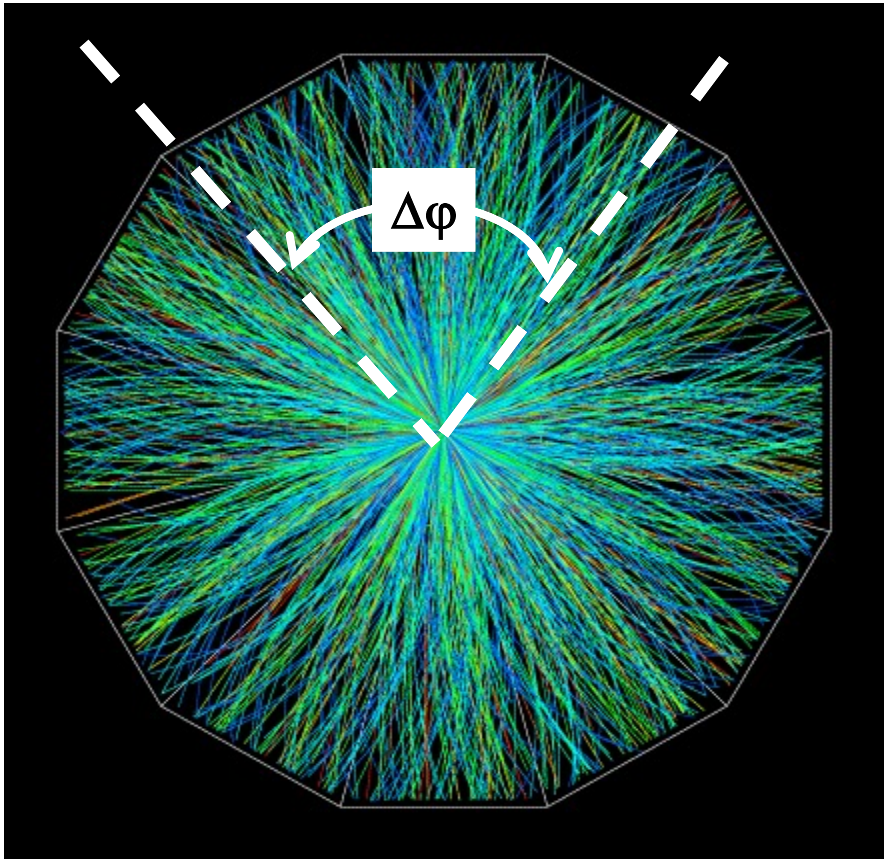
1) At LHC(2.76TeV), the energy loss is stronger than that from RHIC (0.2TeV)

➔ hotter/denser medium created at higher collision energy

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

Jets Observation at RHIC



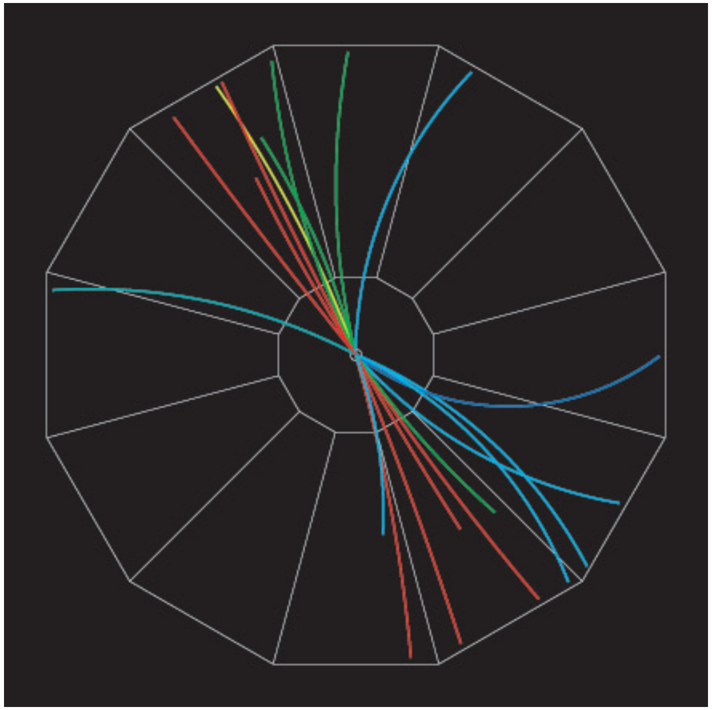


p+p collisions at RHIC
Jet like events observed

Au+Au collisions at RHIC
Jets?

Jets

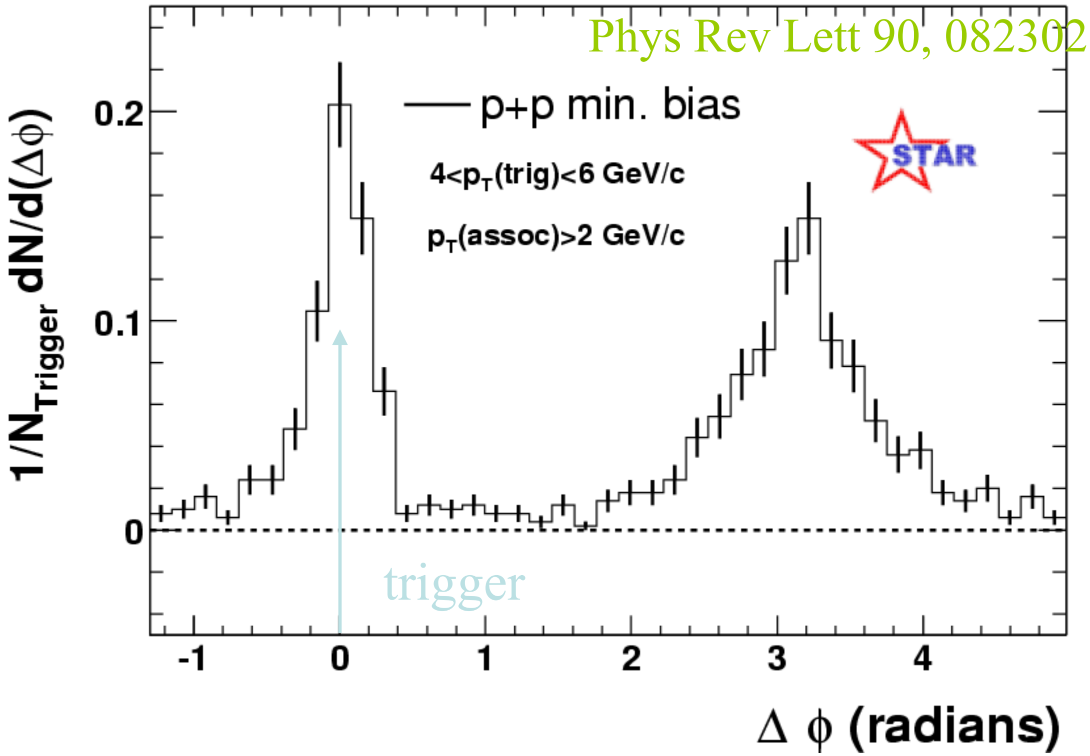
p+p → dijet



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

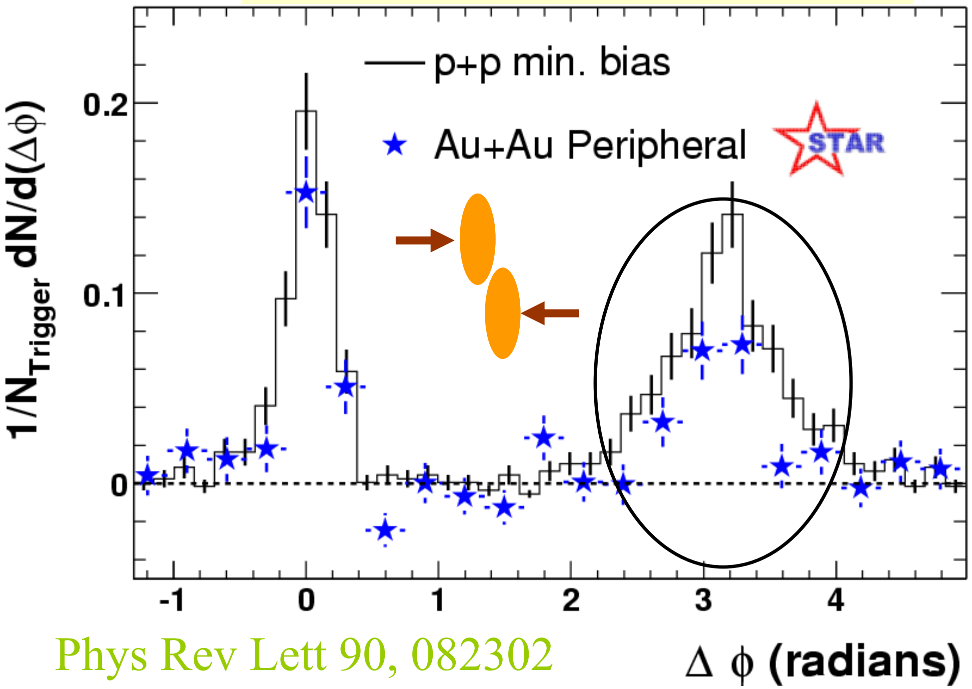
$\Delta\phi$ distribution: 2 GeV/c<p_T<$p_T^{trigger}$

normalize to number of triggers



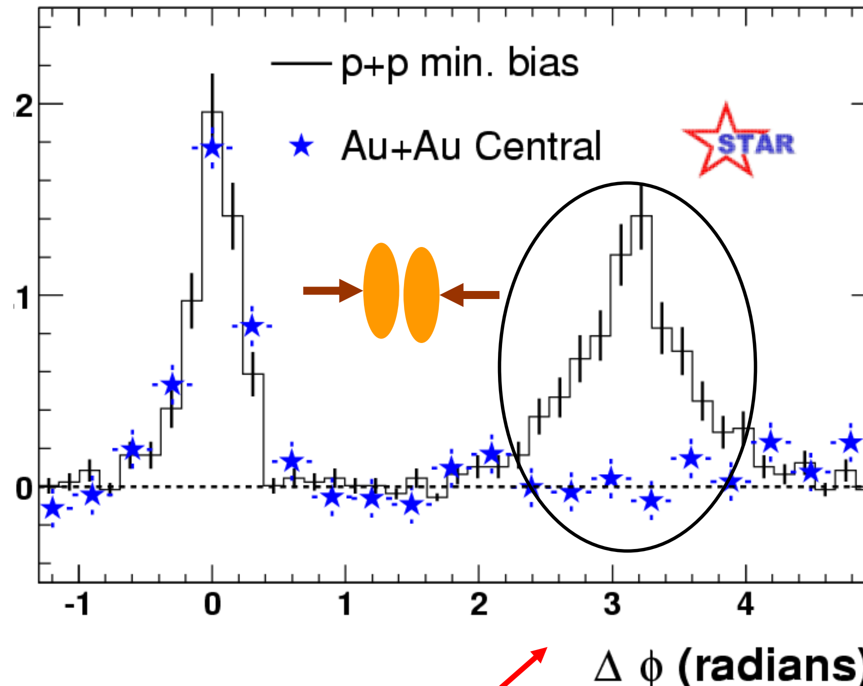
Dihadrons in Au+Au vs p+p

Au+Au peripheral
(large impact parameter)

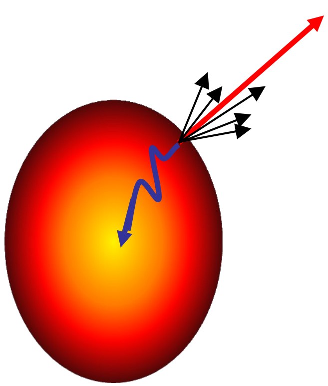


Phys Rev Lett 90, 082302

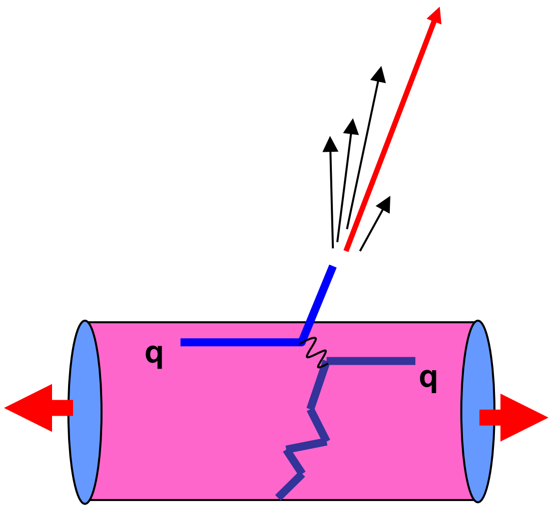
Au+Au central (head-on)



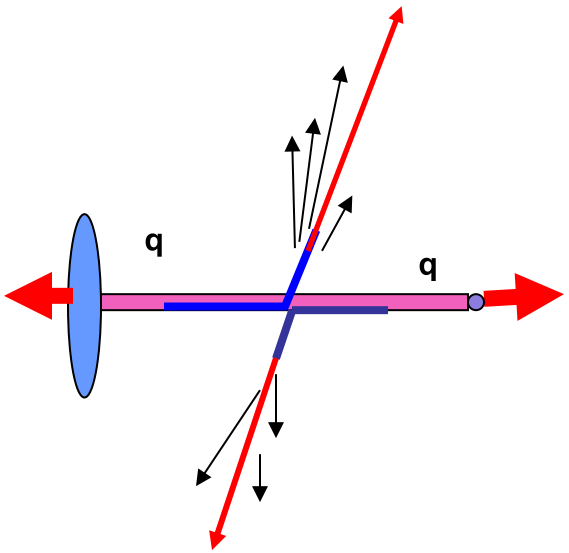
Strong suppression of back-to-back correlations in central Au+Au



d+Au Collisions



Au+Au Geometry

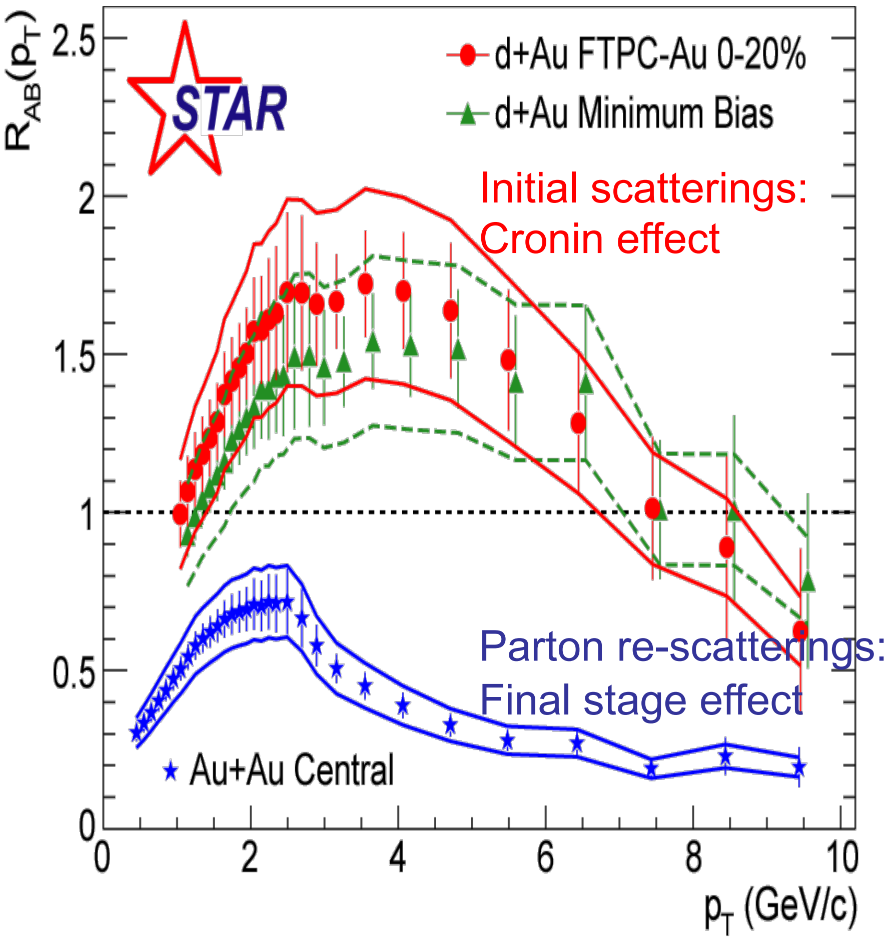


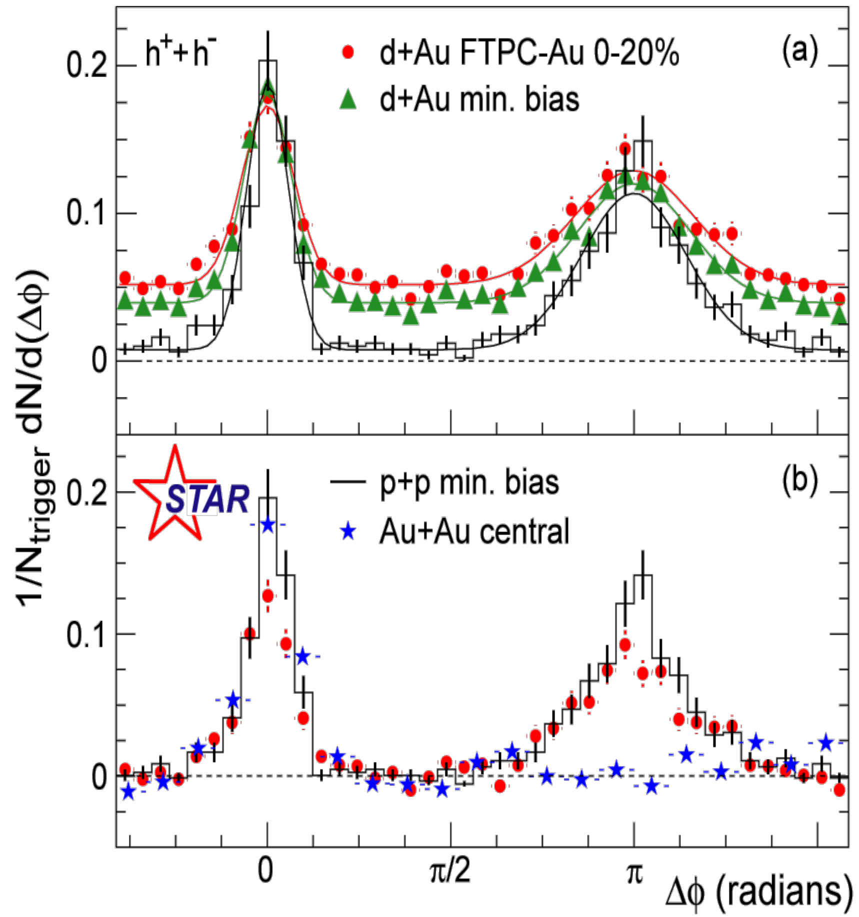
d+Au Geometry

d+Au collisions:

Little energy loss from the dense medium created, But Parton saturation from Au nuclei persists!

Data from d+Au collisions

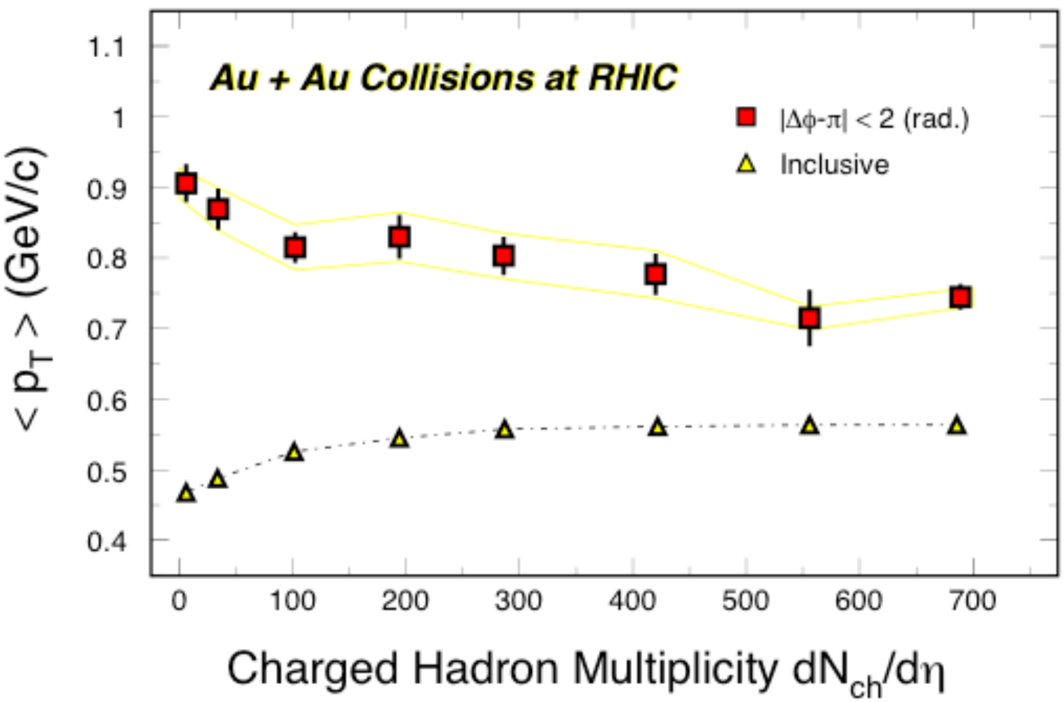


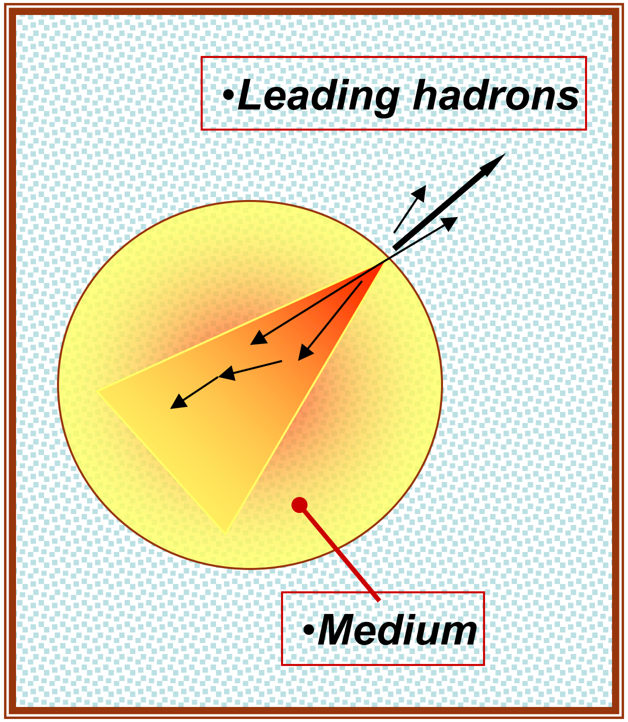


No high p_T suppression !

No disappearance of back-to-back correlations!

Energy Loss and Equilibrium





•In Au +Au collision at RHIC:

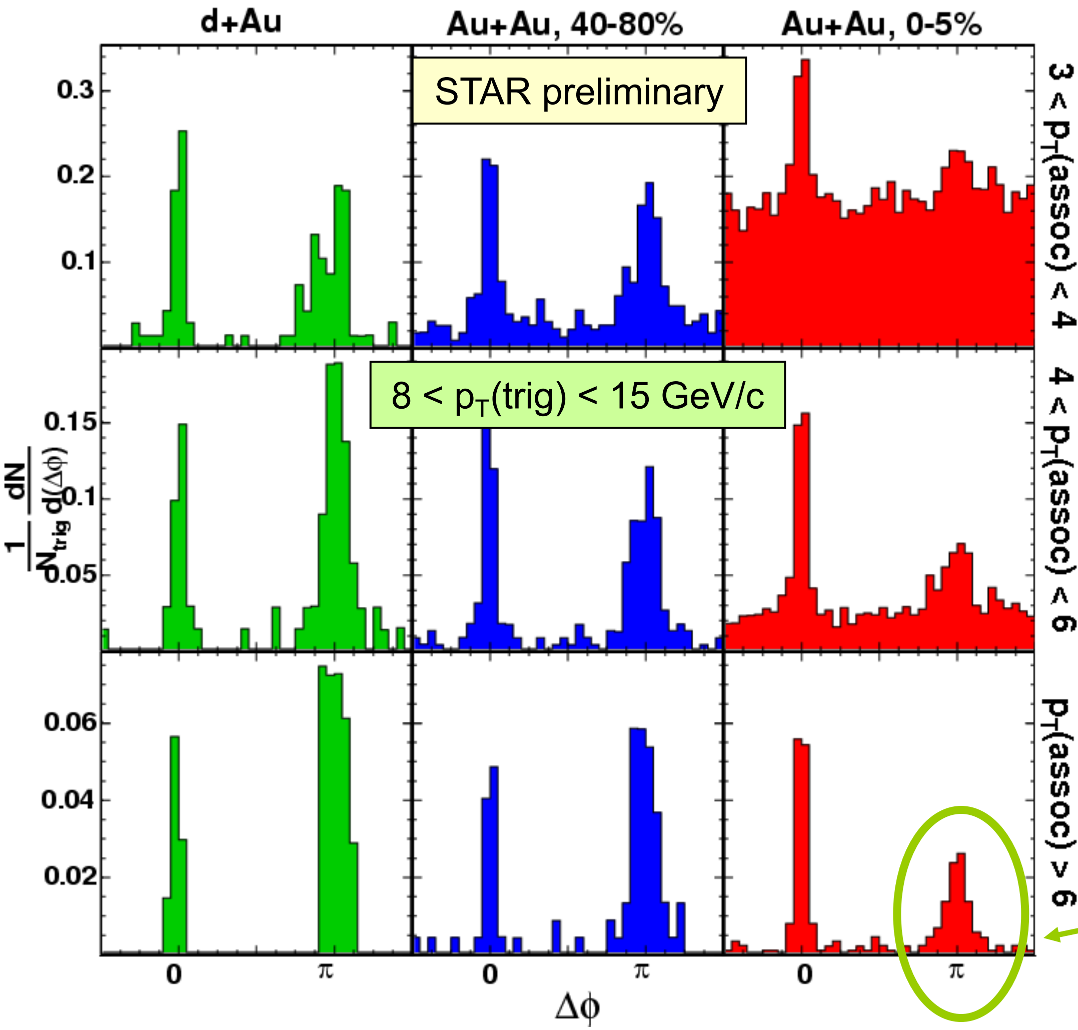
- Suppression at the intermediate p_T region - energy loss

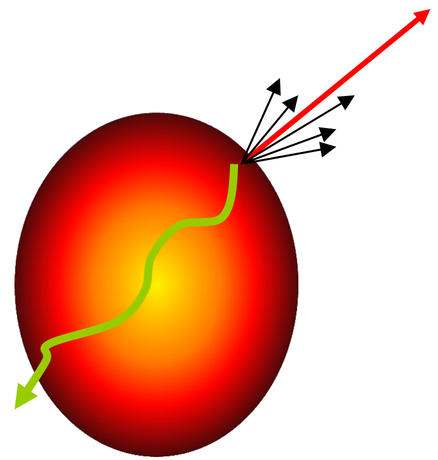
- The energy loss leads to progressive equilibrium in Au+Au collisions

•

STAR: nucl-ex/0404010

Di-hadron Measurements at Higher p_T





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

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

Summary I

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

Large suppression observed for pT ≥ 5 GeV/c indicating hot and dense medium produced in central Au+Au collisions

2）The estimated energy density in central collisions is about 30 times larger than ε_0

Very dense matter has been created in central Au+Au collisions!

This dense matter is responsible for the disappearance of back-to-back correlation and the suppression of high pT particles !

Study bulk property

Outline

- Introduction
- Perfect Liquid at RHIC
  - Energy loss
  - Collectivity
    - Spectra
    - Directed flow v_1
    - Elliptic flow v_2
  - Perfect Liquid
- Criticality
- Summary and Outlook

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***.

Collective Effects

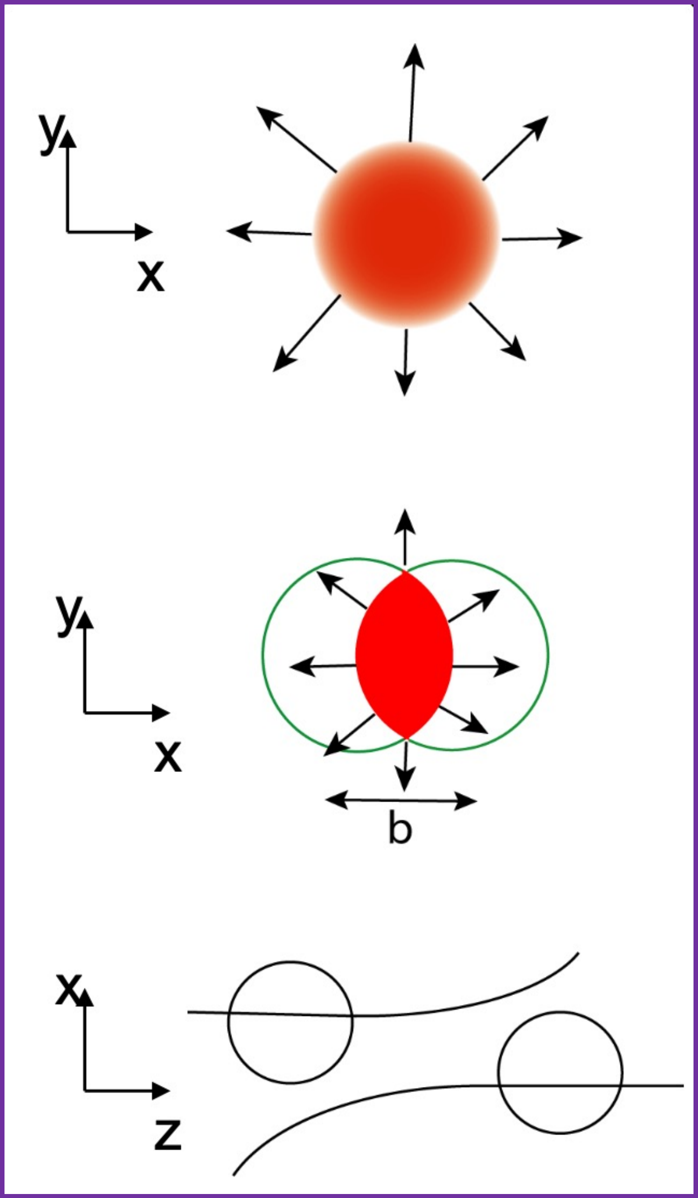
- **By studying collective effects we address the pressure part of the EoS**
- **No direct information on temperature**
- **Equilibrium aspect only circumstantial**

- This is not about rare events (e.g. jets) or rare particles.
- It is about how the system behaves as a whole.
- We need to look at the **bulk** of particle production. All the particles you see are useful here

~98% of all particles are produced with *p*T < 2 GeV/*c*

- **Hydrodynamics:**
  - **Flow = Space-Momentum Correlations**
- **Experimentally:**
  - **Momentum vectors are measured**
  - **Collectivity (Flow) defined in Momentum Space**

Collective Motion

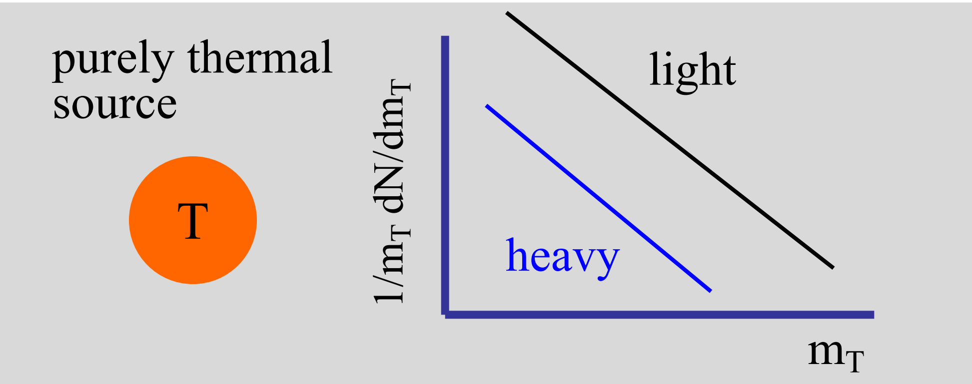


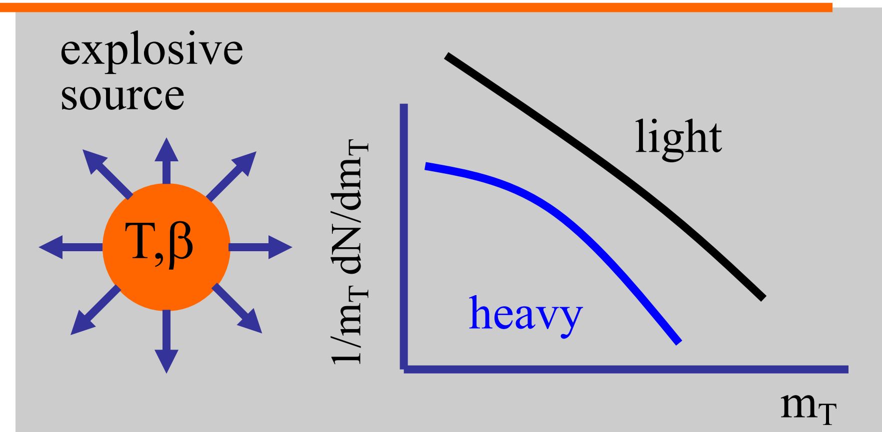
- only type of transverse flow in central collision (b=0) is radial flow
- Integrates pressure history over complete expansion phase

- elliptic flow (v_2) caused by anisotropic initial overlap region (b > 0)
- more weight towards early stage of expansion

- directed flow (v_1) , sensitive to earliest collision stage (b > 0),
- pre-equilibrium at forward rapidity, at midrapidity perhaps different origin

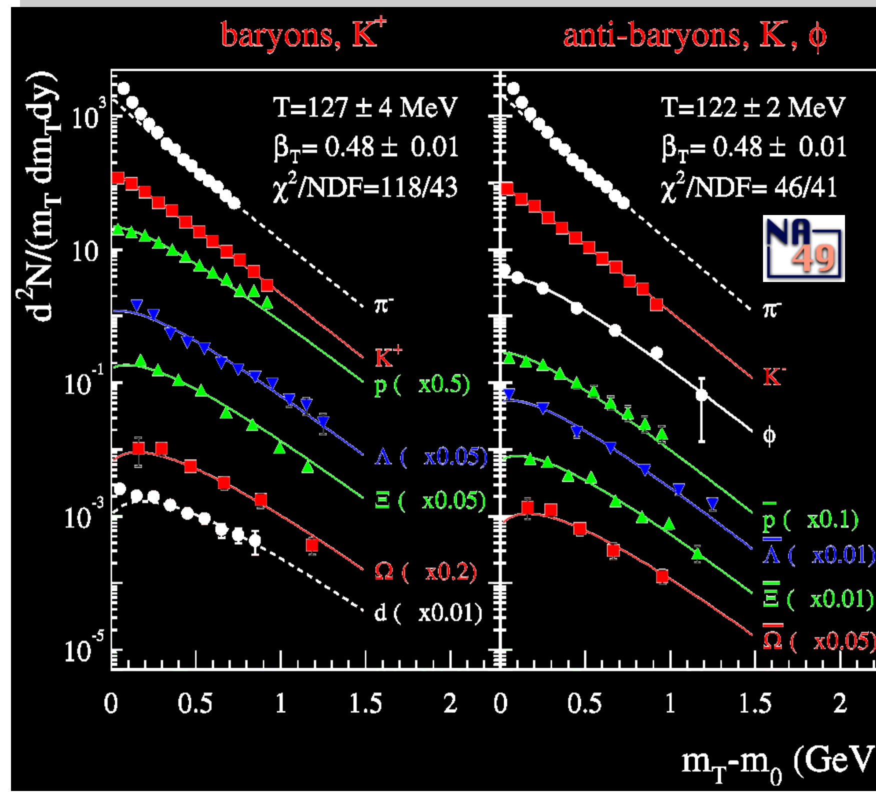
Identified Particle Spectra



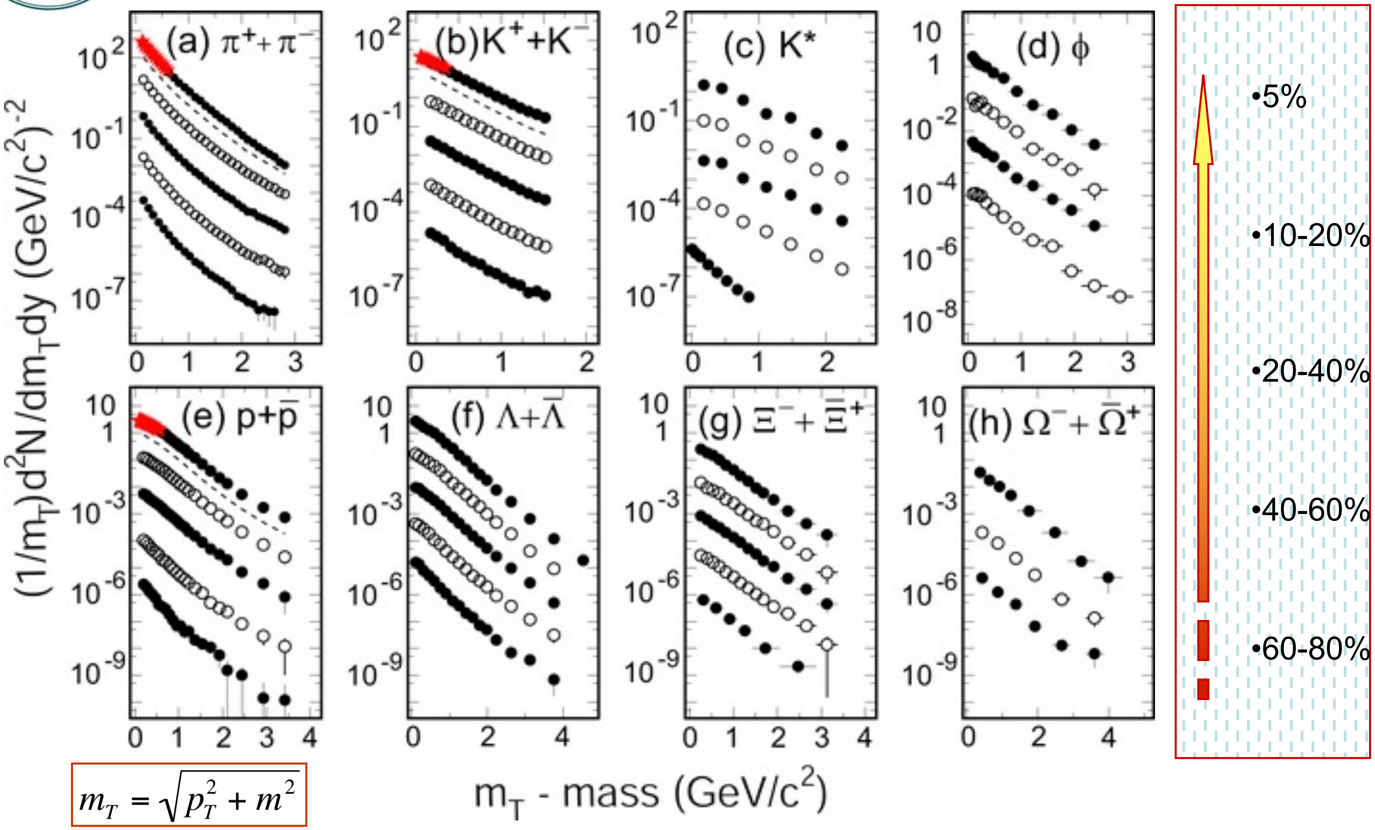


$$\frac{dN}{m_T\ dm_T} \propto e^{-m_T/T}$$

- In p-p at low transverse momenta the particle yields are well described by thermal spectra (m_T scaling)
- Boosted thermal spectra give a very good description of the particle distributions measured in heavy-ion collisions



Hadron Spectra From RHIC



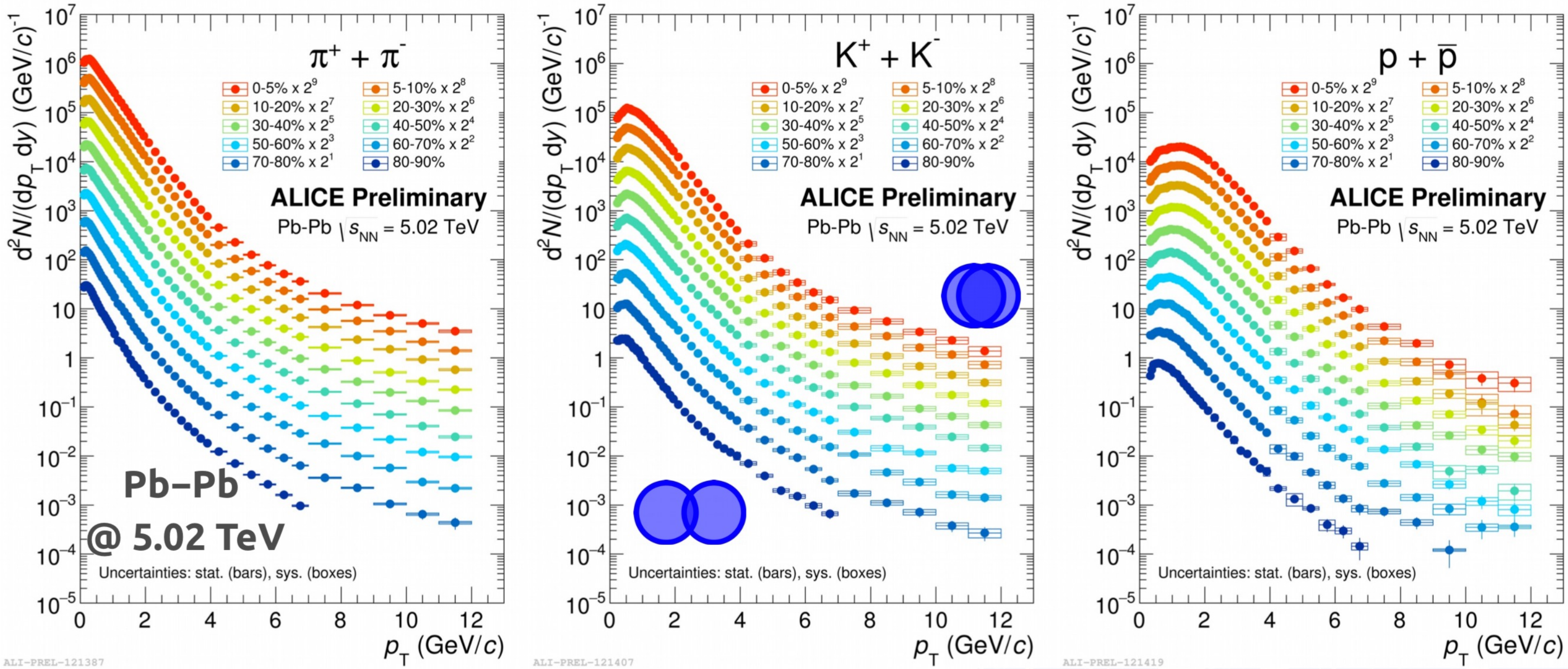
$m_T = \sqrt{p_T^2 + m^2}$

•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 ⇒ collective flow !

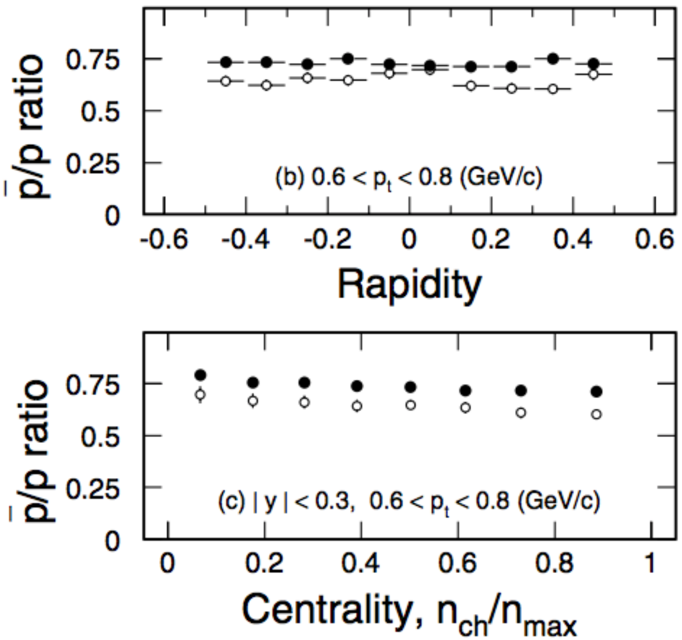
Hadron Spectra From ALICE

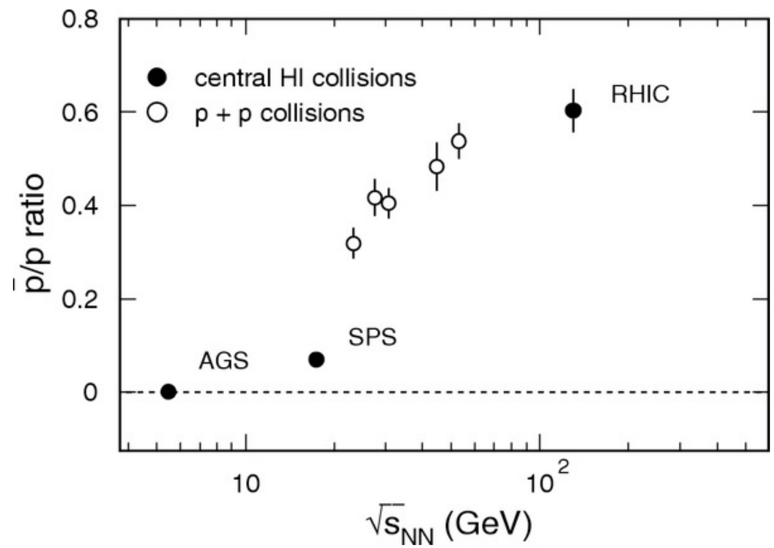


- Measured with different analysis techniques: ITS, TPC, TOF, HMPID and topological identification of K from kinks covering different p_T intervals
- **Mass dependent hardening of the spectra with increasing centrality**

N. Jacazio ALICE QM2017

pbar/p ratio at 130 GeV





STAR: (F. Wang, Nu) *PRL 86, 4778(01).* [90,119903(03)]

Baryon number transport is close related to the initial conditions .

1) At RHIC energy, the midrapidity region is not yet net-baryon free.
2) At midrapidity pbar/p ratio in heavy-ion collisions increases significantly with the collision energy

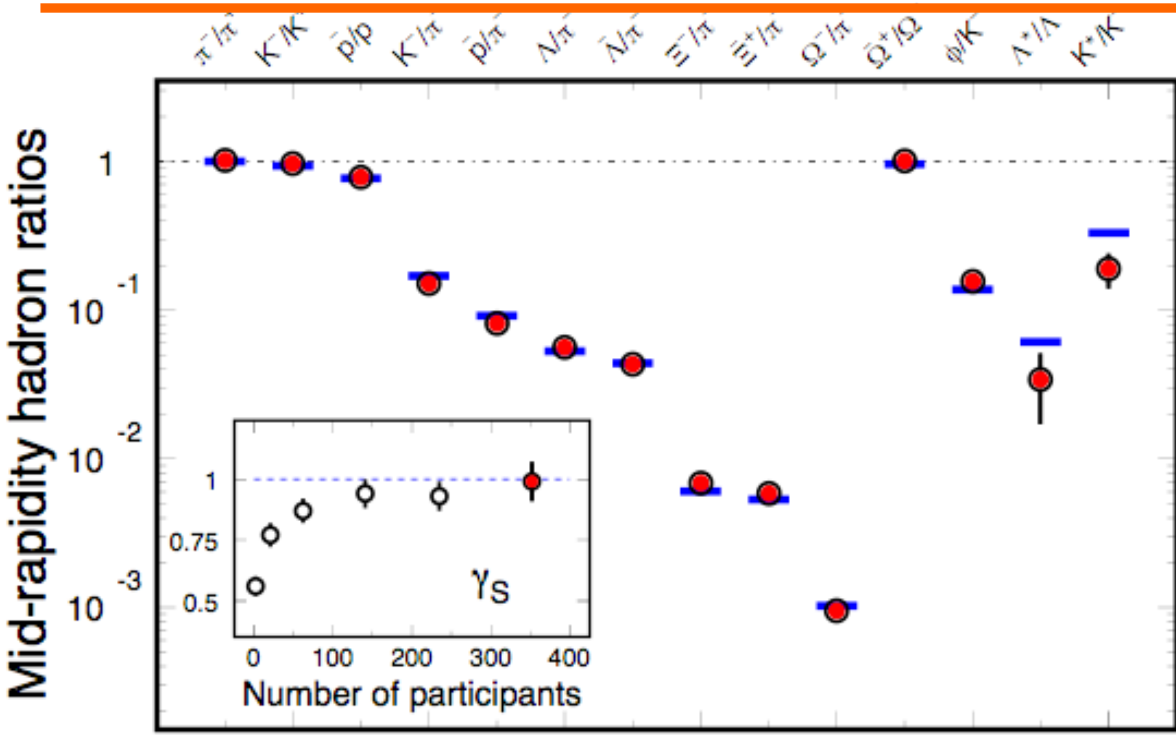
Statistical Model Fits

- 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 ± 10 MeV
μ_B = 25 ± 5 MeV

Necessary for QGP!

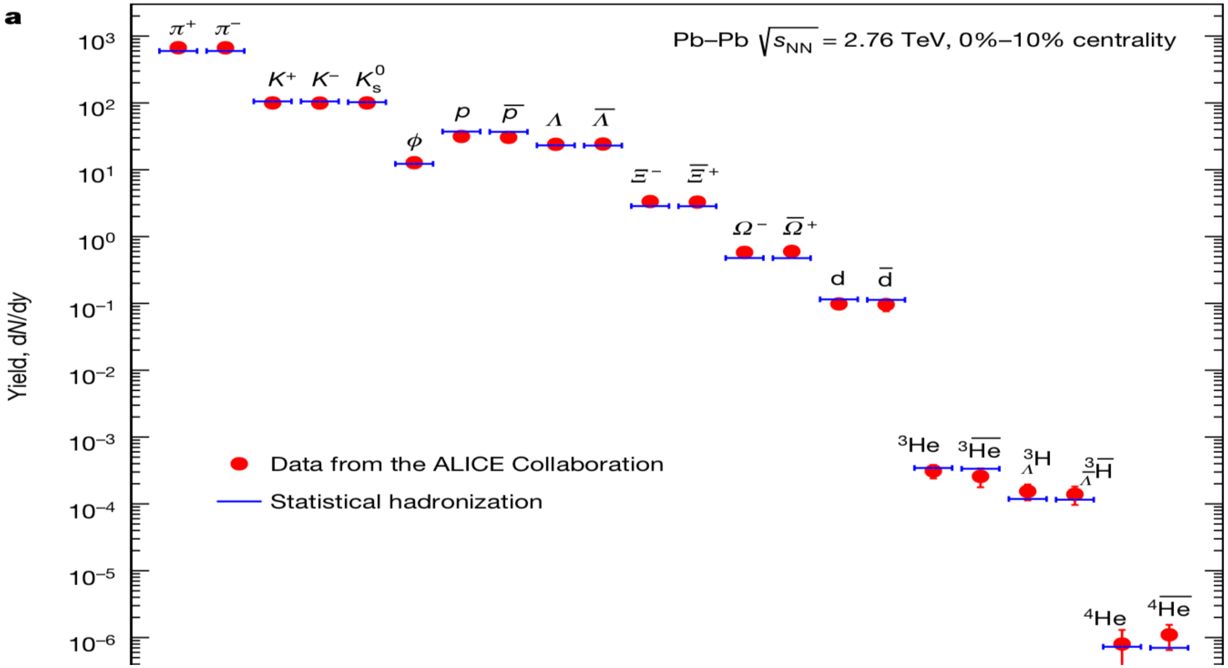
2) The temperature parameter T_{ch} is close to the critical temperature T_C predicted by LGT calculations ➔ chemical equilibrium at the phase boundary (?)

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.

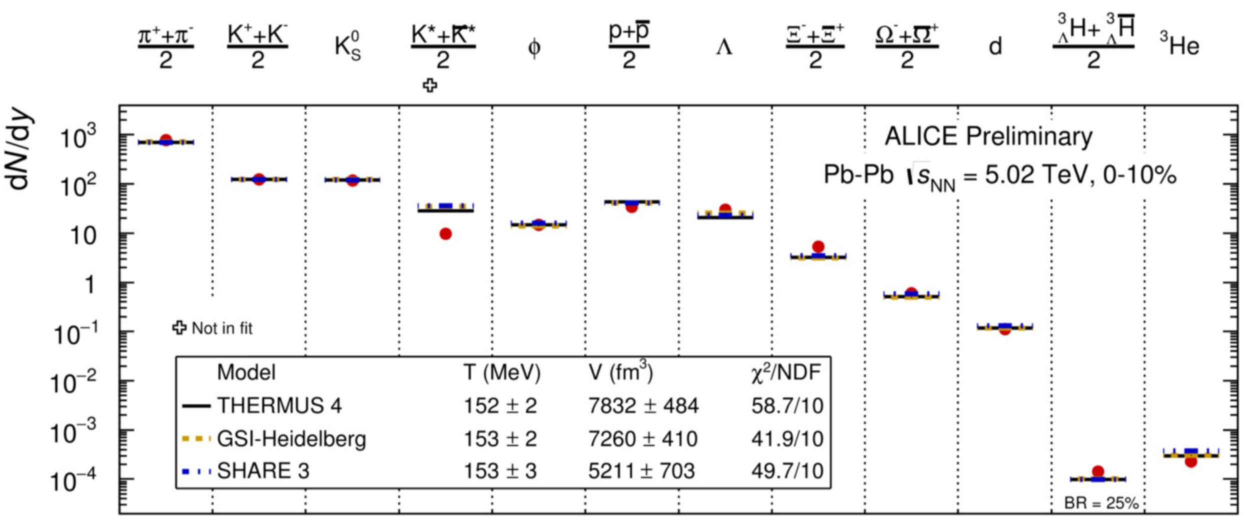
Hadron abundances and predictions of the statistical hadronization model: ALICE



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



Model	T (MeV)	V (fm^3)	χ^2/NDF
THERMUS 4	152 ± 2	7832 ± 484	58.7/10
GSI-Heidelberg	153 ± 2	7260 ± 410	41.9/10
SHARE 3	153 ± 3	5211 ± 703	49.7/10

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:

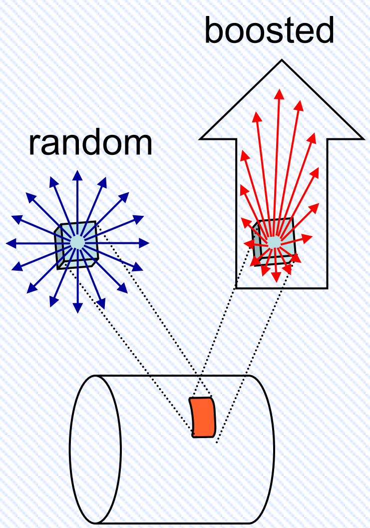
- Local thermal equilibrated
- Boosted radically

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

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

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

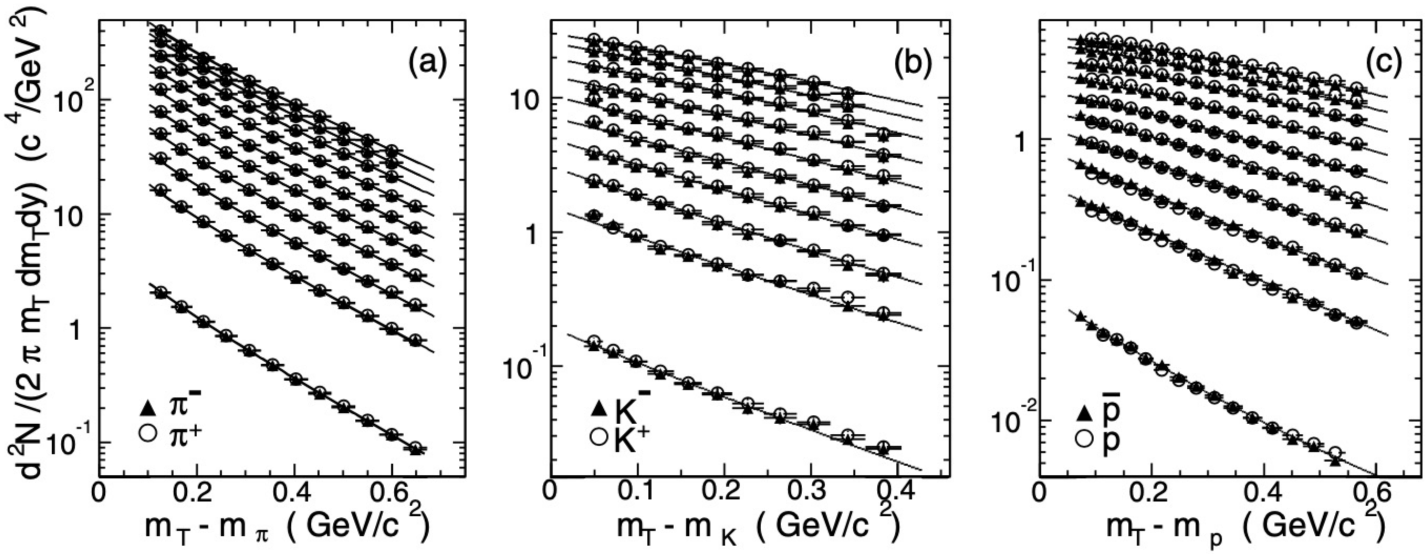
$$\rho = \tanh^{-1}\beta_r \qquad \beta_r = \beta_S\left(\frac{r}{R}\right)^\alpha \qquad \alpha = 0.5,1,2$$

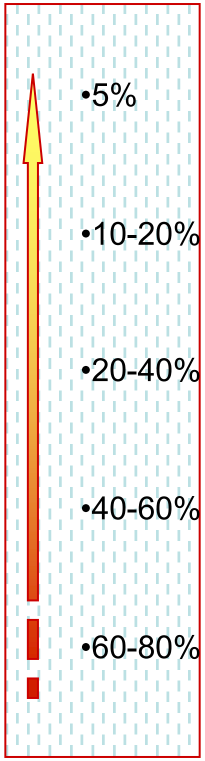


Extract thermal temperature T_{fo} and velocity parameter $\langle\beta_T\rangle$

Hadron Spectra From RHIC

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

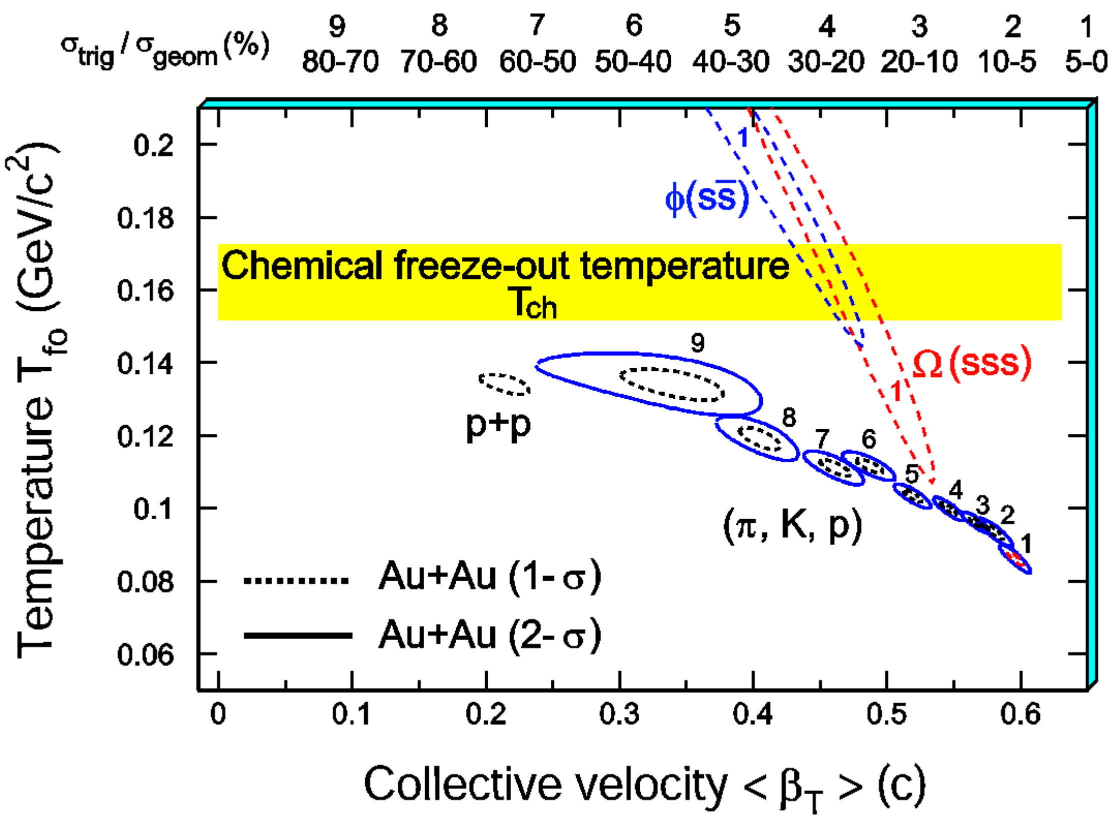




STAR :Phys. Rev. Lett. 92, 112301 (2004)

- 谱线与blast wave 模型下的粒子谱线吻合。该拟合较好地描述了所有粒子的谱，
- 可以用模型的两个参数来表征::一个单一的动力学冻结温度和一个共同的横向流速度。

Thermal fits: T_{fo} vs. $< \beta_T >$ at 200GeV



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

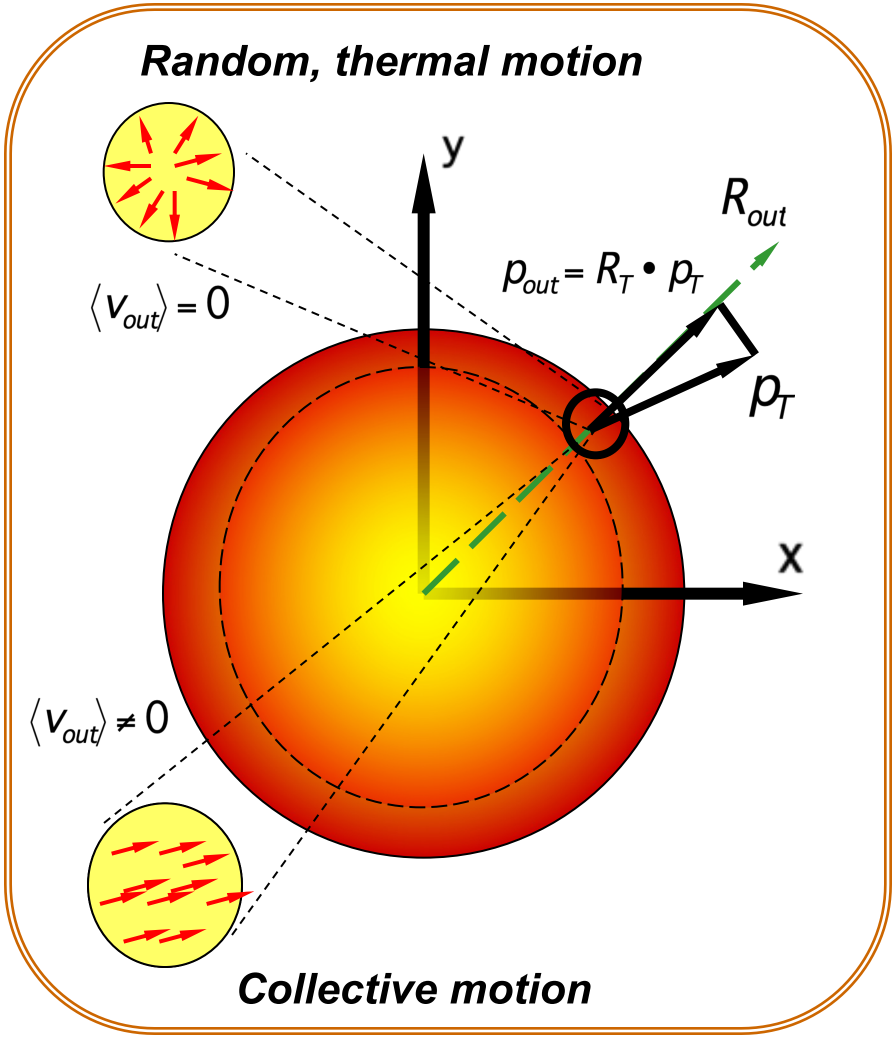
2) At the most central collisions, $<\beta_T>$ reaches 0.6c.

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

- **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***

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

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

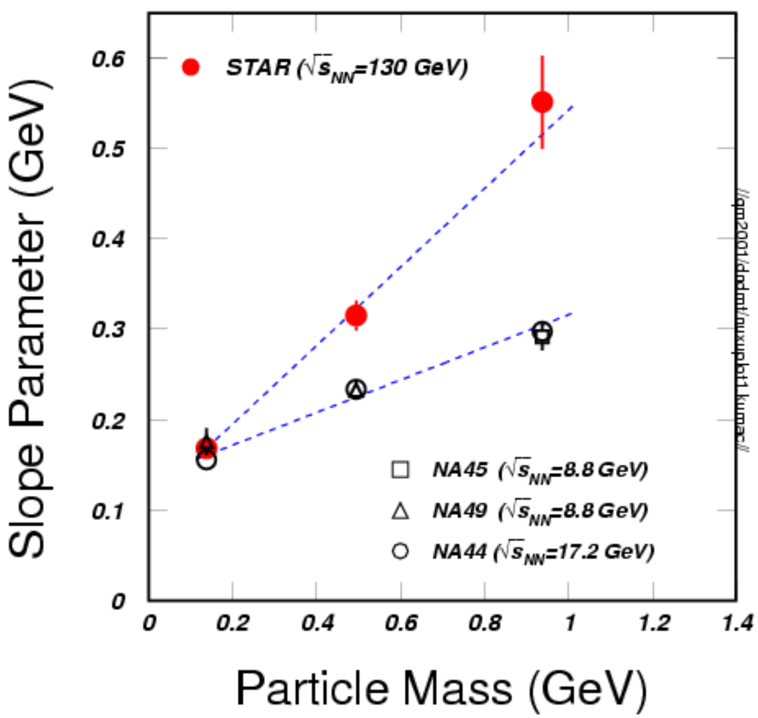
$$\langle p_T \rangle_{thermal} \propto \sqrt{mass \cdot T_{thermal}}$$

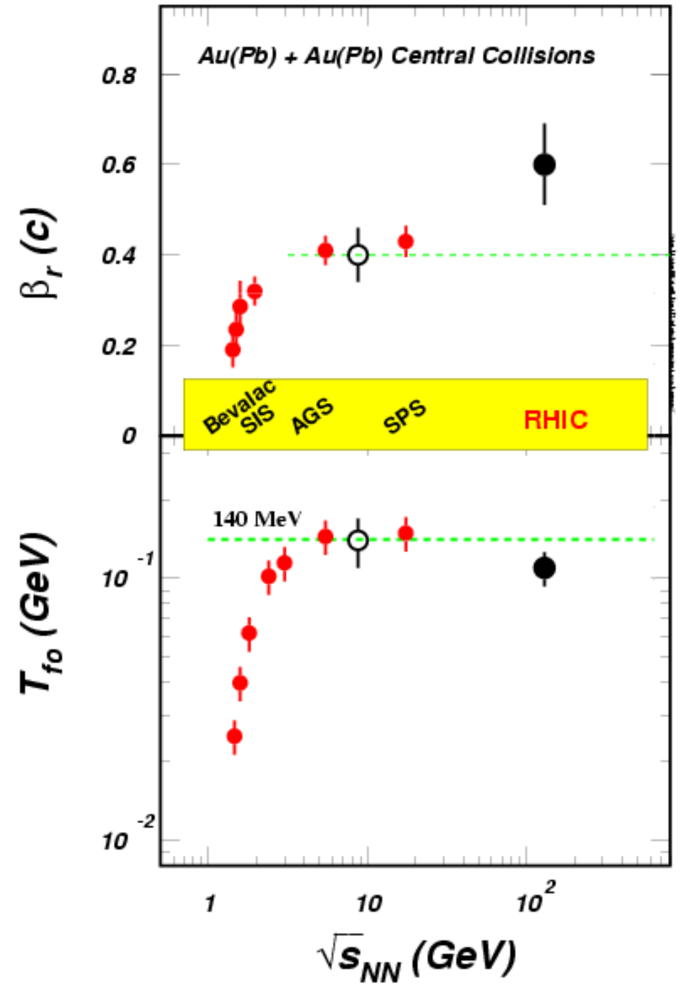
*I.Bearden et al, Phys. Rev. Lett. **78**, 2080(1997).*

Mass Dependence of Slopes

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

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

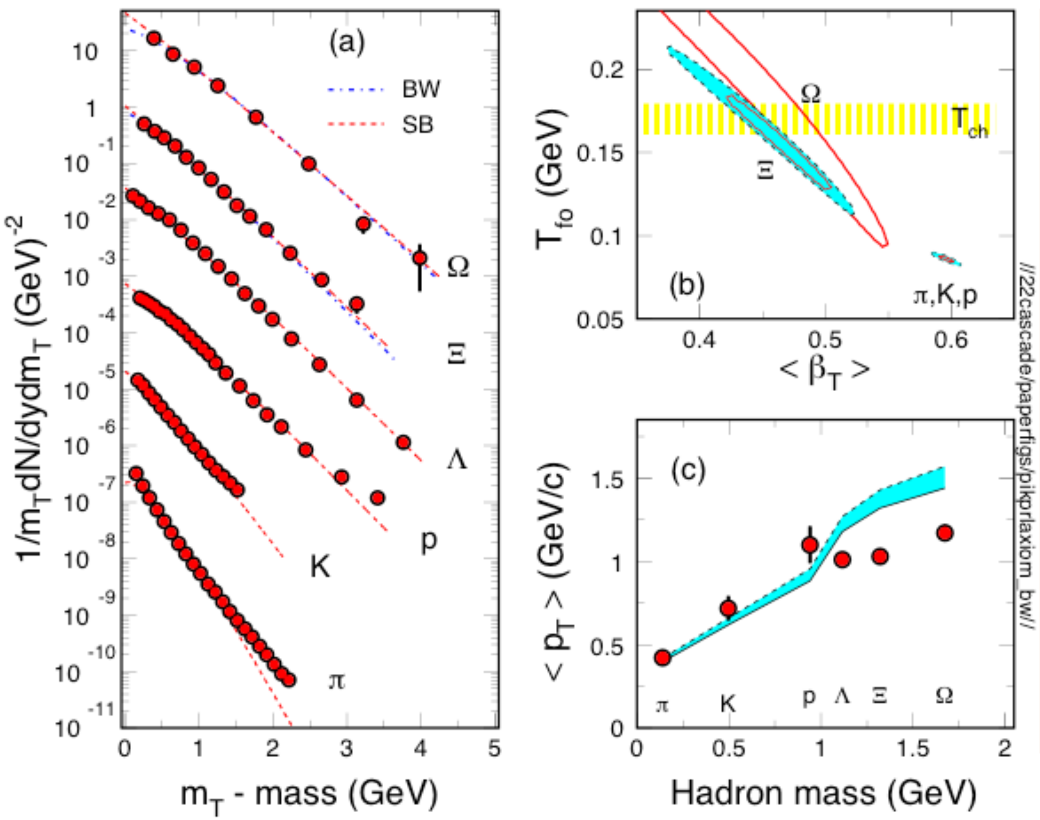




Explosive expansion at RHIC!

Early freeze-out

Central Au+Au collisions at RHIC

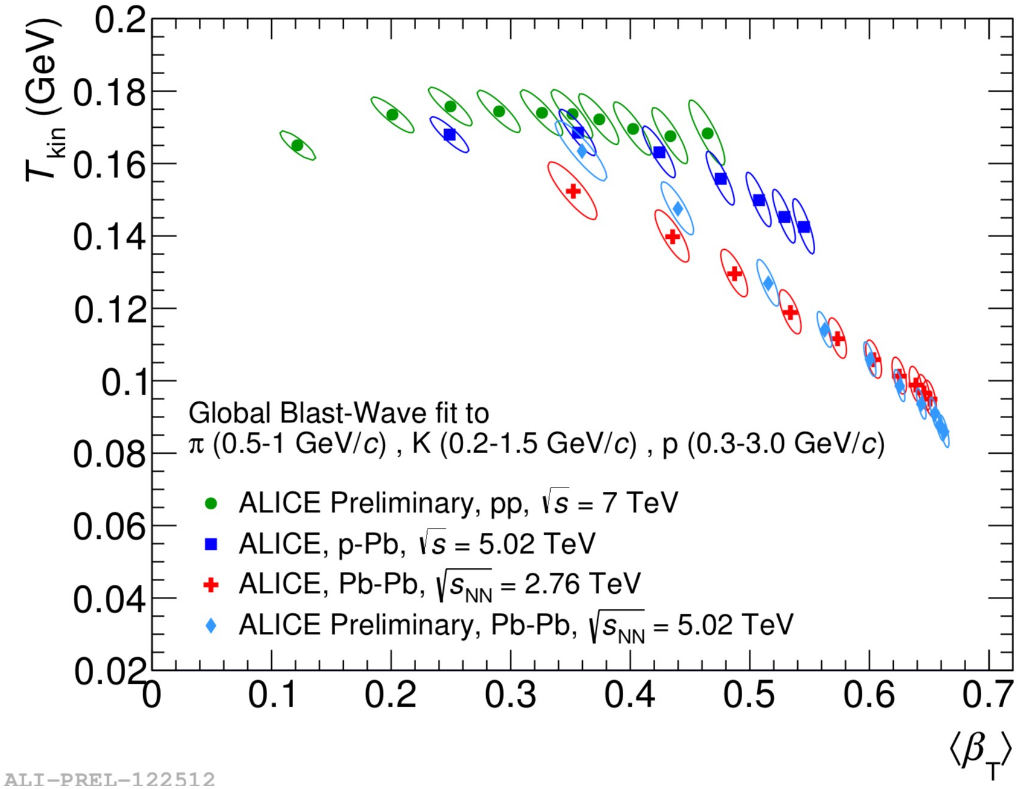


1）Multi-strange hadrons seem to freeze out earlier than others ➜ sensitive probe for early dynamics

2) Model results fit to *π, K, p* spectra well, but over predicted <p_T> for multi-strange hadrons - **Do they freeze-out earlier?**

*PHENIX: Phys. Rev. **C69** 034909 (04).*
*STAR: Phys. Rev. Lett. **92**, 112301(04); Phys. Rev. Lett. **92**, 182301(04).*
*A. Andronic et al., NP**A715**, 529(03).*
*P. Kolb et al., Phys. Rev. **C67** 044903(03)*

Blast Wave Fits: LHC

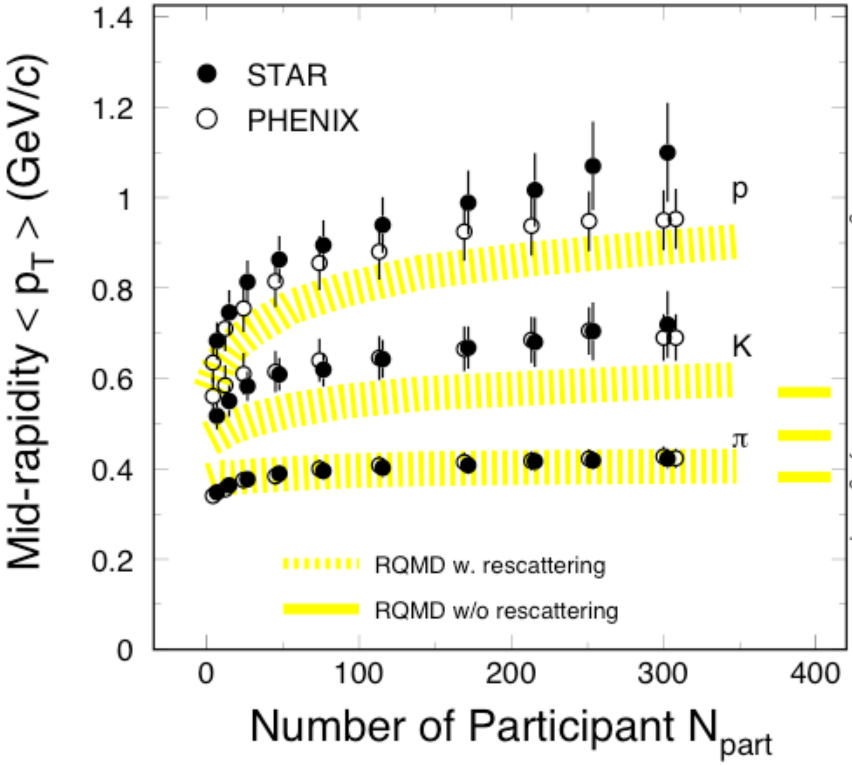


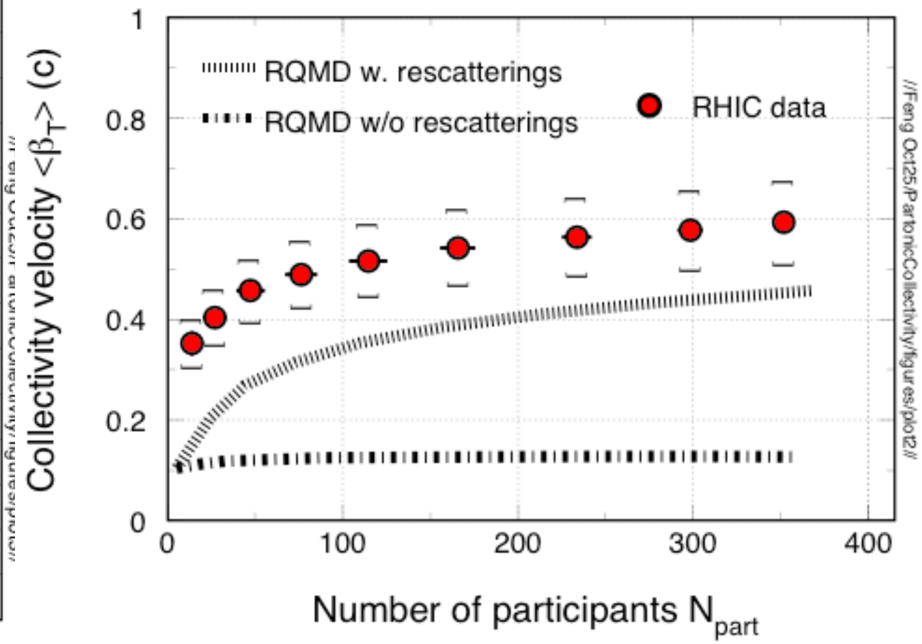
N. Jacazio
ALICE QM2017

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



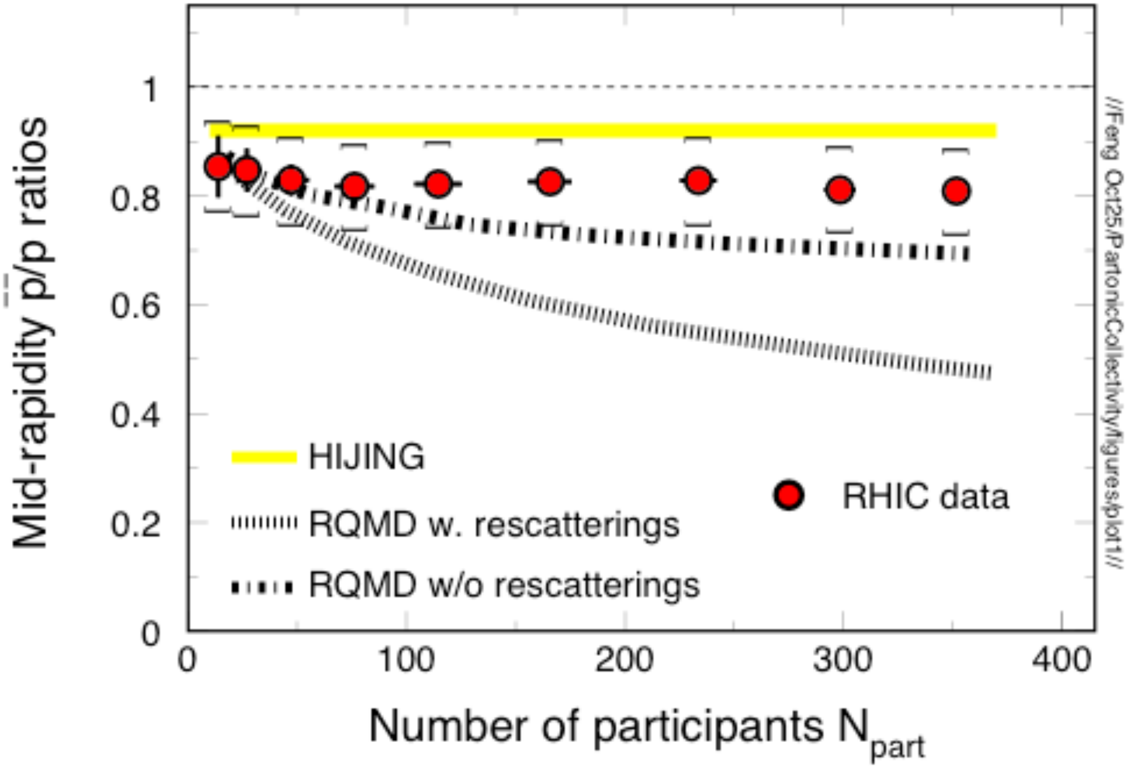


(1) The <pt> increases vs. centrality $\Rightarrow$ collective expansion

(2) Hadronic transport model RQMD calculations reproduced the collectivity for copiously produced hadrons π, K, p.

(3) Re-scatterings are import for collectivity !

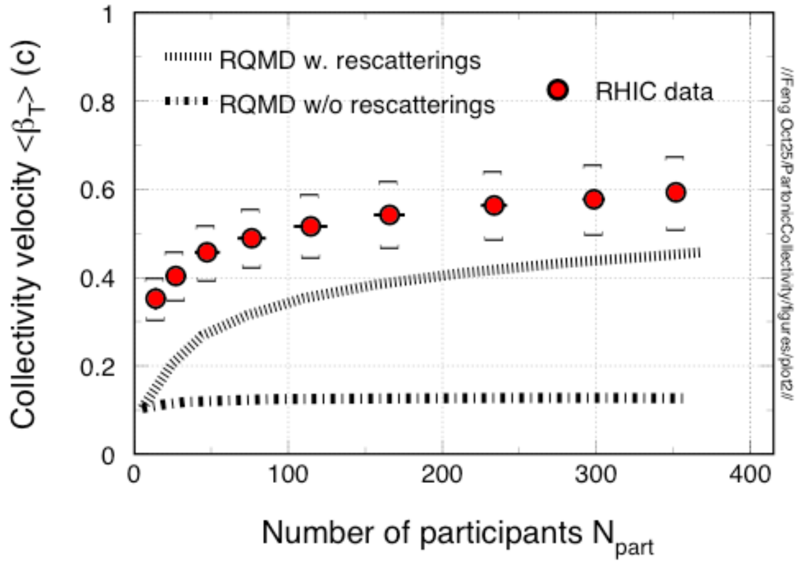
Tests with Transport Model

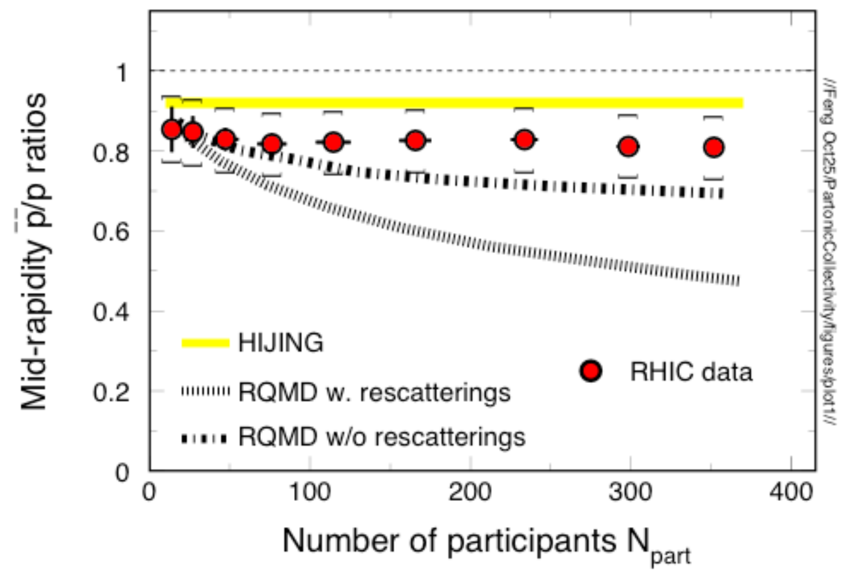


(1) Hadronic transport model RQMD can not reproduced the anti-proton over proton ratios as a function of centrality.

(2) RQMD underestimates pbar yield due to large annihilation X-section
⇒ **re-scattering at earlier pre-hadronic stage?**

Tests with Transport Model





Re-scatterings are import for collectivity !

Hadronic Re-scatterings can not reproduced the anti-proton over proton ratios as a function of centrality.

⇒ re-scattering at earlier pre-hadronic stage?

Summary II: Radial Flow

1) Copiously produced hadrons freeze-out:

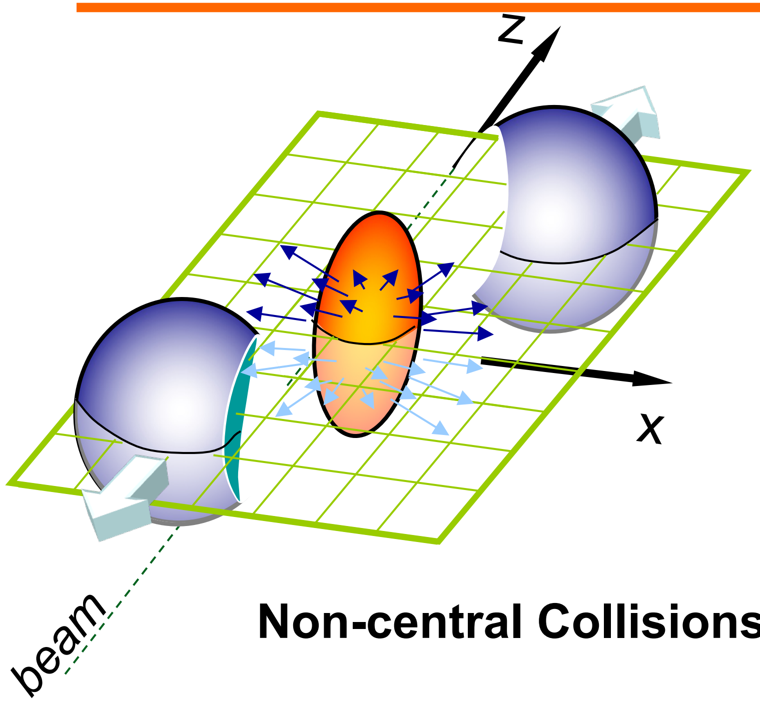
T_{fo} = 100 MeV, β_T = 0.6 (c) > β_T(SPS)

Much stronger collective flow observed in collisions at RHIC than collisions at lower beam energies. ***Early partonic interactions*** are responsible for the increase of pressure gradient at RHIC.

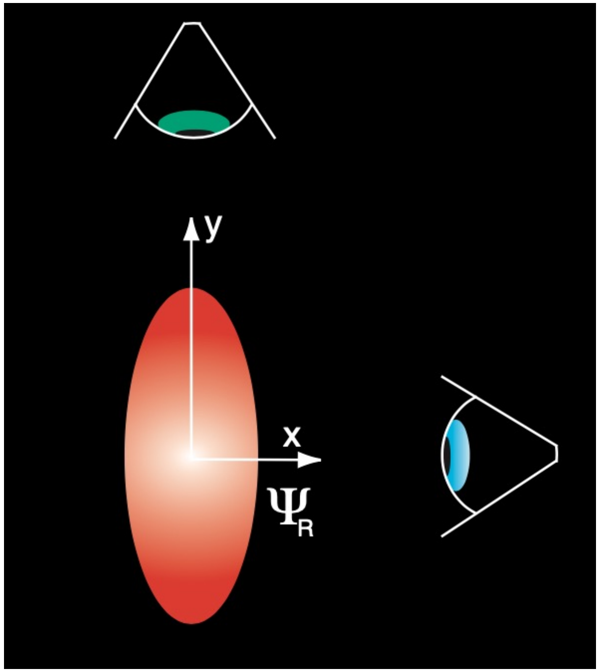
2)* Multi-strange hadrons freeze-out:

T_{fo} = 160-170 MeV (~ T_{ch}), β_T = 0.4 (c)

The Reaction Plane



Non-central Collisions

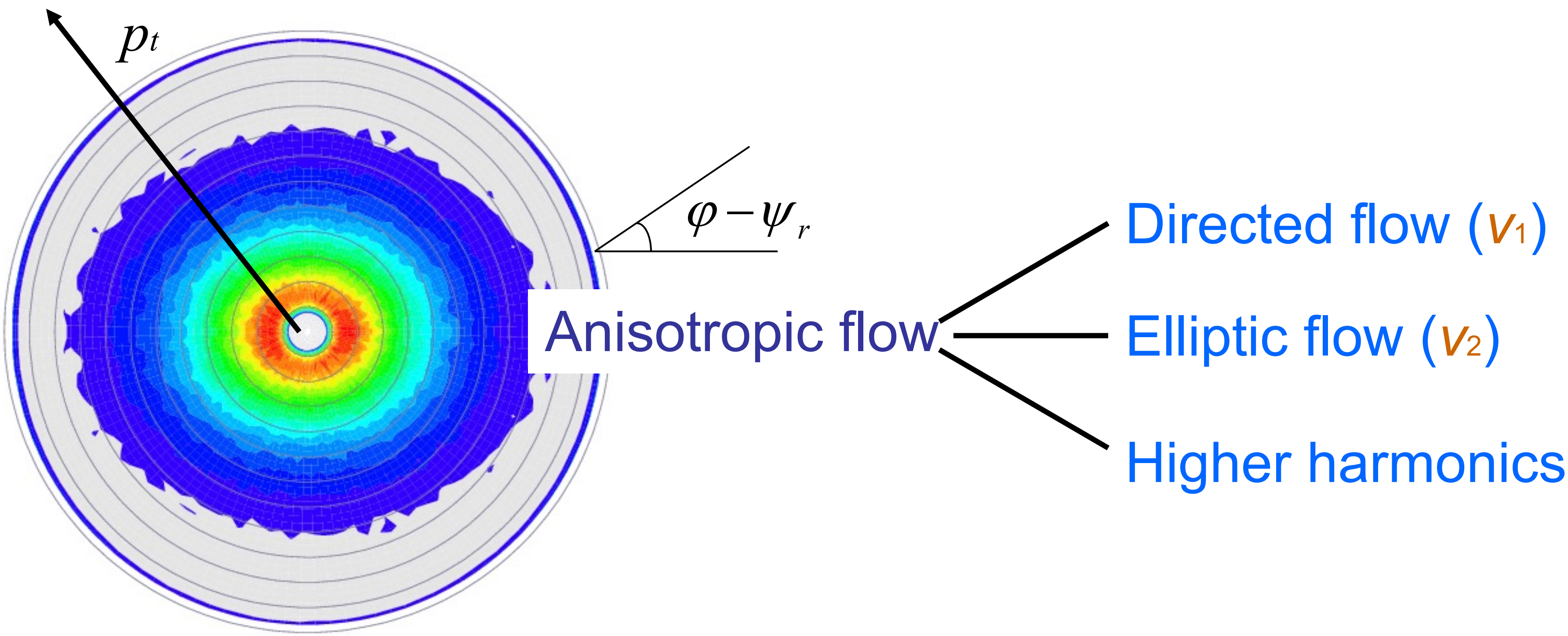


$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_t dp_t dy d(\phi - \Psi_R)}$$

Determine the angel of the reaction plane ψ_R

Experimentally, one only sees outgoing particles, therefore one cannot follow the evolution of v_n through the collision In a model, one can follow how v_n develops in time.

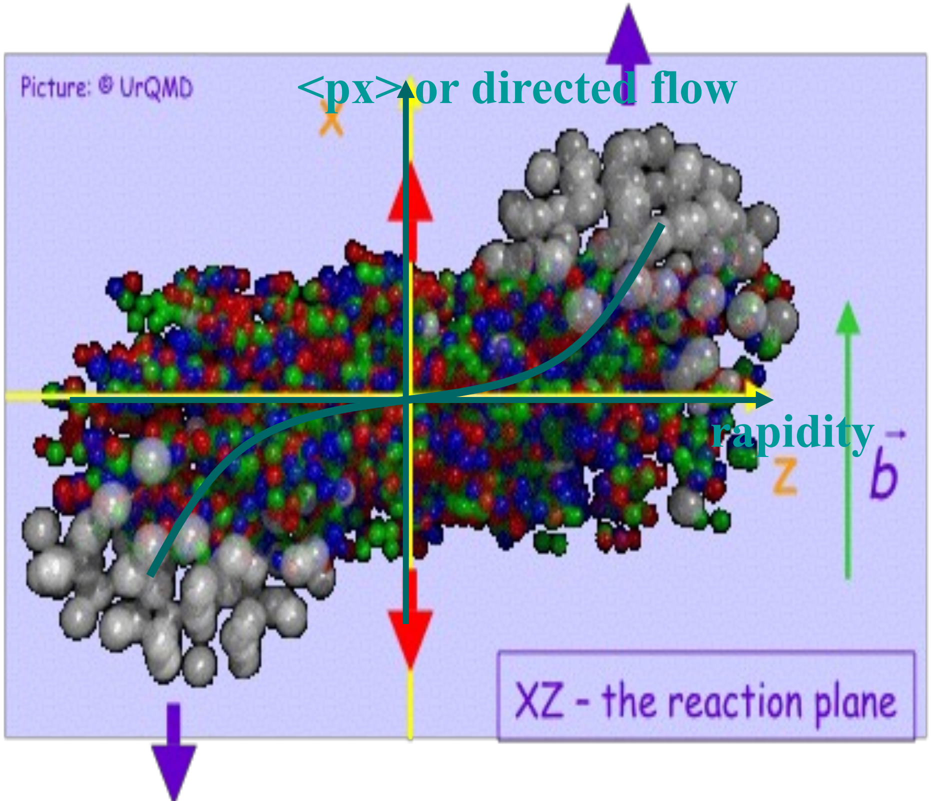
Higher harmonics



$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\varphi-\psi_r)]\right)$$

$$v_n=\langle\cos[n(\varphi-\psi_r)]\rangle$$

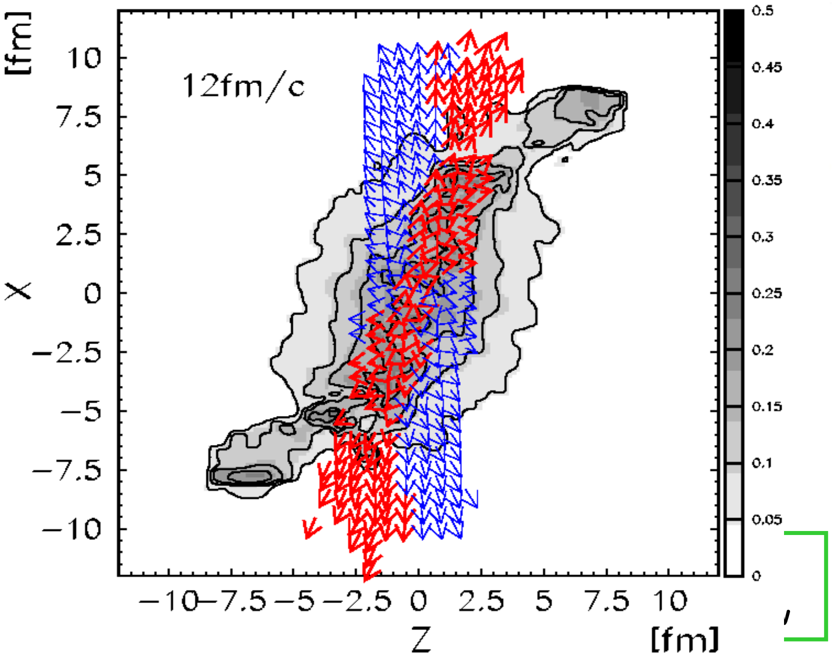
Directed flow (v_1)

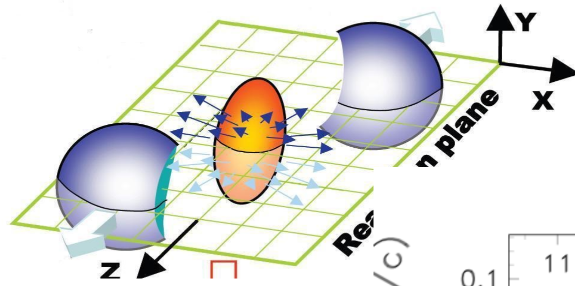


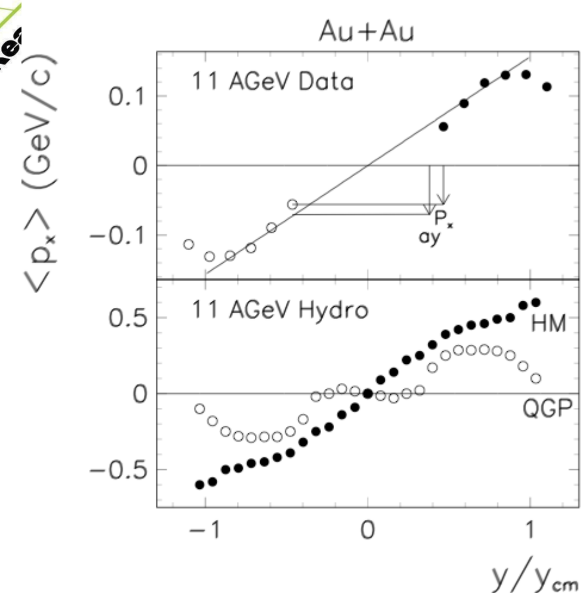
Directed flow: sidewards deflection of particles.

At large rapidity , directed flow is believed to be generated during the nuclear passage time ($2R/\gamma$~0.1 fm/c). It therefore probes the onset of bulk collective dynamics during the thermalization process,

Directed flow





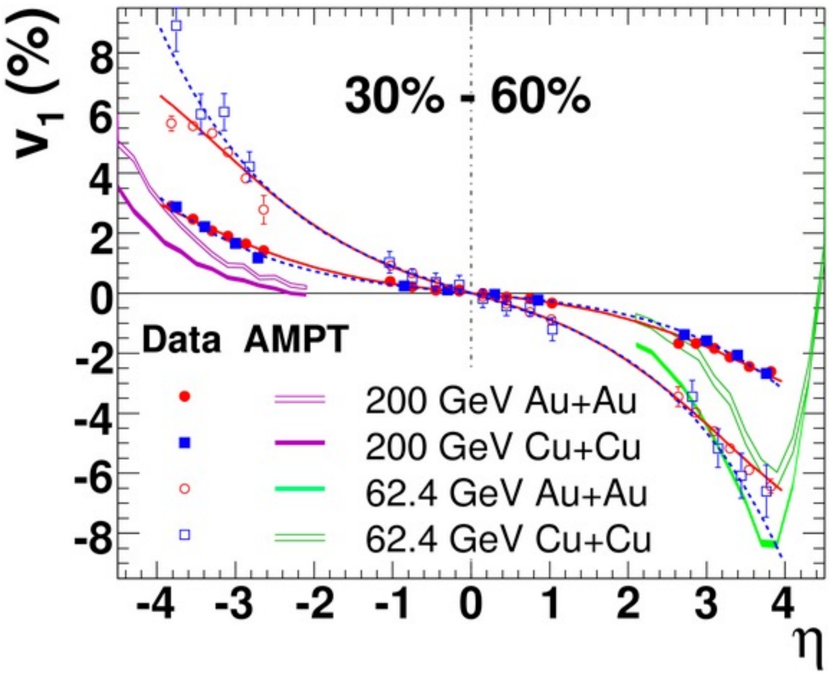


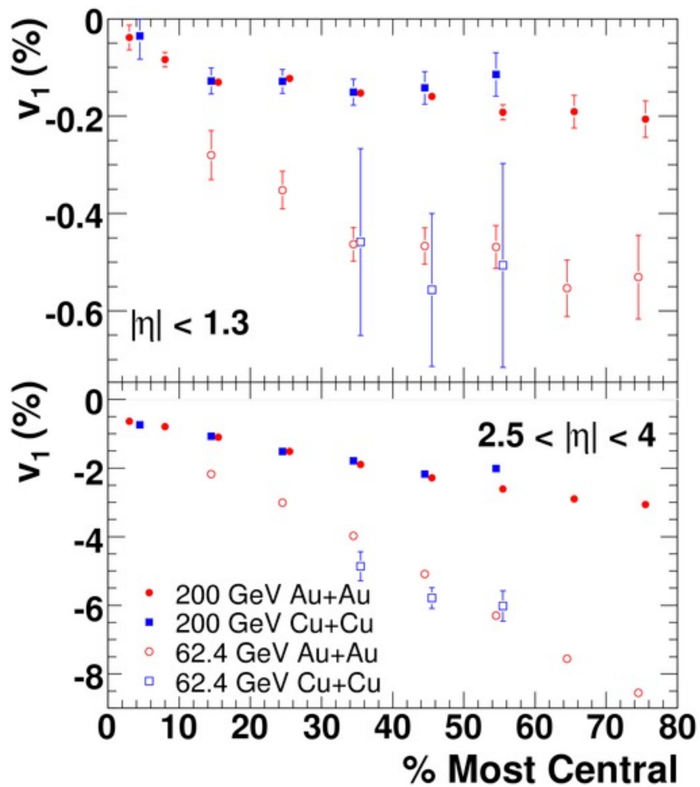
Anti-flow/3rd flow component, with QGP ⇒ v_1 flat at middle rapidity.

Directed flow (v_1) and phase transition

Brachmann, Soff, Dumitru, et. al. , PRC 61 (2000) 024909.
L.P. Csernai, D. Roehrich PLB 458, 454 (1999) ; M.Bleicher and H.Stocker, PLB 526,309(2002)

v_1 from different collision systems

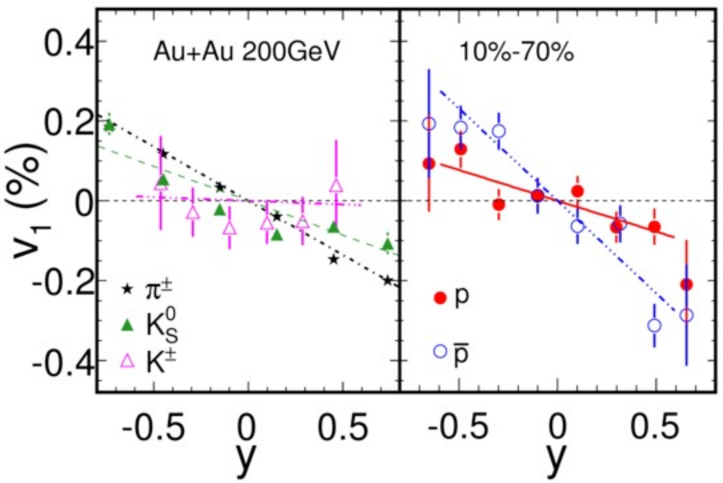


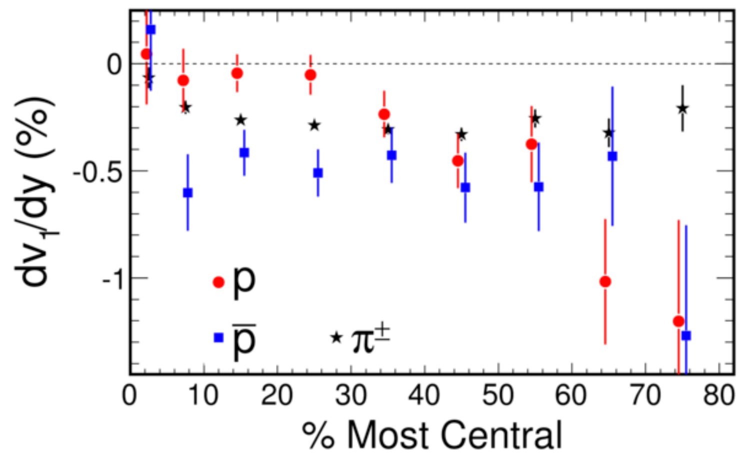


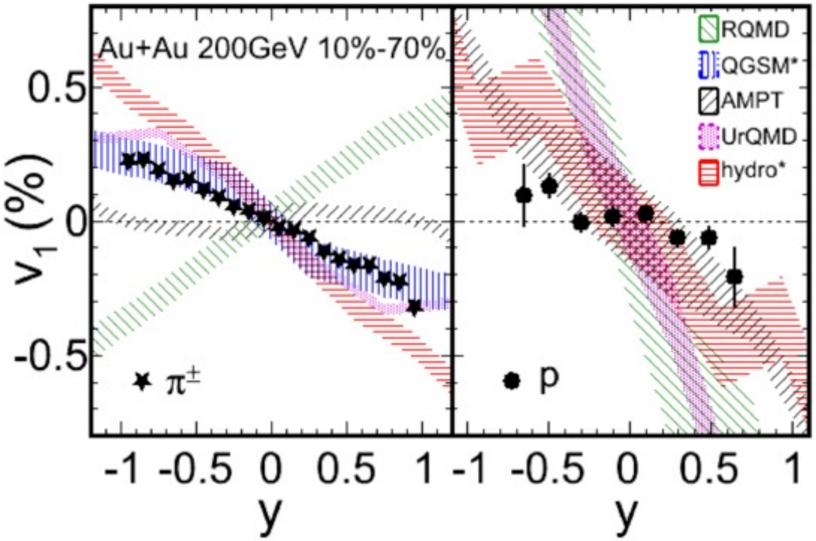
STAR: JY Chen, A. Tang, G. Wang, Y. Yang ,PRL101 252301(2008);
200GeV: 62.4 GeV , Au+Au; 8M:5M； Cu+Cu; 12M,:8M

v_1 is found being independent of collision systems.
decrease with increasing beam energy

PID v_1 *at* 200 GeV





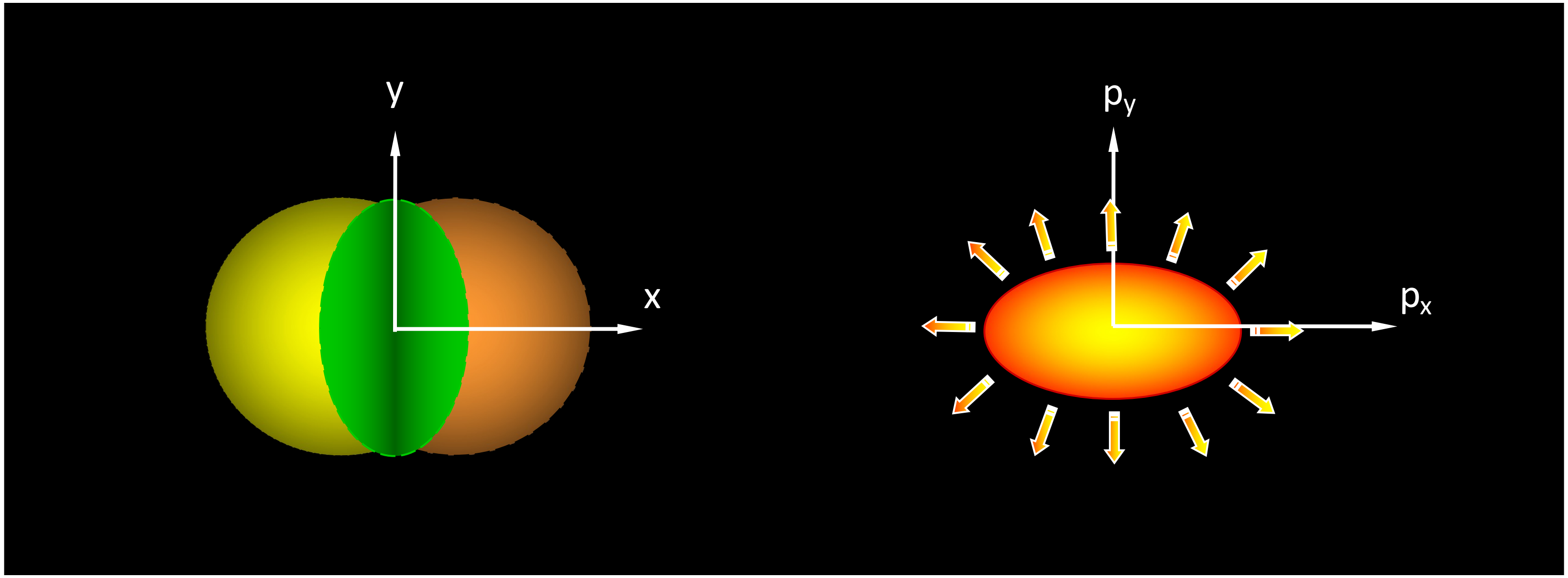


STAR: JY Chen, F Liu, A. Tang, G. Wang ,PRL108 202301(2012); 200GeV 54M

- v_1 slope for the produced particle types are mostly found to be negative at midrapidity
- No model can describe v_1 for pions and protons simultaneously
- Need more mechanism to explain centrality dependence of p and pbar v_1 slope

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.

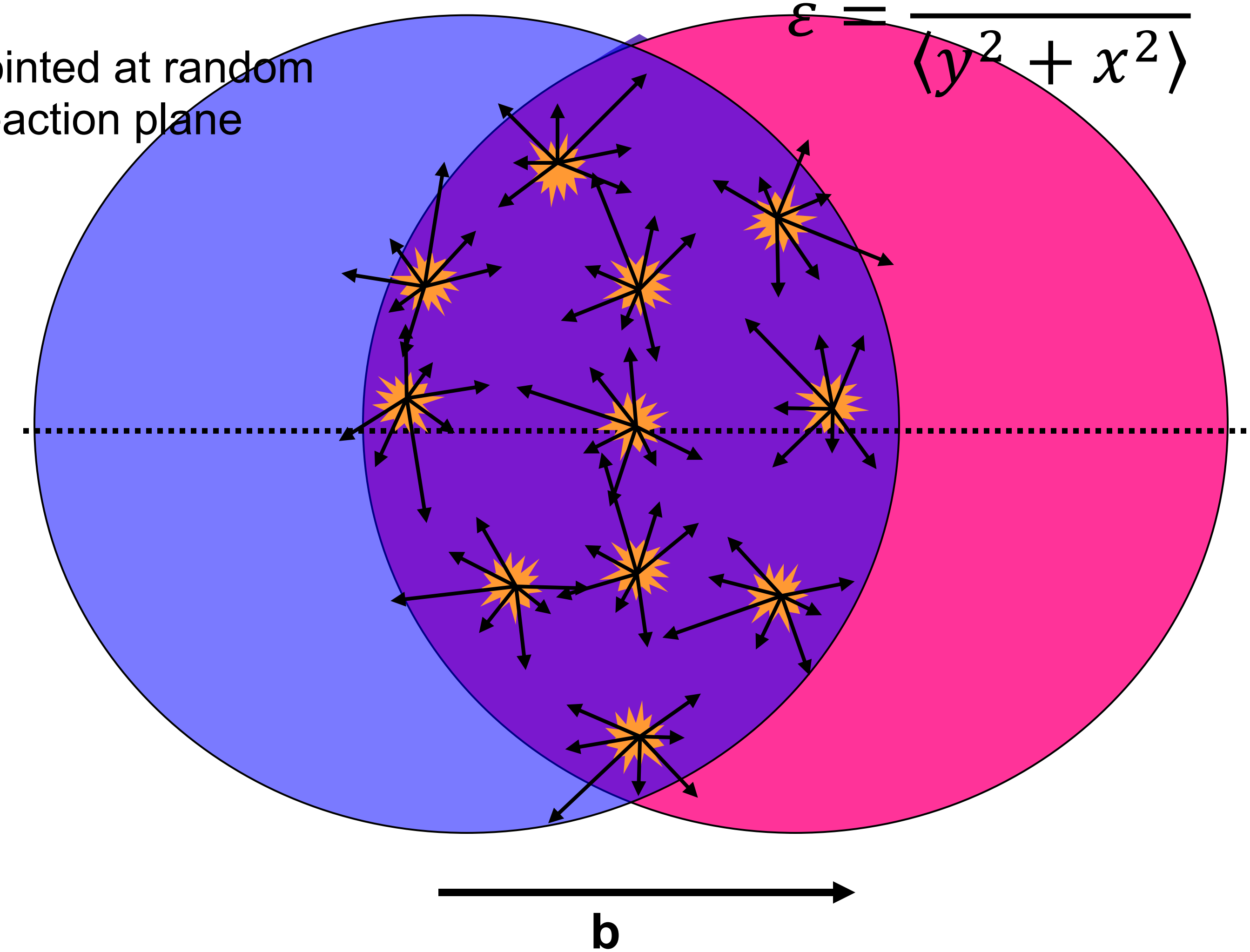
Forming a system and thermalizing

Animation: Mike Lisa

1) Superposition of independent p+p:

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

momenta pointed at random
relative to reaction plane



Forming a system and thermalizing

Animation: Mike Lisa

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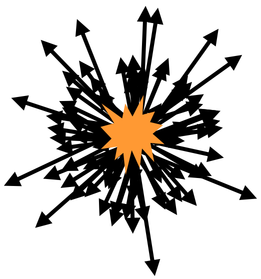
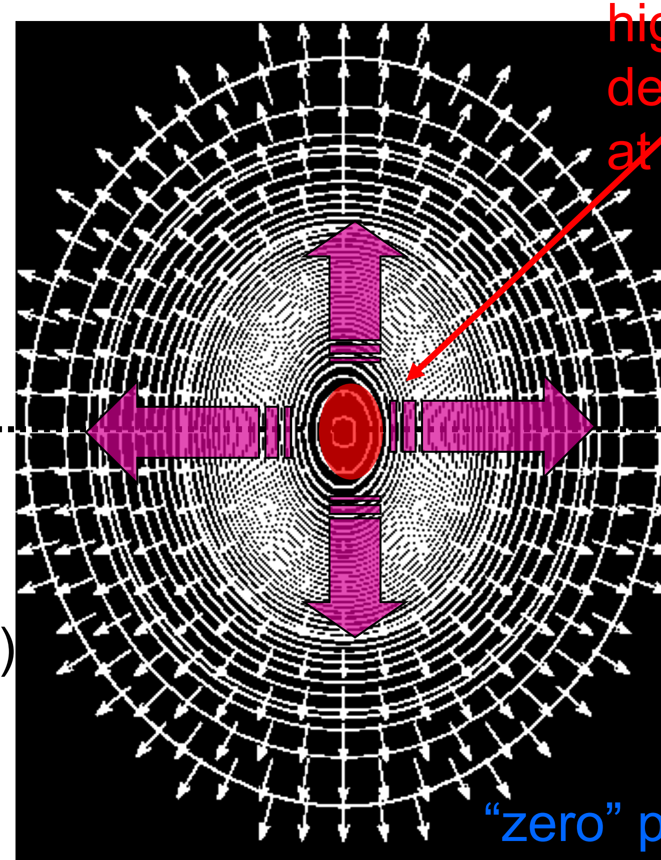




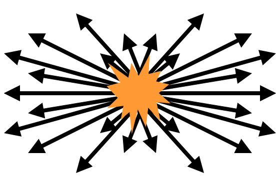
high density / pressure at center

"zero" pressure in surrounding vacuum

b

2) Evolution as a **bulk <u>system</u>**

Pressure gradients (larger in-plane) push bulk "out" → "flow"

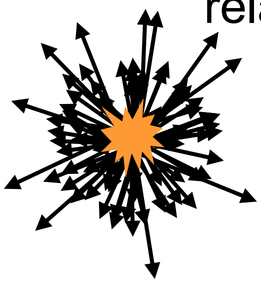


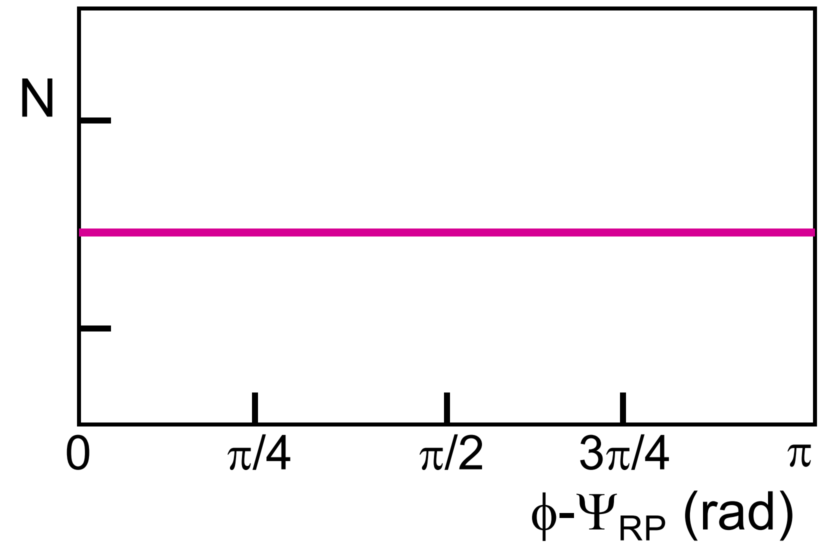
more, faster particles seen in-plane

How does the system evolve?

1) Superposition of independent p+p:

momenta pointed at random relative to reaction plane





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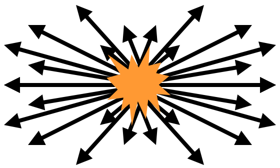
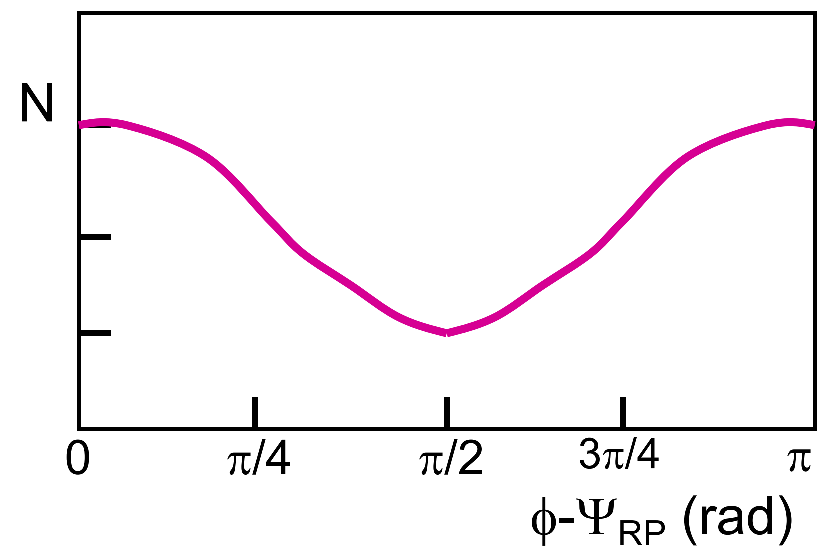
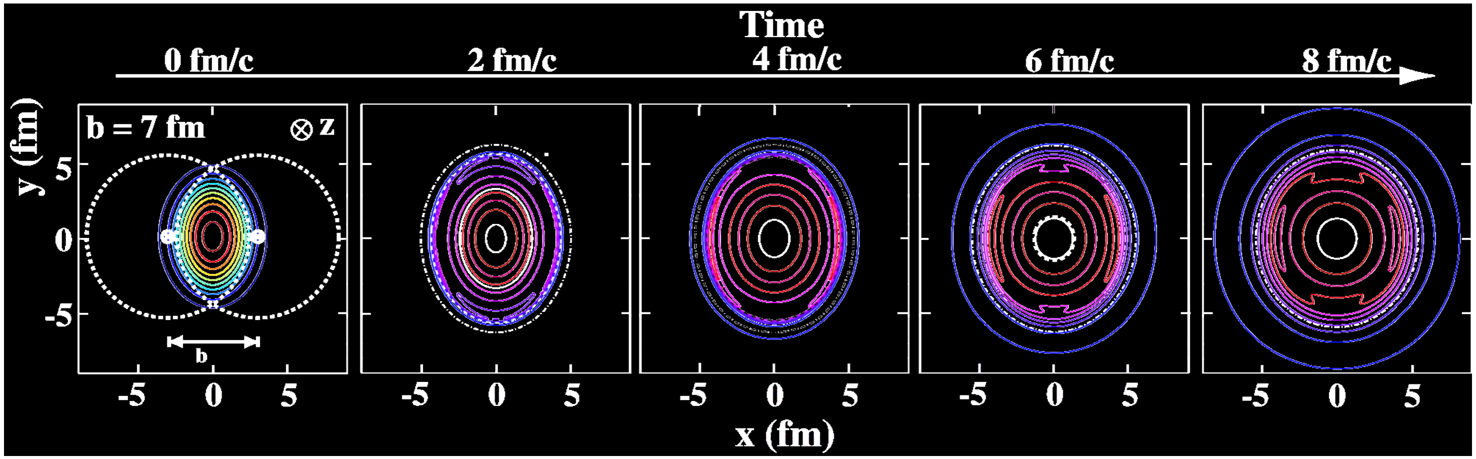
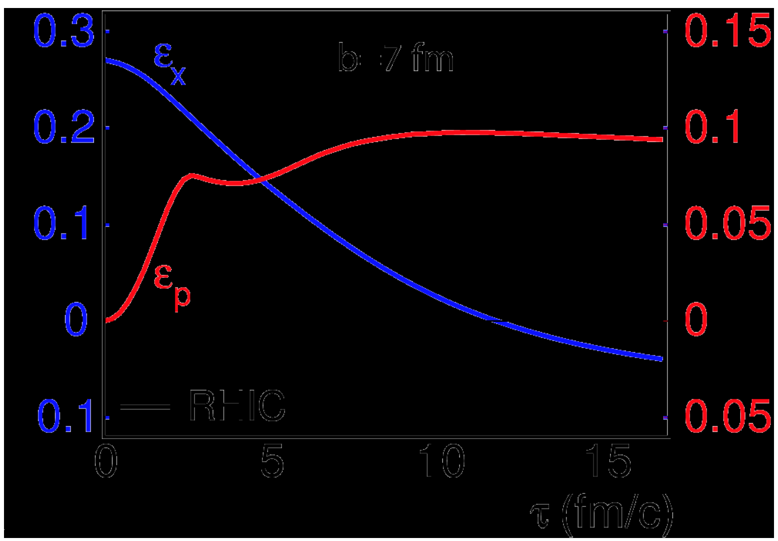


more, faster particles seen in-plane



A Hydrodynamic description



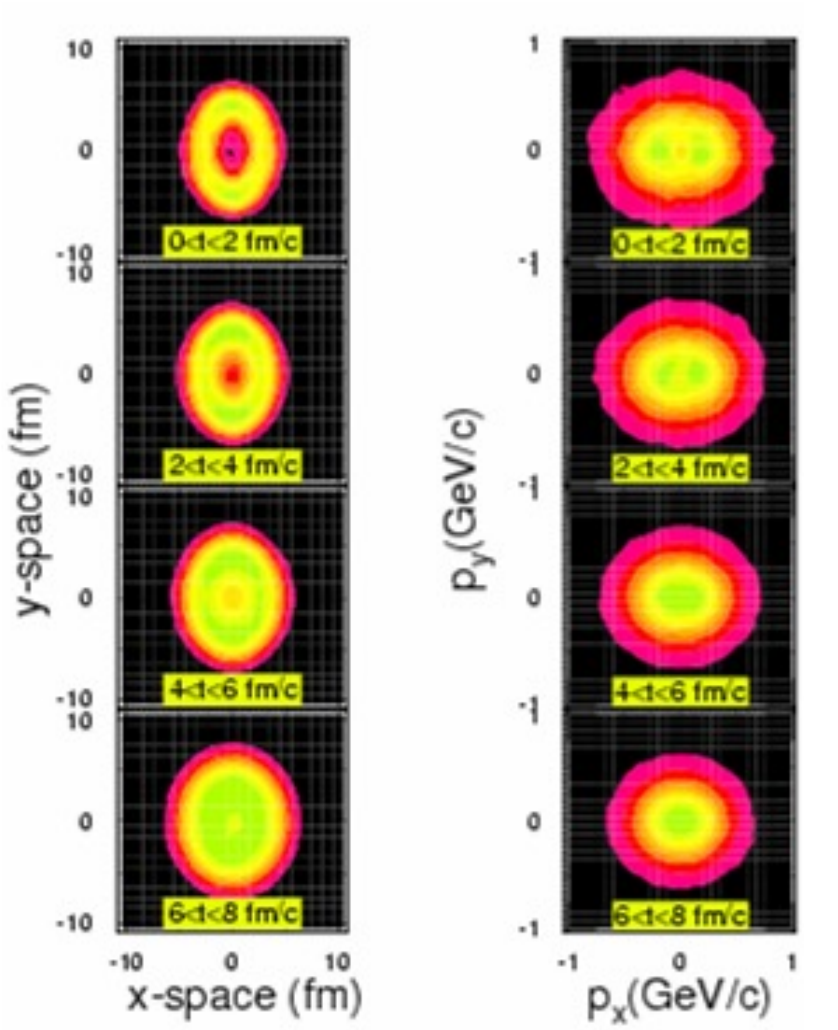


- Multiple interactions lead to thermalization -> limiting behavior ideal hydrodynamic flow
- The driving force of elliptic flow dominates at “early” times

P.F. Kolb and U. Heinz, in Quark Gluon Plasma, nucl-th/0305084

Space-momentum correlation

Jingbo Zhang, J. Yang, et al.-LBNL



RQMD(v2.4) Au+Au at 200 GeV

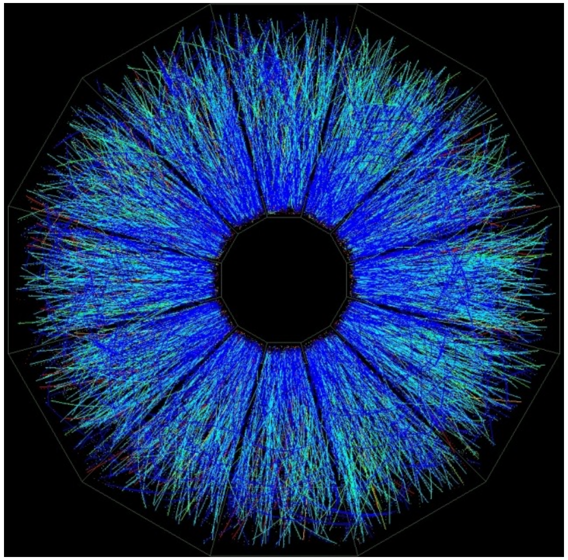
1) Spatial anisotropy leads to momentum space anisotropy.

2) At early time, the anisotropy is the strongest

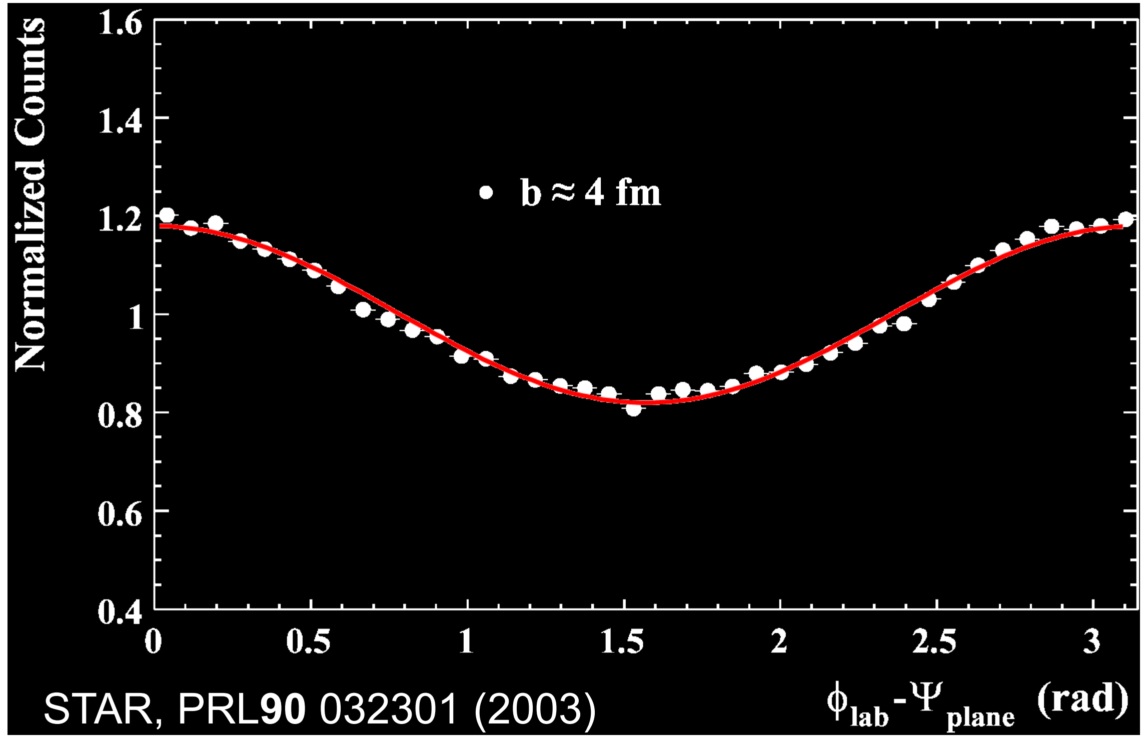
3) Space part can be tested via two-particle correlation functions measurements

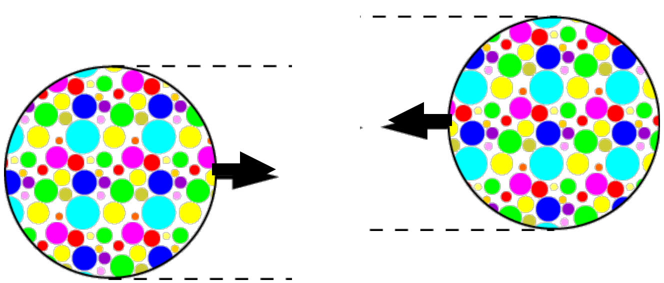
4) Anisotropy in space is not totally 'quenched' at later time.

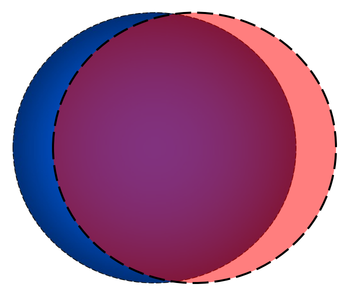
Measurements in STAR at RHIC



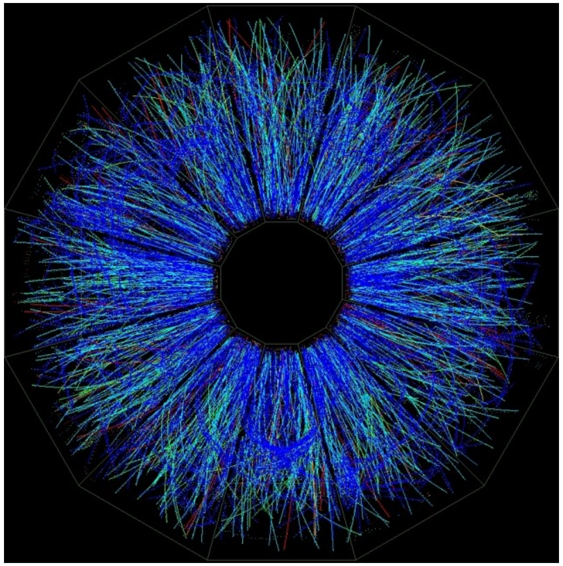
"central" collision



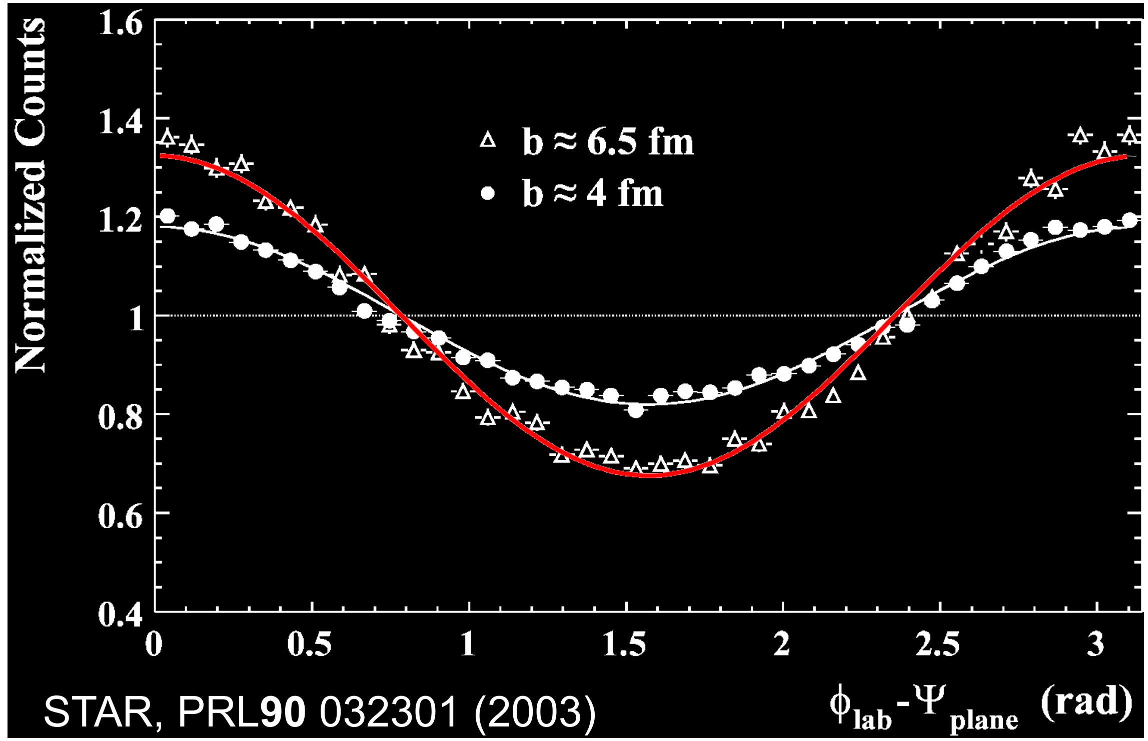




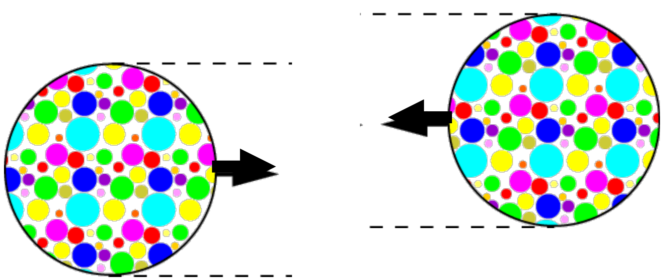
Measurements in STAR at RHIC

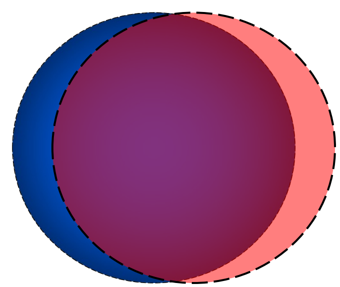


“mid-central” collision

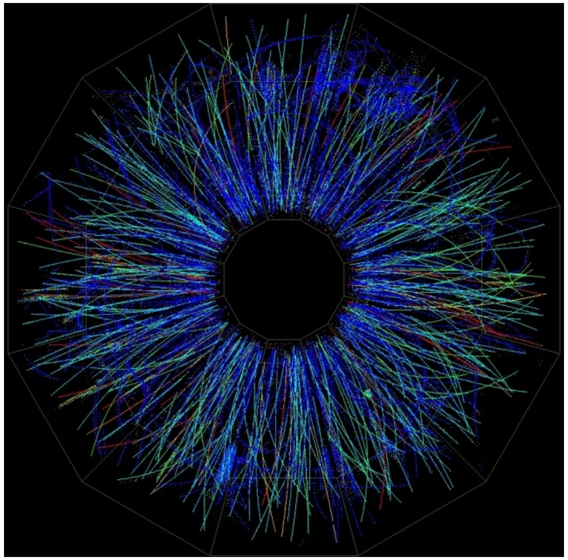


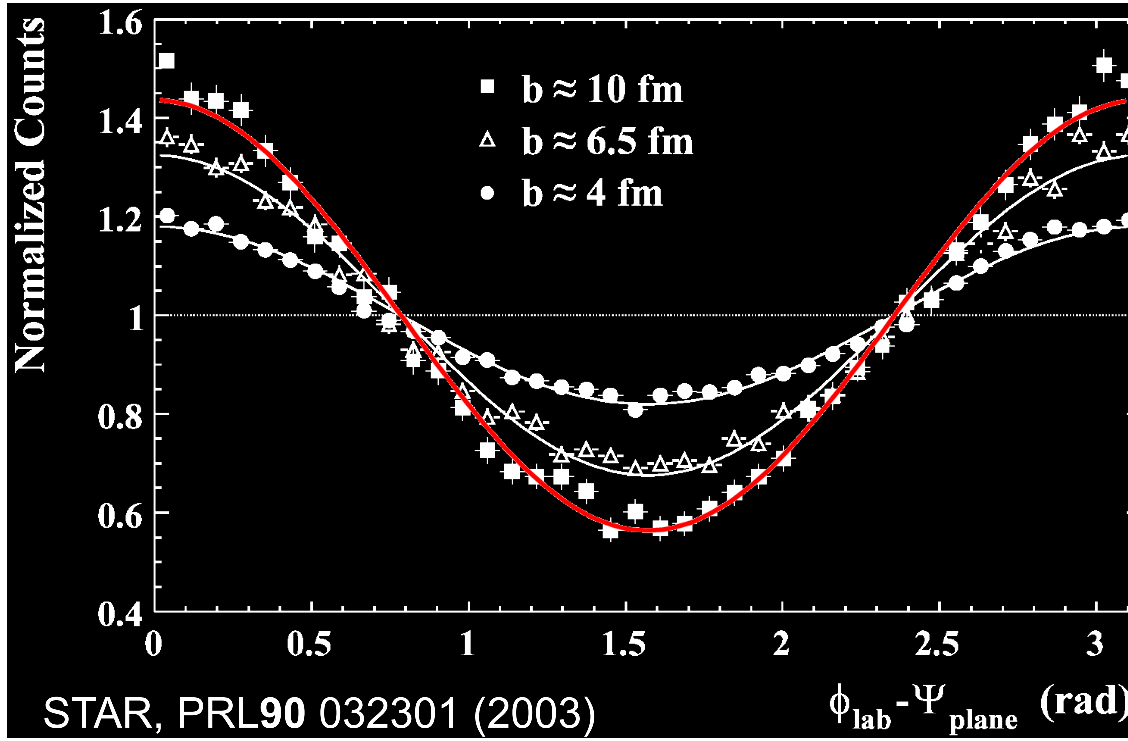
STAR, PRL**90** 032301 (2003)





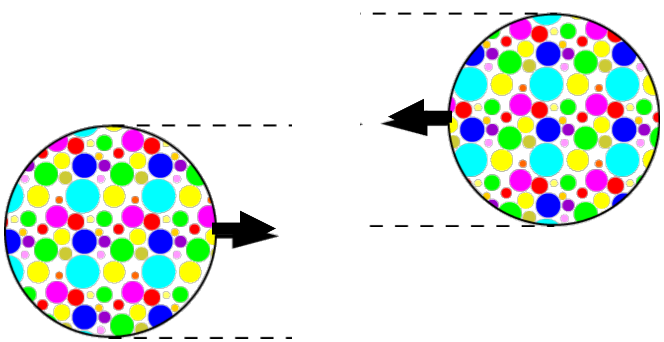
Measurements in STAR at RHIC

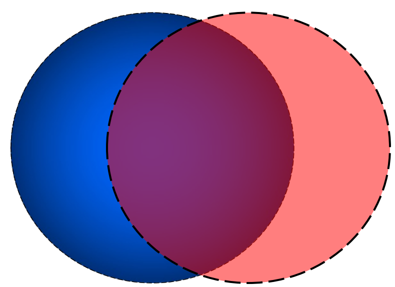




STAR, PRL**90** 032301 (2003)

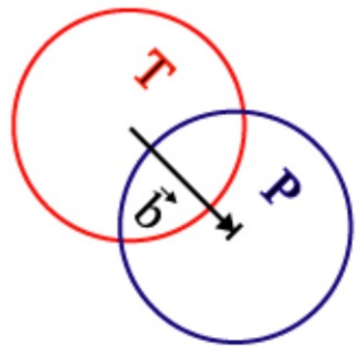
“peripheral” collision

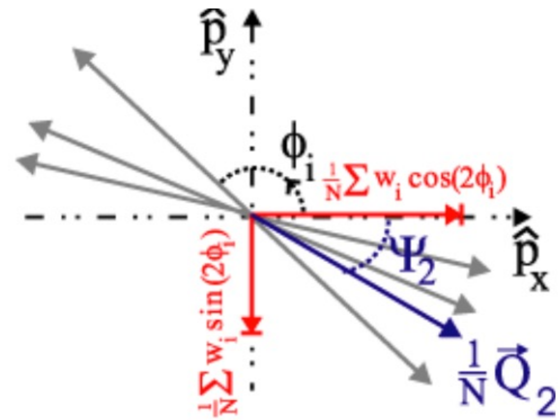




Event Plane Method

Estimation of the true reaction plane using elliptic flow itself.





- - flow vector

$$Q_n \cos(n\Psi_n) = X_n = \sum_i w_i \cos(n\phi_i) \quad Q_n \sin(n\Psi_n) = Y_n = \sum_i w_i \sin(n\phi_i)$$

where sum over all particles

- event plane angle $$\Psi_n = \left(\tan^{-1}\frac{\sum_i w_i \cos(n\phi_i)}{\sum_i w_i \sin(n\phi_i)}\right)/n$$

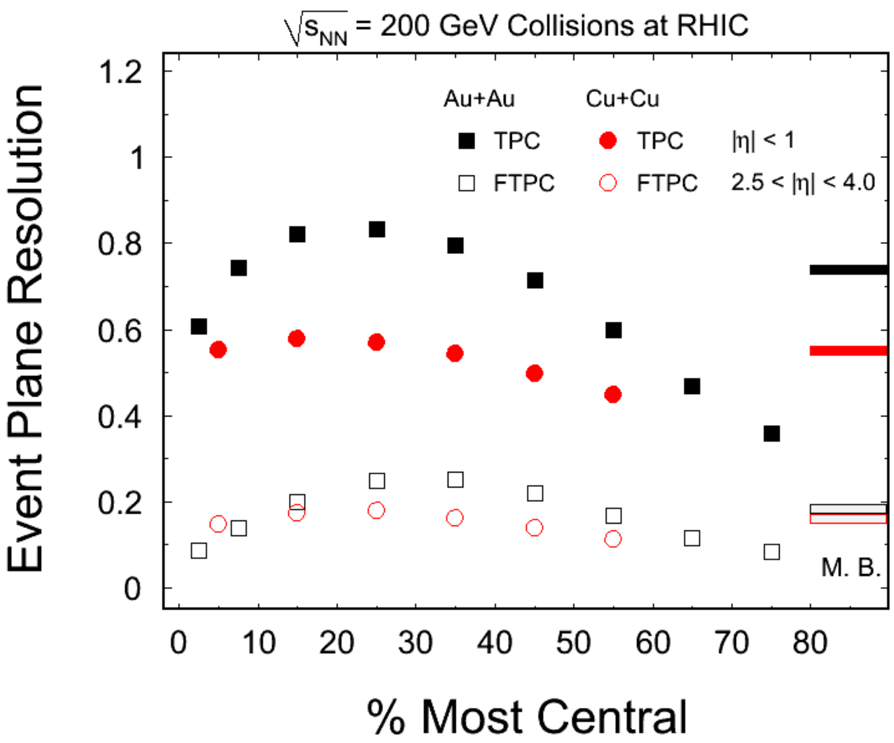
$$v_n^{obs} = \langle\cos[n(\phi - \Psi_n)]\rangle$$
$$v_n = v_n^{obs}/\langle\cos[n(\Psi_n - \Psi_r)]\rangle$$

- Non-flow: not correlated to EP.
  - resonance, jets.

A. M. Poskanzer, S. A. Voloshin, Phys. Rev. C58, 1671 (1998)

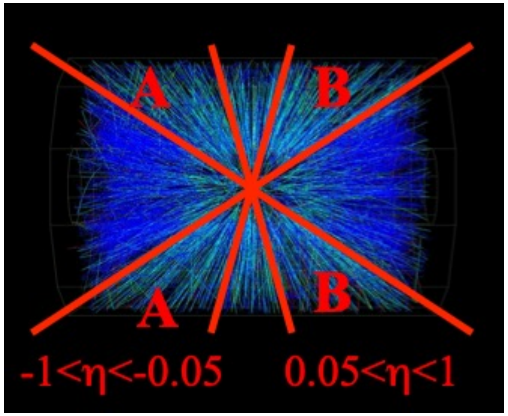
Event Plane Resolution

due to the finite number of detected particles there is a limited resolution in the event plane angle



$$v_n^{obs} = \langle \cos[n(\phi - \Psi_m)] \rangle$$

$$v_n = v_n^{obs} / \langle \cos[n(\Psi_n - \Psi_r)] \rangle$$



$$\langle \cos n(\Psi_n^{EP} - \Psi_r) \rangle = C \times \sqrt{\langle \cos[n(\Psi_n^a - \Psi_n^b)] \rangle}$$

Basics of hydrodynamics: ideal

Energy-momentum conservation	Charge conservation
$\partial_\mu T^{\mu\nu} = 0.$	$\partial_\mu N^\mu = 0$

Local conservation of particle number and energy-momentum

$\Longleftrightarrow$ **Hydrodynamical equations of motion!**

System always in local equilibrium: ideal hydrodynamics

$$T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu}$$

$$N^\mu = n u^\mu$$

Six unknown: ε, P, u^μ, and n, only five equations-of-motion

The equation of state (EoS), *P*(*T,μ*) closes the system of hydrodynamic equations and makes it uniquely solvable (given initial conditions)

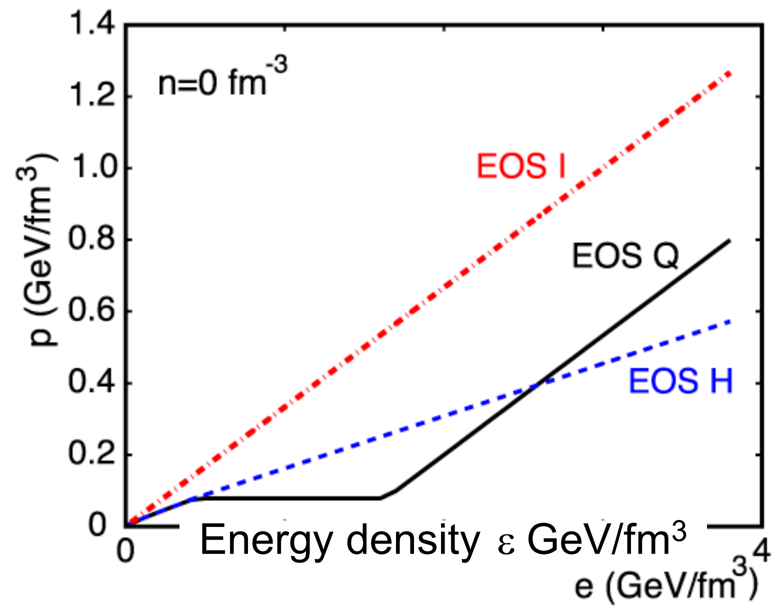
Equation of State

$$\partial_\mu T^{\mu\nu} = 0$$

$$\partial_\mu j^\mu = 0 \qquad j^\mu(x) = s(x)u^\mu(x)$$

$$T^{\mu\nu} = [\varepsilon(x) + p(x)]u^\mu u^\nu - g^{\mu\nu} * p(x)$$

EoS usually given by lattice QCD calculations and hadron resonance gas model



<u>Equation of state</u>:

- **EOS I** : ideal gas of massless partons
- **EOS H**: resonance gas:
- **EOS Q**: connecting an ideal gas of massless partons at high temperature to a Hagdorn hadron resonance gas at low temperature via a first-order phase transition.

T_{crit}= 165 MeV, $B^{1/4}$ = 0.23 GeV ε_{lat}=1.15 GeV/fm^3

*P. Kolb et al., Phys. Rev. **C62**, 054909 (2000).*

Basics of hydrodynamics: viscous

Energy-momentum conservation	Charge conservation
$\partial_\mu T^{\mu\nu} = 0.$	$\partial_\mu N^\mu = 0$

Include near-equilibrium corrections: viscous hydrodynamics

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$N^\mu = n u^\mu + n^\mu$$

- Π: Bulk pressure
- $\pi^{\mu\nu}$: Shear tensor
- n^μ: Charge diffusion

Basics of hydrodynamics: 1^{st} order

Energy-momentum conservation	Charge conservation
$\partial_\mu T^{\mu\nu} = 0.$	$\partial_\mu N^\mu = 0$

Include near-equilibrium corrections: viscous hydrodynamics

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$N^\mu = n u^\mu + n^\mu$$

Bulk pressure (Π); Shear tensor ($\pi^{\mu\nu}$); Charge diffusion (n^μ)

Include 1^{st}-order gradient expansion: Navier-Stokes equation

$$\pi^{\mu\nu} = -\eta\sigma^{\mu\nu}$$

η: shear viscosity coefficient

$$\Pi = -\zeta\nabla^\perp_\lambda u^\lambda$$

ζ : bulk viscosity coefficient

Need 9 additional equations

Hydrodynamics applies only if the expansion converges, i.e., viscous terms are small.
Viscosity slows down the expansion

Basics of hydrodynamics: 2st order

Energy-momentum conservation	Charge conservation
$\partial_\mu T^{\mu\nu} = 0.$	$\partial_\mu N^\mu = 0$

Include near-equilibrium corrections: viscous hydrodynamics

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$N^\mu = n u^\mu + n^\mu$$

Bulk pressure (Π), Shear tensor ($\pi^{\mu\nu}$), Charge diffusion (n^μ)

Include 2st-order gradient expansion:

$$\pi^{\mu\nu} = -\eta\sigma^{\mu\nu} + \eta\tau_\pi \left[{}^{<}D\sigma^{\mu\nu>} + \frac{\nabla^\perp_\lambda u^\lambda}{3}\sigma^{\mu\nu} \right] + \kappa \left[R^{<\mu\nu>} - 2u_\lambda u_\rho R^{\lambda<\mu\nu>\rho} \right] + \lambda_1 \sigma^{<\mu}{}_\lambda \sigma^{\nu>\lambda}$$
$$+\lambda_2 \sigma^{<\mu}{}_\lambda \Omega^{\nu>\lambda} + \lambda_3 \Omega^{<\mu}{}_\lambda \Omega^{\nu>\lambda} + \kappa^* 2u_\lambda u_\rho R^{\lambda<\mu\nu>\rho} + \eta\tau^*_\pi \frac{\nabla^\perp_\lambda u^\lambda}{3}\sigma^{\mu\nu} + \bar{\lambda}_4 \nabla^{<\mu}_\perp \ln\epsilon \nabla^{\nu>}_\perp \ln\epsilon$$

$$\Pi = -\zeta\left(\nabla^\perp_\lambda u^\lambda\right) + \zeta\tau_\Pi D\left(\nabla^\perp_\lambda u^\lambda\right) + \xi_1 \sigma^{\mu\nu}\sigma_{\mu\nu} + \xi_2 \left(\nabla^\perp_\lambda u^\lambda\right)^2$$
$$+\xi_3 \Omega^{\mu\nu}\Omega_{\mu\nu} + \bar{\xi}_4 \nabla^\perp_\mu \ln\epsilon \nabla^\mu_\perp \ln\epsilon + \xi_5 R + \xi_6 u^\lambda u^\rho R_{\lambda\rho}\,.$$

Taken from 1712.05815

Many transport coeff.→ probe microscopic theory, QCD

Hydro Models for Heavy-Ion Collisions

- Need initial conditions for Hydro: ε, u^μ at $\tau = \tau_0$ — unknown
- Need equation of state $p = p(\varepsilon)$, which gives $c^2_s = dp/d\varepsilon$ — want to study
- Need functions for transport coefficients η, ζ. — want to study
- Need algorithm to solve (nonlinear!) hydro equations
- Need method to convert hydro information to particles ("freeze-out") — unknown

- Use another model to fix unknowns (and add new assumptions. . .)

  initial: color glass condensate or pQCD+saturation

  initial and/or final: hadronic cascade

  EoS: lattice QCD

- Use data to fix parameters:

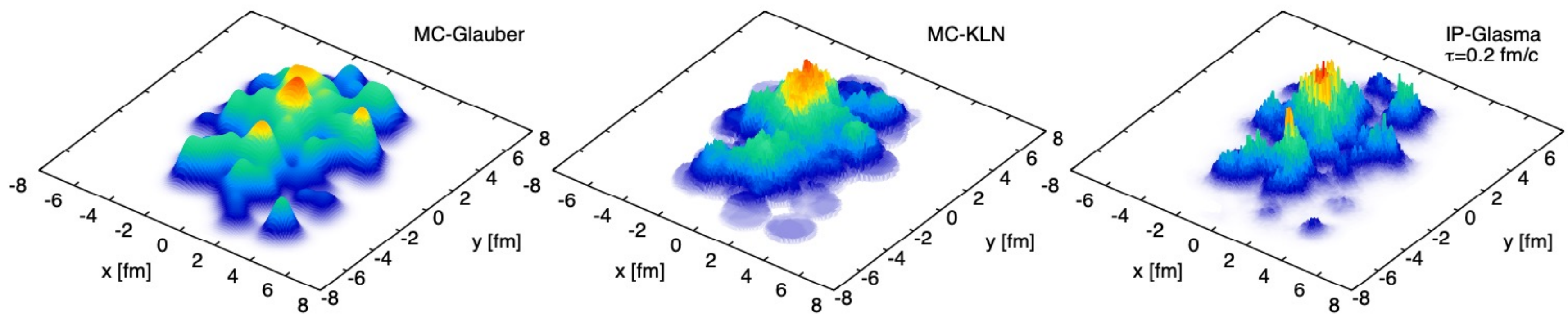
use one set of data $\frac{dN}{dyp_Tdp}|_{b=0}$ $\frac{dN}{dyp_Tdp}(b)$

fix parameters to fit it $T_{\rm fo} = 130\text{MeV}$, $\varepsilon_{0,max} = 29.6\text{GeV/fm}^3$ $,\tau_0 = 0.6$ fm/c

predict another set of data HBT. V_2。。。

Initial conditions

- MC Glauber is simple phenomenological description where energy/entropy density ~ Npart and/or Ncoll
- Other models include dynamics of particle production: EKRT, EPOS, MC-KLN, IP-Glasma, ... via strings, partons, classical fields, ..., while the geometry is dictated by sampled nucleon positions
- Different models give different *energy density distributions*



C. Gale, S. Jeon, B. Schenke, Int.J.Mod.Phys. A28 (2013) 1340011

Hydro Motivated Fit

$$v_2(p_t) = \frac{\int_0^{2\pi} d\phi_b \cos(2\phi_b) I_2(\alpha_t) K_1(\beta_t)(1+2s_2\cos(2\phi_b))}{\int_0^{2\pi} d\phi_b I_0(\alpha_t) K_1(\beta_t)(1+2s_2\cos(2\phi_b))}$$

I_0, I_2, and K_1 are modified Bessel functions,

$$\alpha_t(\phi_b) = \left(\frac{p_t}{T_f}\right)\sinh(\rho(\phi_b)) \quad \beta_t(\phi_b) = \left(\frac{m_t}{T_f}\right)\cosh(\rho(\phi_b))$$

$$\rho(\phi_b) = \rho_0 + \rho_a \cos(2\phi_b)$$

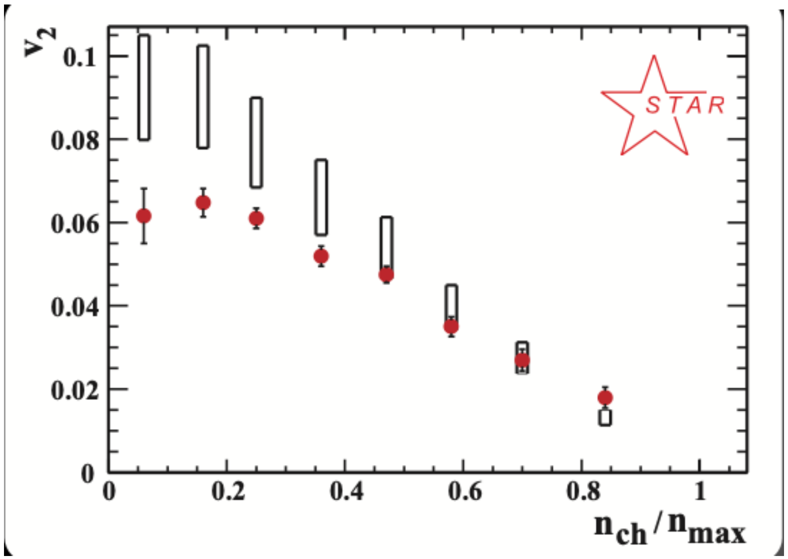
STAR Phys. Rev. Lett. 87, 182301 (2001)

ρ_0: mean transverse expansion rapidity , ρ_a : amplitude of its azimuthal variation,

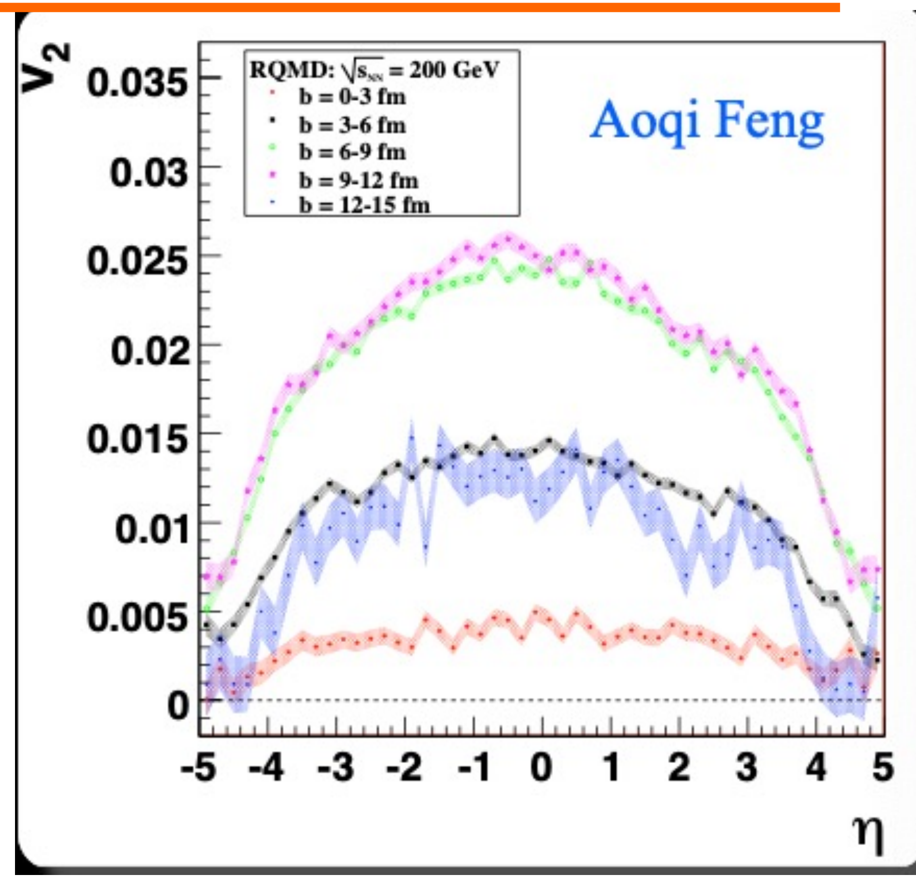
$s_2 = 0$ spatially isotropic freeze-out hypersurface in the transverse plane.

extra parameter, s_2, describing the variation in the azimuthal density of the source elements, spatially anisotropic freeze-out hypersurface,

Flow at RHIC

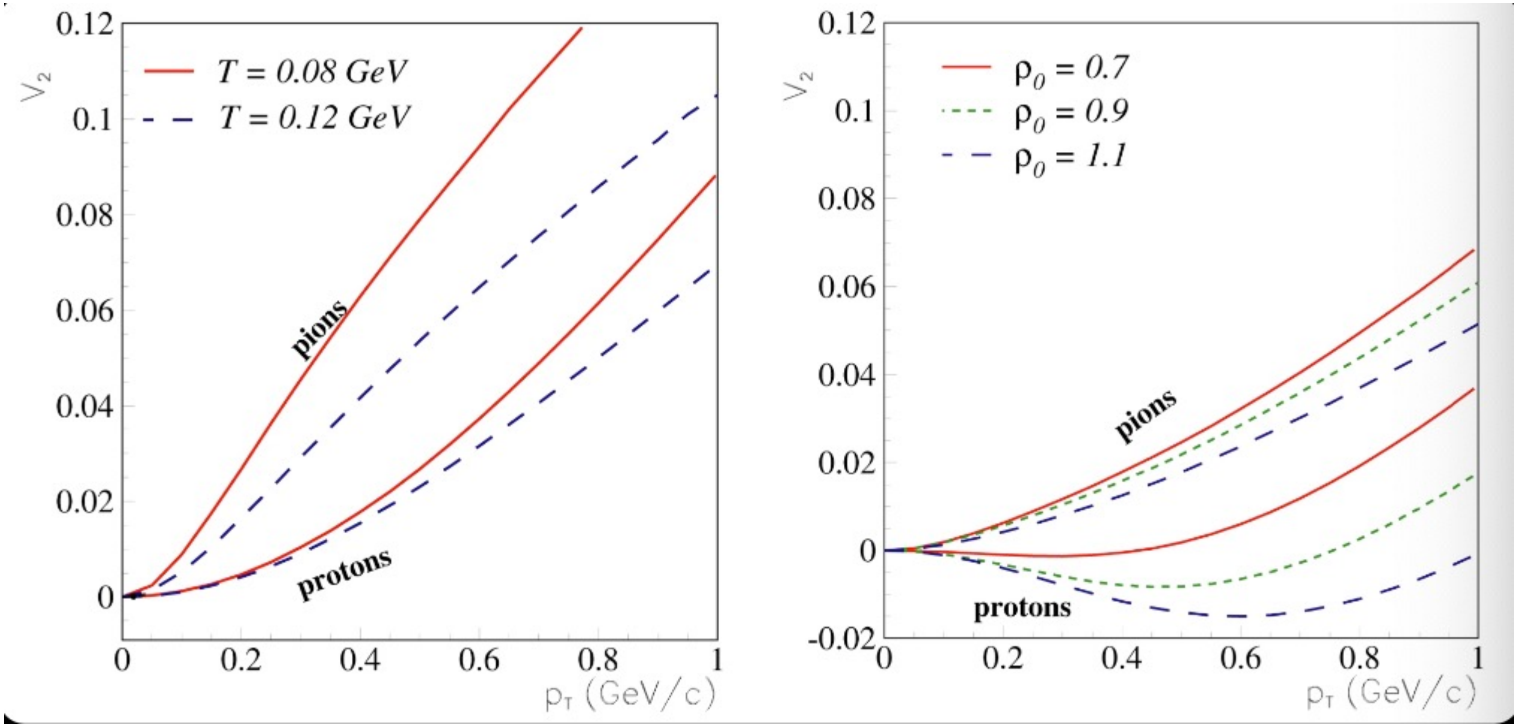


STAR Phys. Rev. Lett. 86, 402–407 (2001)



ideal hydro works beautifully in central and semi-central collisions
collisions hadron transport calculations are factors 2-3 off

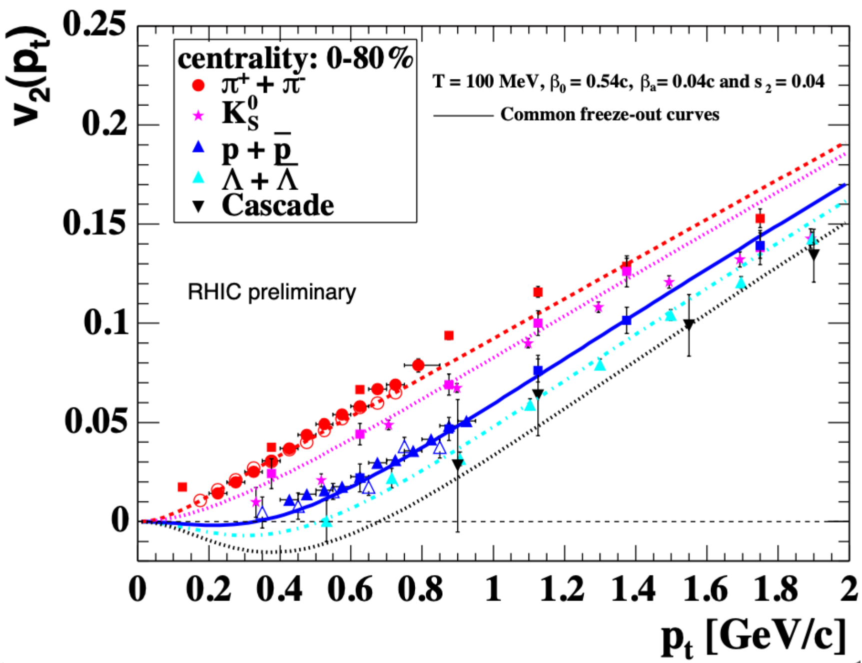
The effect of freeze-out temperature and radial flow on v_2

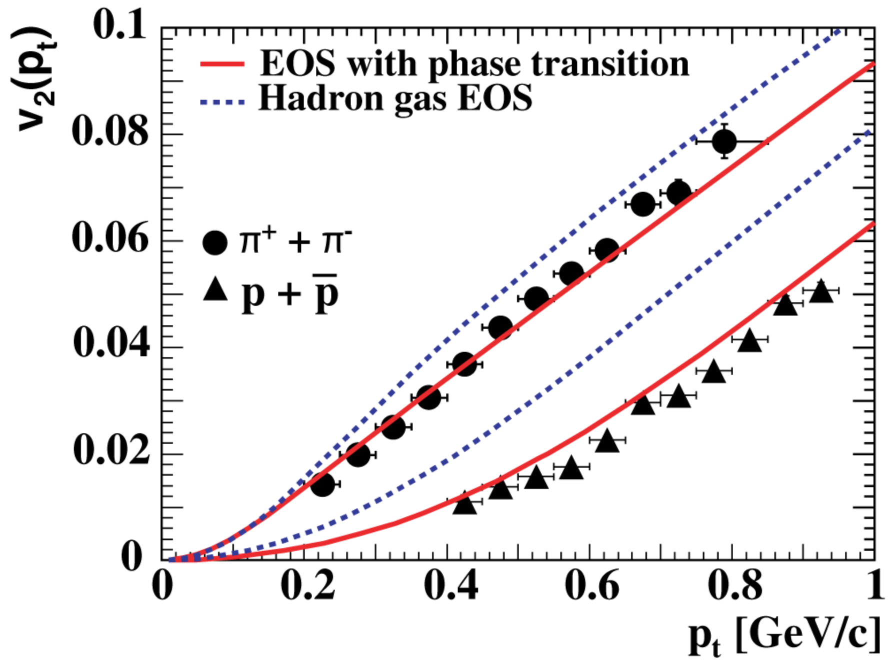


F. Retiere and M.A. Lisa, Phys.Rev.C70:044907,2004

light particle v_2(pt) very sensitive to temperature
heavier particles v_2(pt) more sensitive to transverse flow

v_2 at Low p_T Region： Mass dependence





the observed particles are characterized by a single freeze-out temperature and a common azimuthal dependent boost velocity

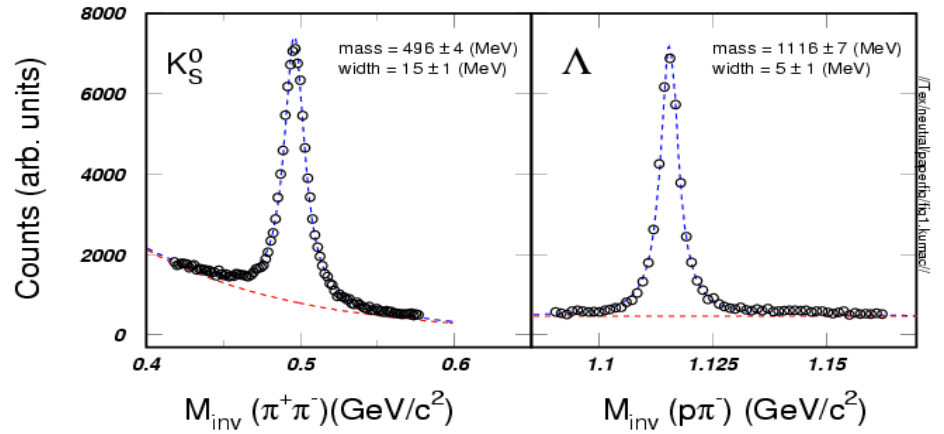
- pions to Cascade follow the mass dependence at low-p_t
- Ideal hydro not perfect agreement but plasma EoS favored

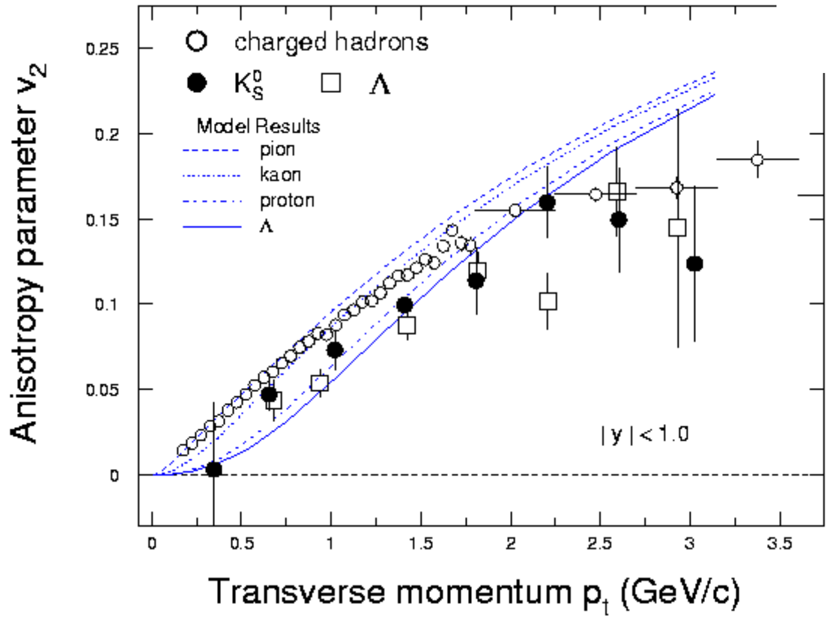
v_2 in Au Au Collisions at 130 GeV

V0 reconstruction

$$K_S^0 \rightarrow \pi^+ + \pi^- \quad 68.95\%$$

$$\Lambda(\overline{\Lambda}) \rightarrow p + \pi^-(\overline{p} + \pi^+) \quad 63.9\%$$



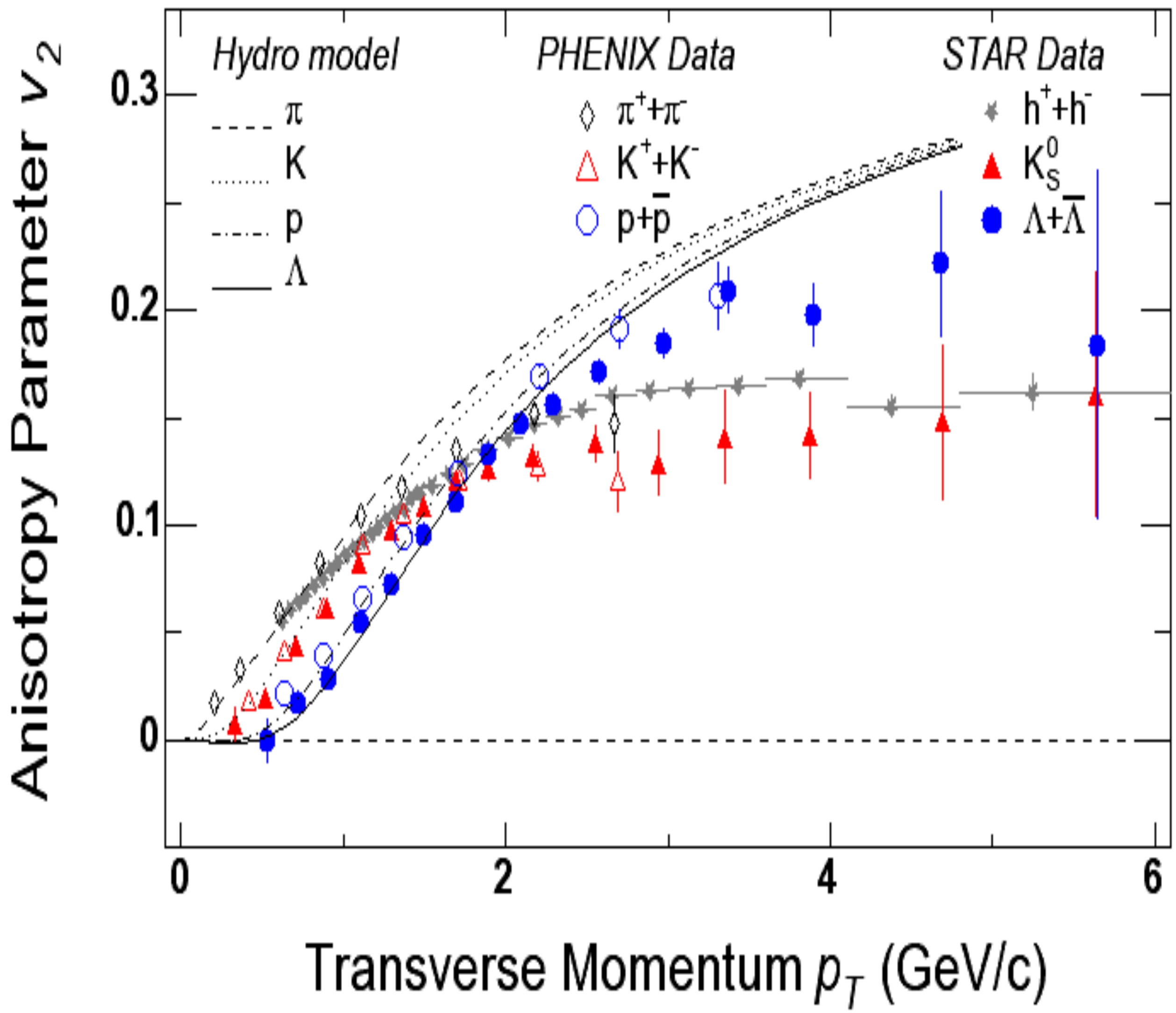


STAR(JH Fu) PRL 89, 132301(2002)
200k minibias, 180k central events

- Increase with p_t up to about 1.5 GeV/c
- At high p_t seem to be saturate

Elliptic Flow v_2

PRL **92** (2004) 052302; PRL **91** (2003) 182301

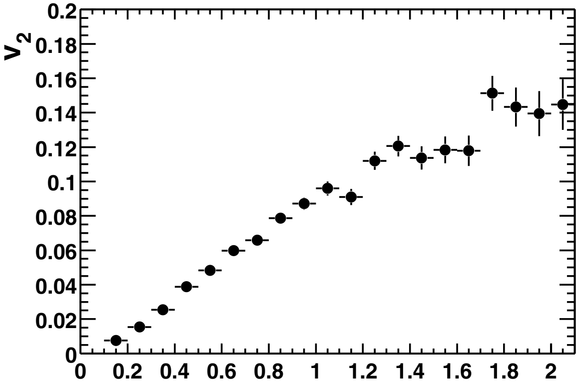


Hydro calculations break-down at higher p_T (as expected).

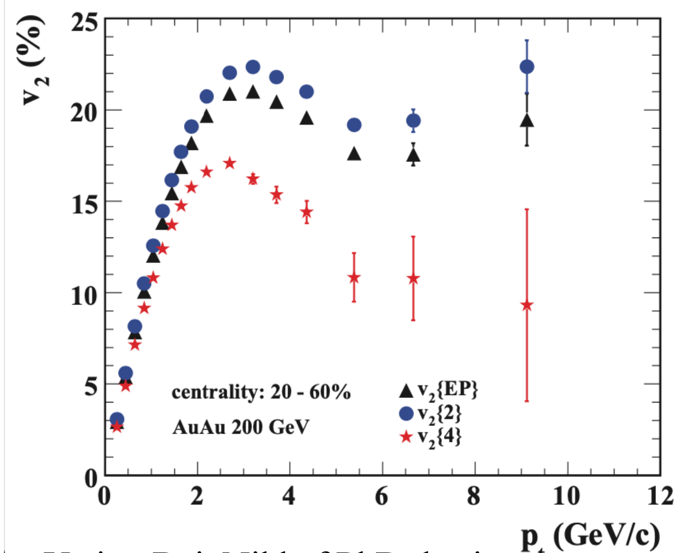
How is v_2 established at p_T above 2 GeV/c?

Why is baryon v_2 so large?

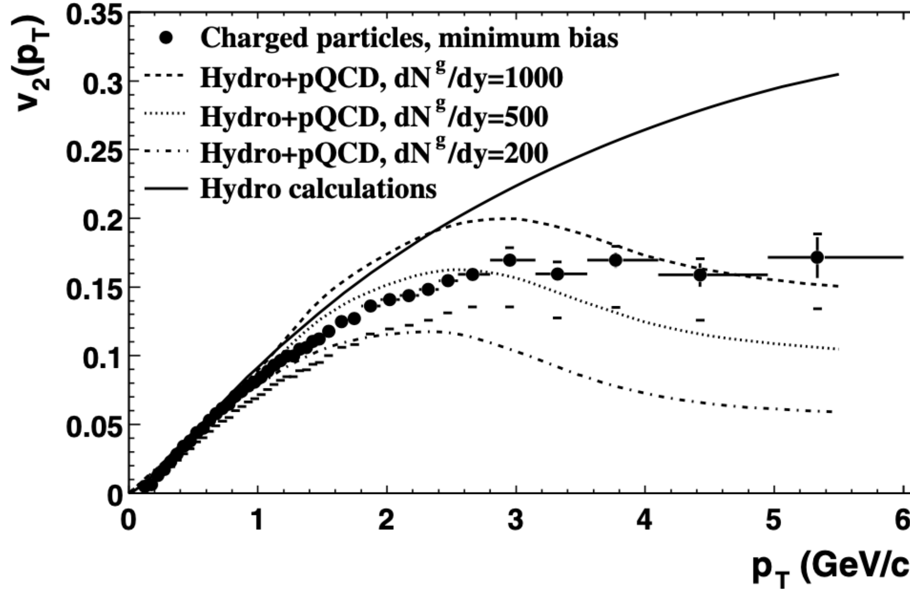
parton energy loss



STAR PRL 86,402(2001)



Yuting Bai, Nikhef PhD thesis



M. Gyulassy, I. Vitev and X.N. Wang, Phys. Rev. Lett. 86, 2537(2001).

$$v_2(p_t) \approx \frac{v_{2s}(p_t)dN_s + v_{2h}(p_t)dN_h}{dN_s + dN_h}$$

Particle Identification

Rest are constructed: Invariant Mass + Decay Topology

V0 decay vertices

$K_s \rightarrow \pi^+ + \pi^-$

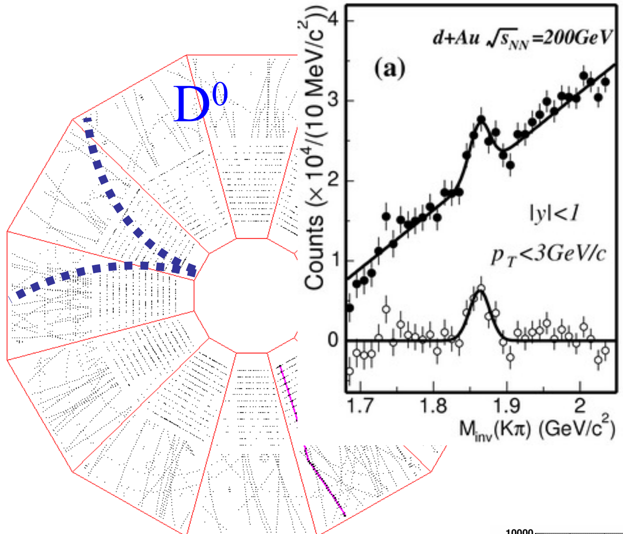
$\Lambda \rightarrow p + \pi^-$

$\bar{\Lambda} \rightarrow \bar{p} + \pi^+$

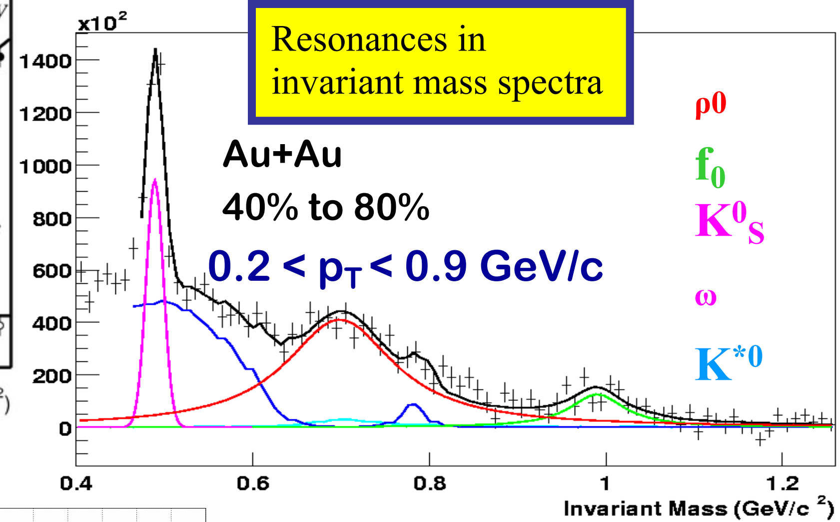
$\Xi^- \rightarrow \Lambda + \pi^-$

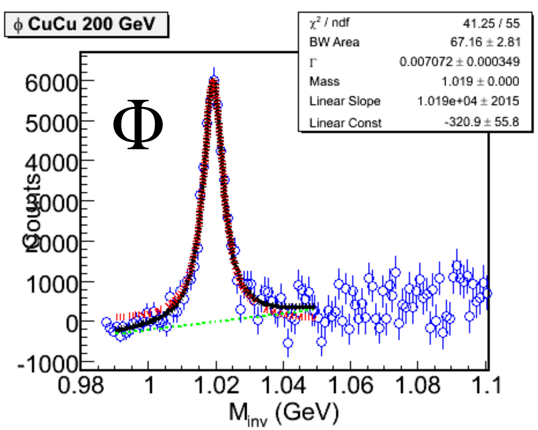
$\Xi^+ \rightarrow \bar{\Lambda} + \pi^+$

$\Omega \rightarrow \Lambda + K^-$

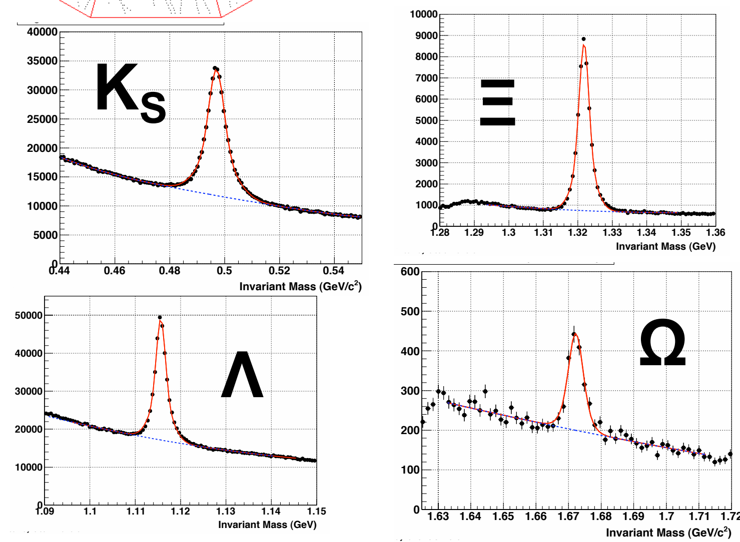


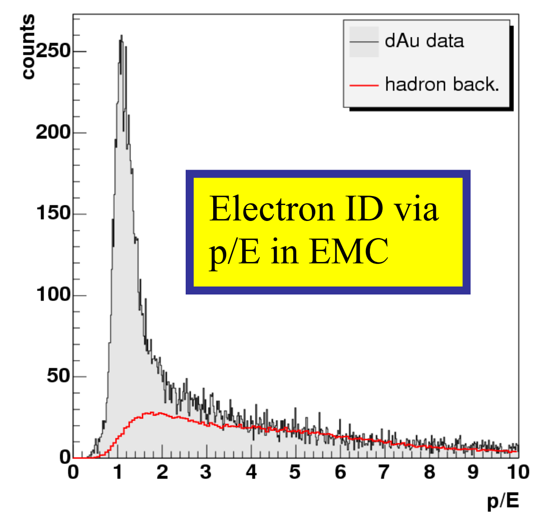
Resonances in invariant mass spectra





$$M^2 = E^2 - p^2$$

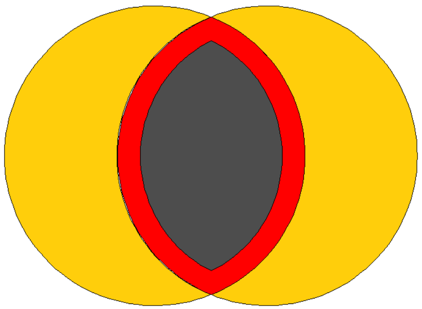




Electron ID via p/E in EMC

π^0, K^0_s, ρ, ω K*, Λ, φ Ξ Ω, D0 …..

Constituent Quark Degree of Freedom



Hadronization Scheme for Bulk Partonic Matter:

K_S – two quark coalescence

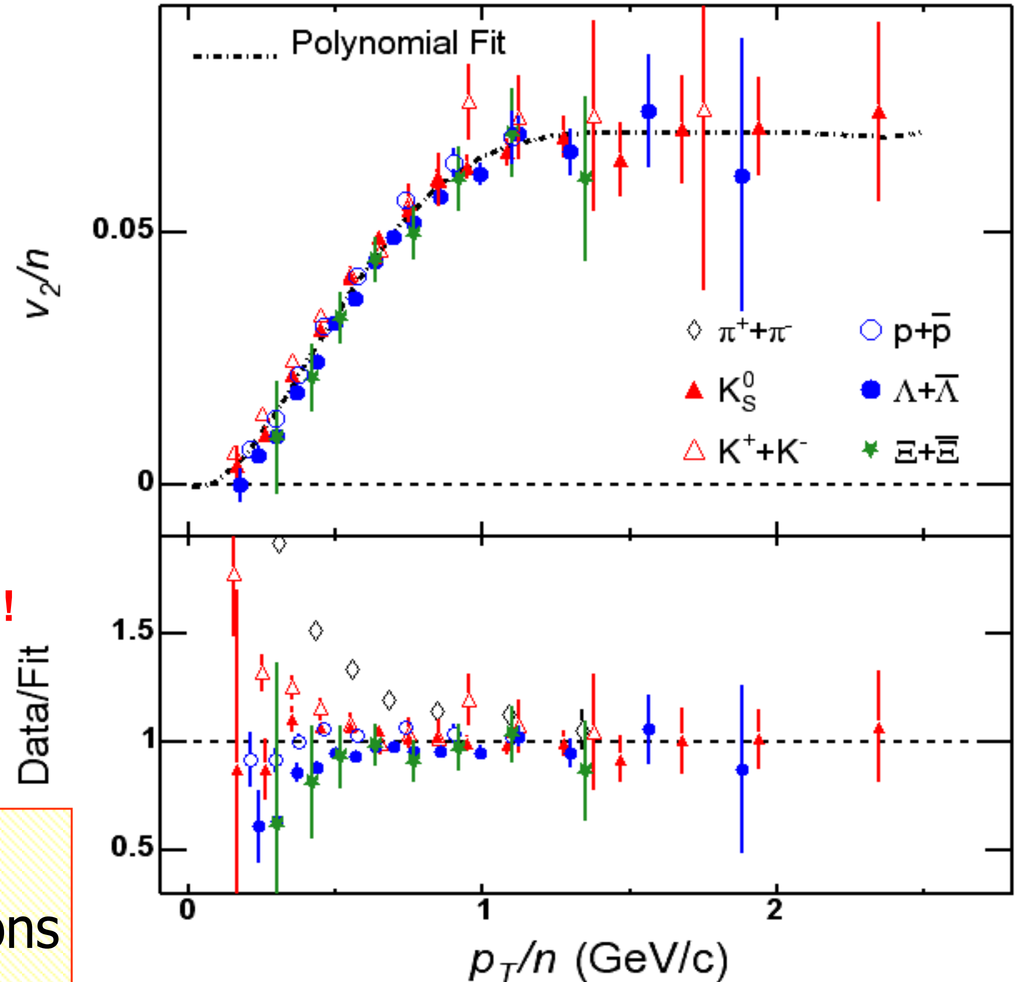
Λ– three quark coalescence from the partonic matter surface?!

Particle v_2 may be related to quark matter anisotropy !!

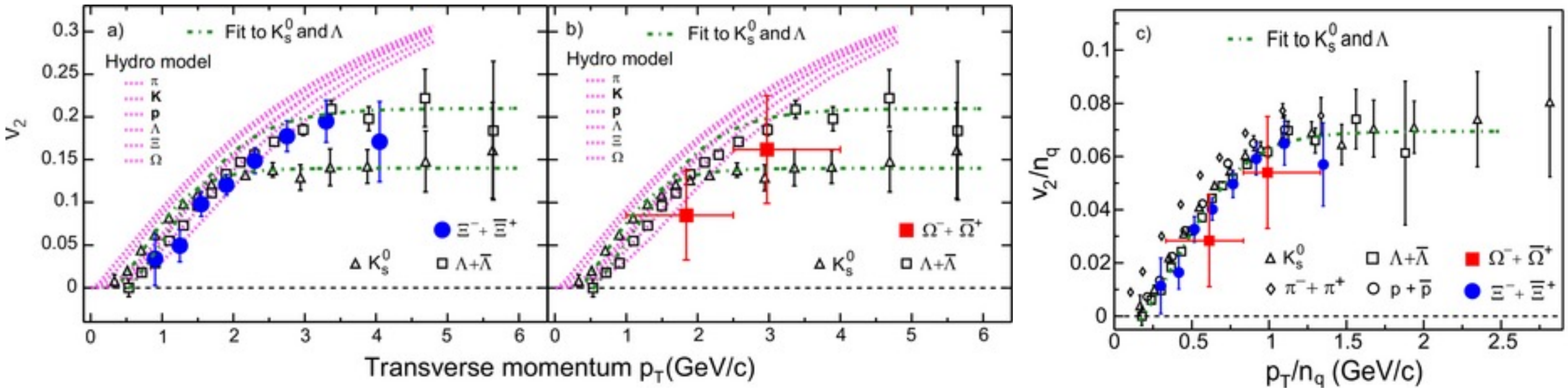
For hadron formation by coalescence of co-moving partons

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

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



NQ Scaling for Identified Particles

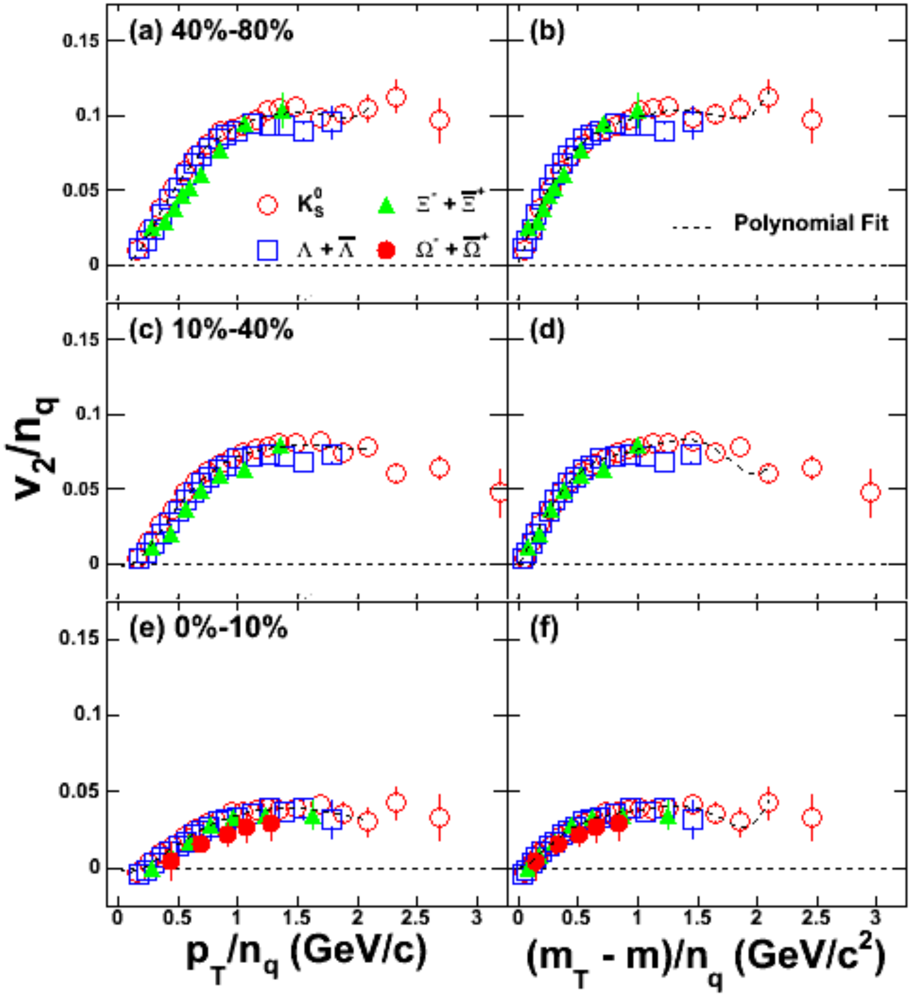


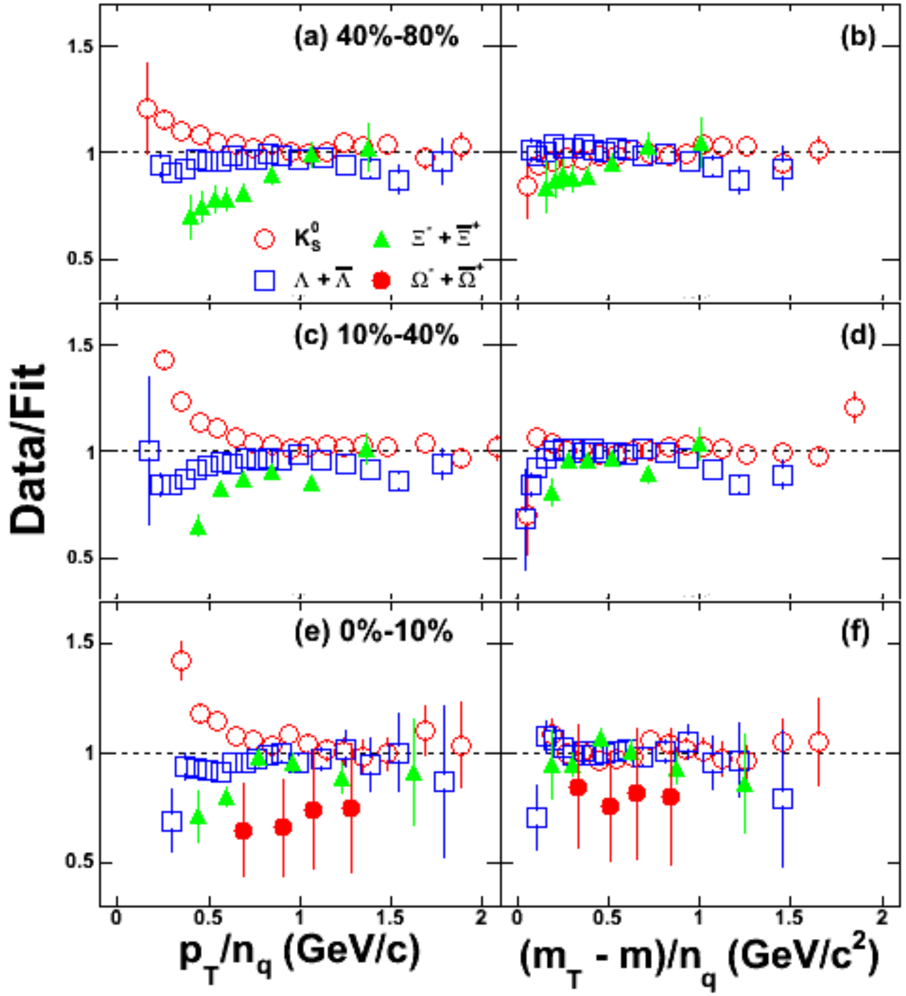
STAR： Nucl. Phys. A 757, 102, (2005);（H. Long, JH Fu, H. Huang, N. Xu) PRL 92,052302 (2004) ;
J. Phys. G 30, S1207, (2004); PHENIX: PRL 91,182301, (2003) .
Fit: X. Dong, S. Esumi, P. Sorensen, N. Xu, Z. Xu, PLB 597, 328 (2004) .

- Minimum bias data!
- At intermediate p_T, v_2 scales with the number of quarks.
- Coalescence/Reco models can account for NQ scaling.
- Multi-strange hadrons have small hadronic cross section.

Partonic collectivity, de-confinement at RHIC.

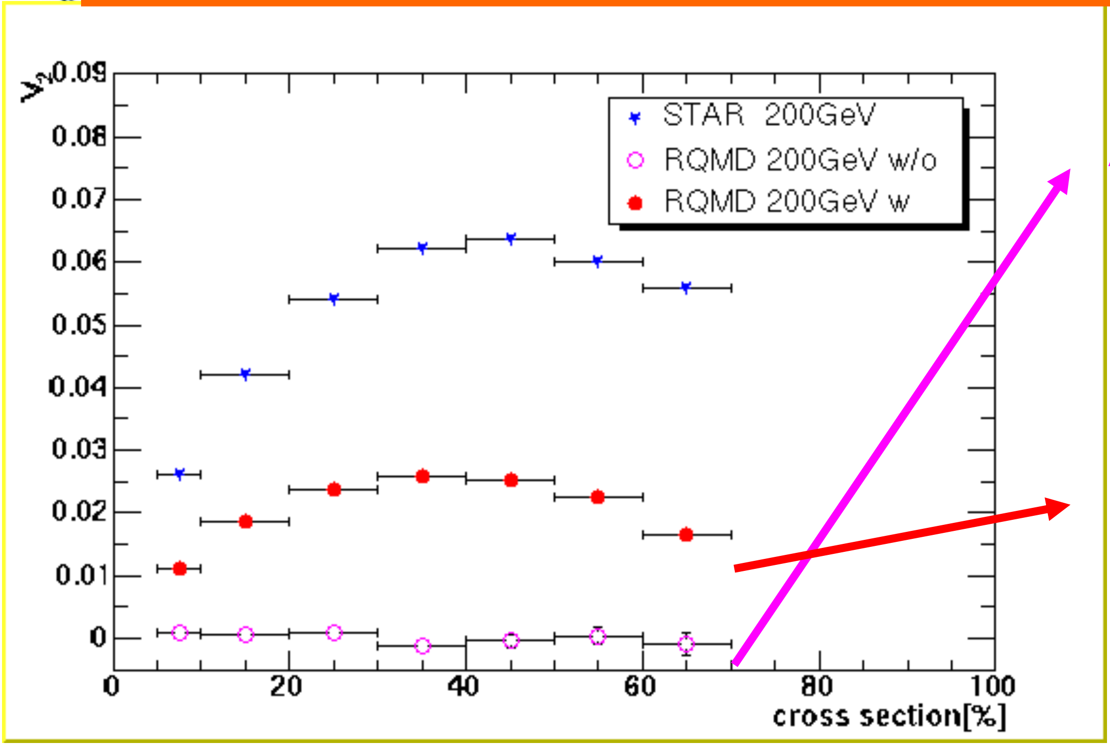
Centrality Dependence of NQ Scaling





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

Model Calculation



Almost zero.Even though initial space anisotropy exists,momentum anisotropy can't be converted into.

Reproduce the trend of experiment but have smaller value than experiment's.

Re-scatterings only among hadrons are not enough.

1 Re-scatterings are necessary.

2 Re-scatterings at partonic level are essential.

Originates from at partonic stage?

Methods Using Multi-Particle Correlations

- since reaction plane cannot be measured event-by-event, consider quantities which do not depend on it's orientation: multi-particle azimuthal correlations

$$\left\langle e^{in(\phi_1-\phi_2)}\right\rangle = \left\langle e^{in\phi_1}\right\rangle \left\langle e^{-in\phi_2}\right\rangle + \left\langle e^{in(\phi_1-\phi_2)}\right\rangle_{corr}$$

zero for symmetric detector when averaged over many events

$$\langle\langle 2\rangle\rangle = \left\langle\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\right\rangle = \left\langle\left\langle e^{in(\phi_1-\Psi_{RP}-(\phi_2-\Psi_{RP}))}\right\rangle\right\rangle$$

$$= \left\langle\left\langle e^{in(\phi_1-\Psi_{RP})}\right\rangle\left\langle e^{-in(\phi_2-\Psi_{RP})}\right\rangle\right\rangle = \langle v_n^2\rangle$$

assuming that only correlations with the reaction plane are present

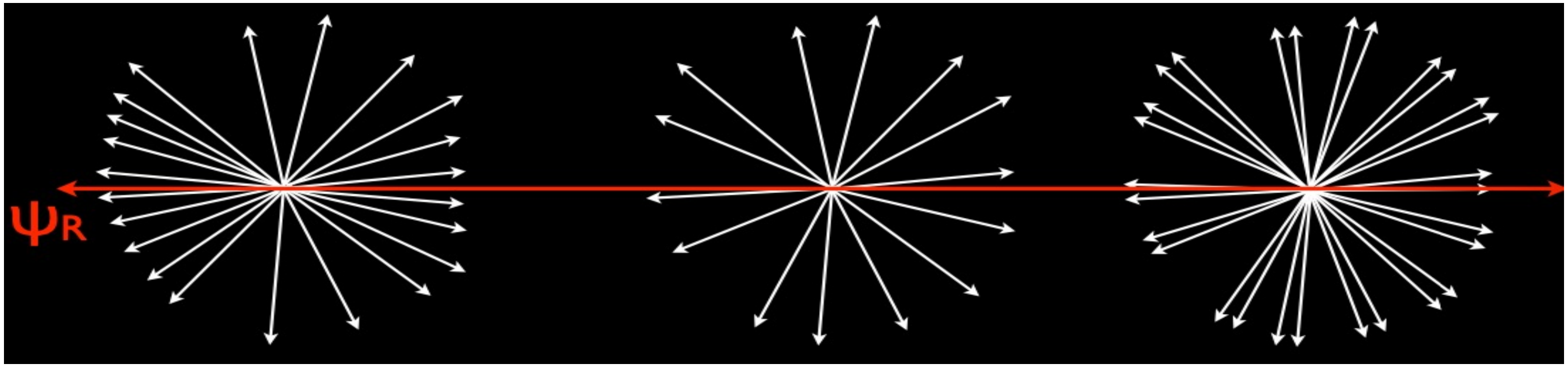
$$\left\langle\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle\right\rangle$$

do not depend on frame Φ + α (shifting all particles by fixed angle) gives same answer for the correlation

nonflow

- there are other sources of correlations between the particles which are not related to the reaction plane which break the factorization, lets call those δ_2 for two particle correlations

$$\left\langle\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\right\rangle = \langle v_n^2 \rangle + \delta_2$$



$v_2 > 0, v_2\{2\} > 0$ $v_2 = 0, v_2\{2\} = 0$ $v_2 = 0, v_2\{2\} > 0$

Method Comparisons

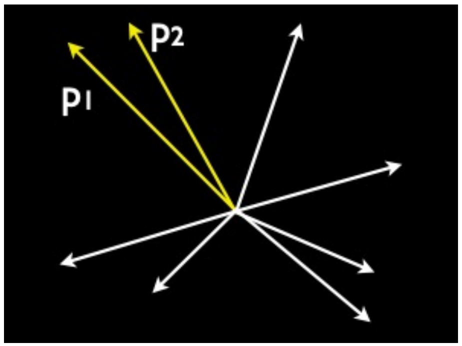
- **Two-particle:**
  - $v_2\{2\}$: each particle with every other particle
  - $v_2\{subEP\}$: each particle with the EP of the other subevent
  - $v_2\{EP\}$ "standard": each particle with the EP of all the others
- **Many-particles:**
  - $v_2\{4\}$: 4-particle - 2 * (2-particle)^2
  - $v_2\{LYZ\}$: Lee-Yang Zeros multi-particle correlation

- **Two-particle:**
  - v_2 is assumed to be the only or dominant source of correlation in azimuth between particles.
  - sensitive to non-flow effects

  correlations from resonance decay, jets
- **Many-particles:**
  - measure flow by a cumulant expansion of multiparticle azimuthal correlations
  - reduce nonflow effects originate from a few particle correlations
  - limited by statistics

nonflow

$$\left\langle\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\right\rangle = \langle v_n^2\rangle + \delta_2$$



particle 1 coming from the resonance. Out of remaining M-1 particles there is only one which is coming from the same resonance, particle 2. Hence a probability that out of M particles we will select two coming from the same resonance is ~ 1/(M-1). From this we can draw a conclusion that for large multiplicity:

$$\delta_2 \sim 1/M$$

therefore to reliably measure flow:

$$\langle v_n^2\rangle \gg 1/M \;\rightarrow\; v_n \gg 1/M^{1/2}$$

not easily satisfied: M=200 v_n >> 0.07

Multi-particle correlations

use the fact that flow is a correlation between all particles:
use multi-particle correlations

$$\left\langle\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\right\rangle = v_n^2 + \delta_2$$

$$\left\langle\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle\right\rangle = v_n^4 + 4v_n^2\delta_2 + 2\,\delta_2^2 + \delta_4$$

build cumulants with the multi-particle correlations   Ollitrault and Borghini

$$c_n\{2\} \equiv \left\langle\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\right\rangle = v_n^2 + \delta_2$$

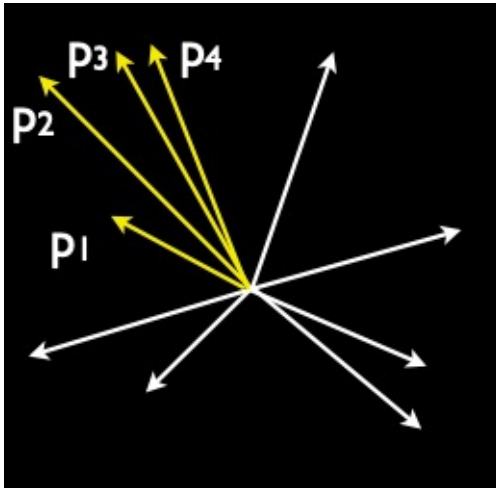
$$c_n\{4\} \equiv \left\langle\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle\right\rangle - 2\left\langle\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\right\rangle^2$$

$$= v_n^4 + 4v_n^2\delta_2 + 2\,\delta_2^2 - 2(v_n^2 + \delta_2)^2 + \delta_4$$

$$= -v_n^4 + \delta_4$$

got rid of two particle non-flow correlations!

4-particle correlations



Particle 1 coming from the mini-jet.To select particle 2 we can make a choice out of remaining M-1 particles; once particle 2 is selected we can select particle 3 out of remaining M-2 particles and finally we can select particle 4 out of remaining M-3 particles. Hence the probability that we will select randomly four particles coming from the same resonance is 1/(M-1)(M-2) (M-3). From this we can draw a conclusion that for large multiplicity:

$$\delta_2 \sim 1/M. \quad , \delta_4 \sim 1/M^3$$

therefore to reliably measure flow:

$$v_n^2 \gg 1/M \rightarrow v_n \gg 1/M^{1/2}$$

$$v_n^4 \gg 1/M^3 \rightarrow v_n \gg 1/M^{3/4}$$

- it is possible to extend this:

for large k

$$v_n^{2k} \gg 1/M^{2k-1} \rightarrow \; v_n \gg 1/M^{\frac{2k-1}{2k}}$$

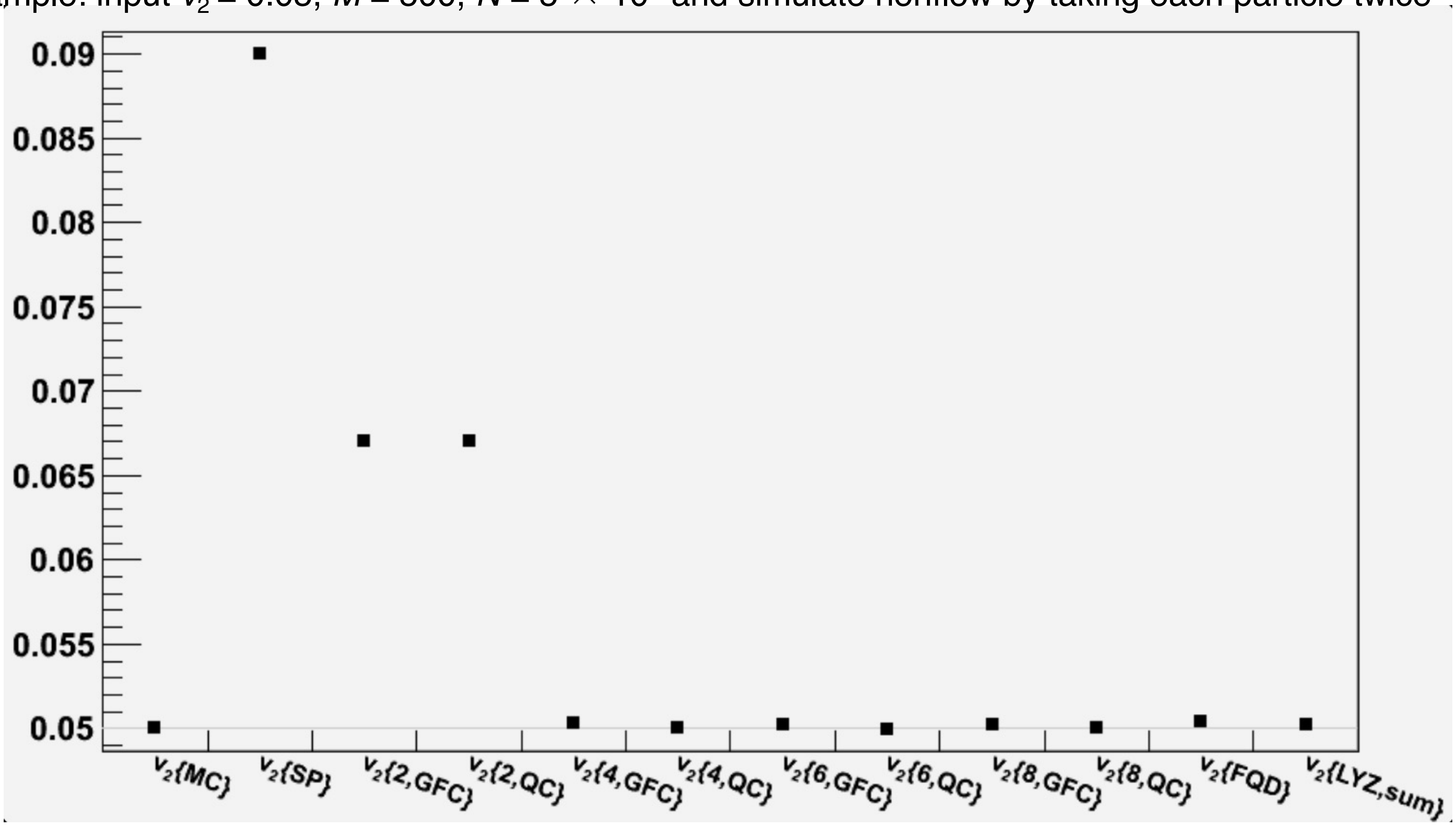
$$v_n \gg 1/M$$

as an example: M=200 v_n >> 0.005 (more than order of magnitude better than two particle correlations)

to reliably measure small flow in presence of other correlations one needs to use multi-particle correlations!

nonflow example

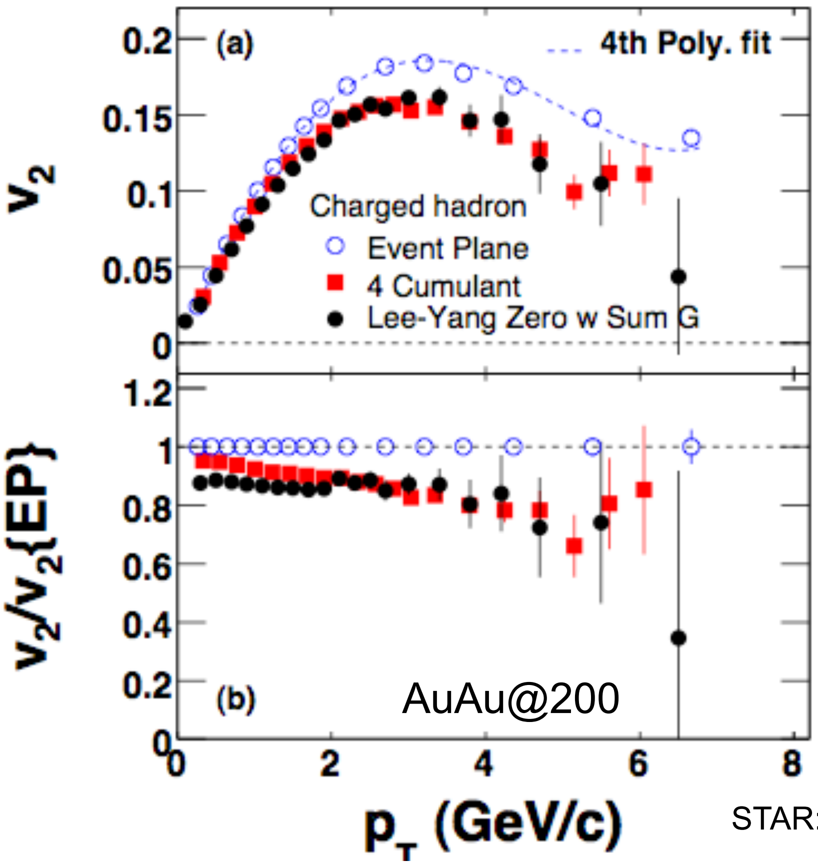
Example: input $v_2 = 0.05$, $M = 500$, $N = 5 \times 10^6$ and simulate nonflow by taking each particle twice

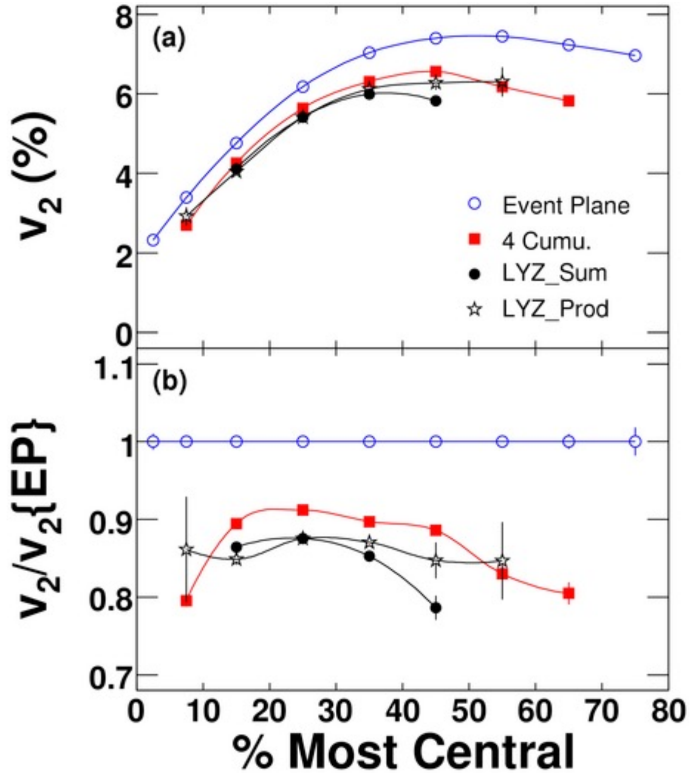


from: Raimond Snellings

only two particle methods are biased

Systematic Study of v_2





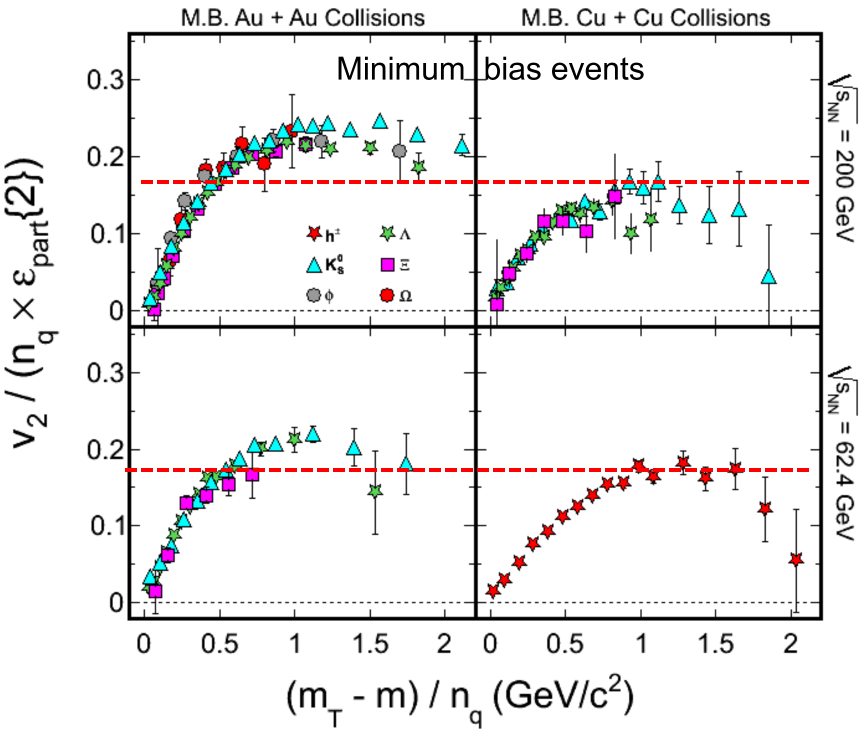
STAR: Y. Bai, Y. Lv, A. Tang, N. Xu ,PRC **77**,54901 (2008) . 25M

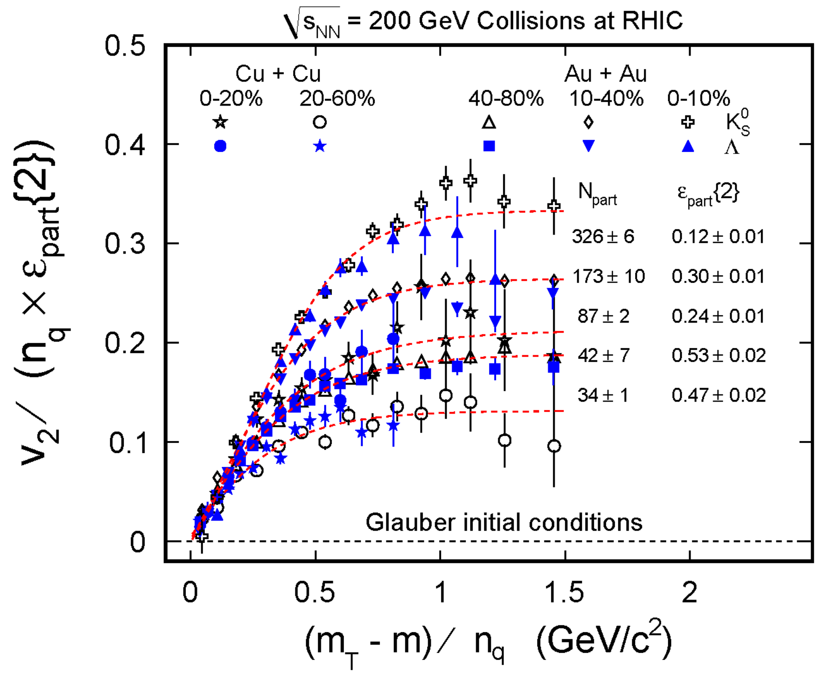
- Non-flow contribution at large p_T region
- most peripheral collisions nonflow might be larger
- most central collisions, fluctuations could be important

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)





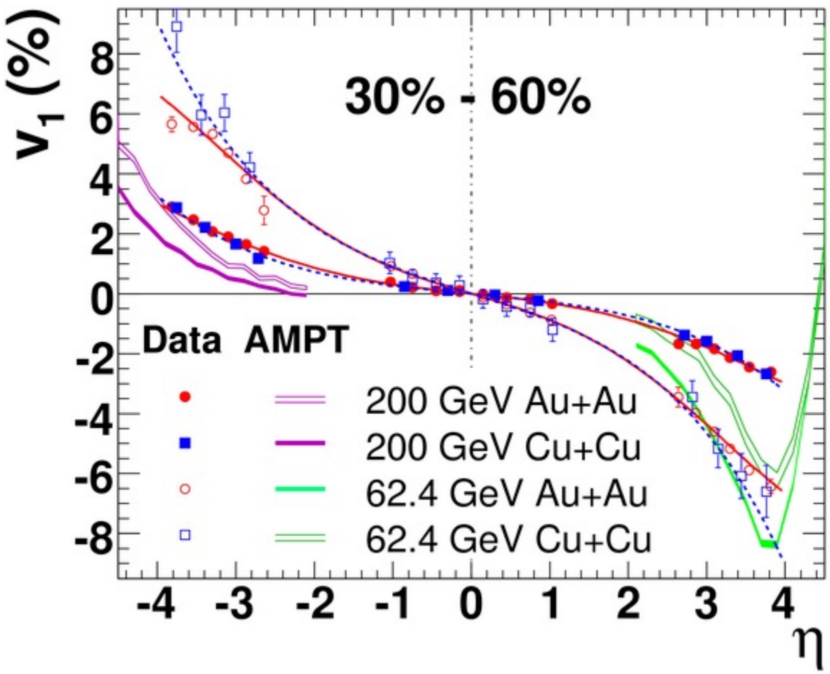
Au+Au and Cu+Cu at 200 GeV **Scaled by eccentricity** remove the initial geometry

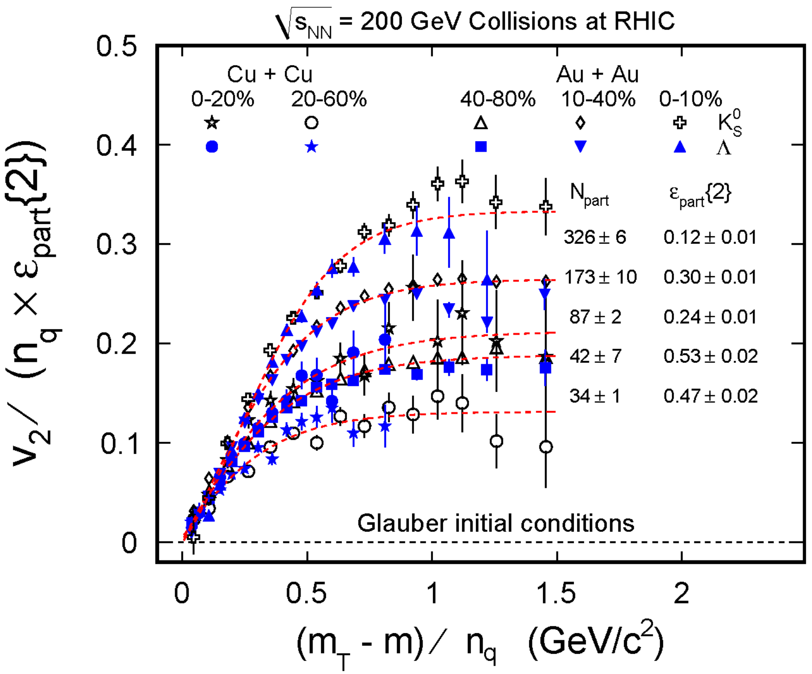
- ➢NQ scaling for each centrality bin

➢Collective flow: depends on the number of participants

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

v_1 & v_2 from different collision systems



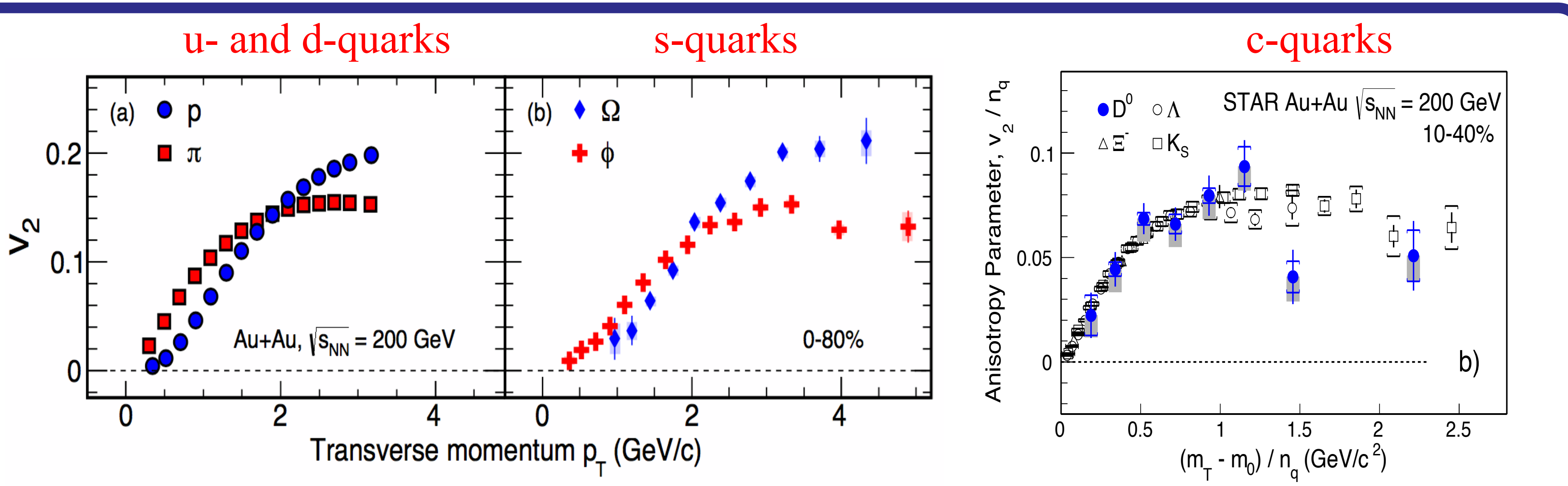


v_1 is found being independent of collision systems. decrease with increasing beam energy

v_2 Collective flow: depends on the number of participants

v_1 *dependent on r*apidity lost

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;

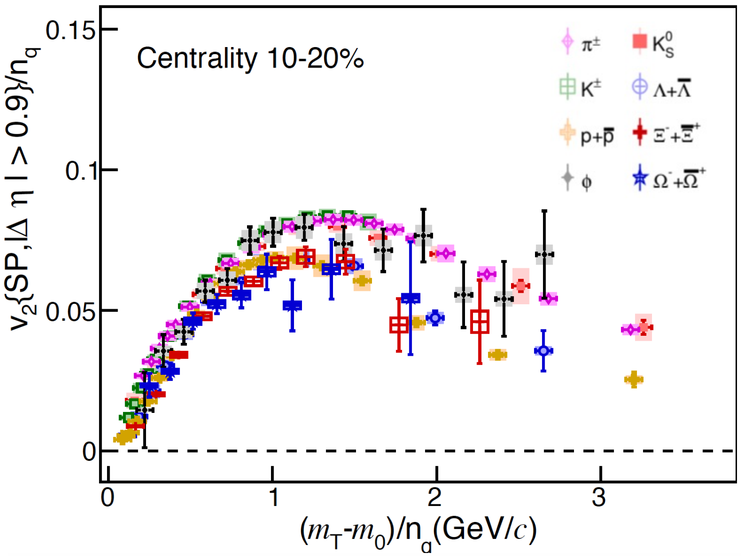
➔ ***Partonic Collectivity, necessary for QGP!***

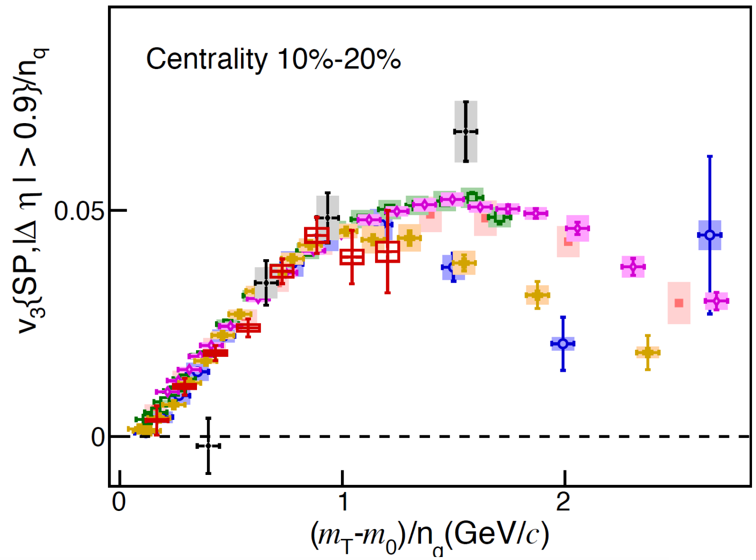
➔ ***De-confinement in Au+Au collisions at RHIC!***

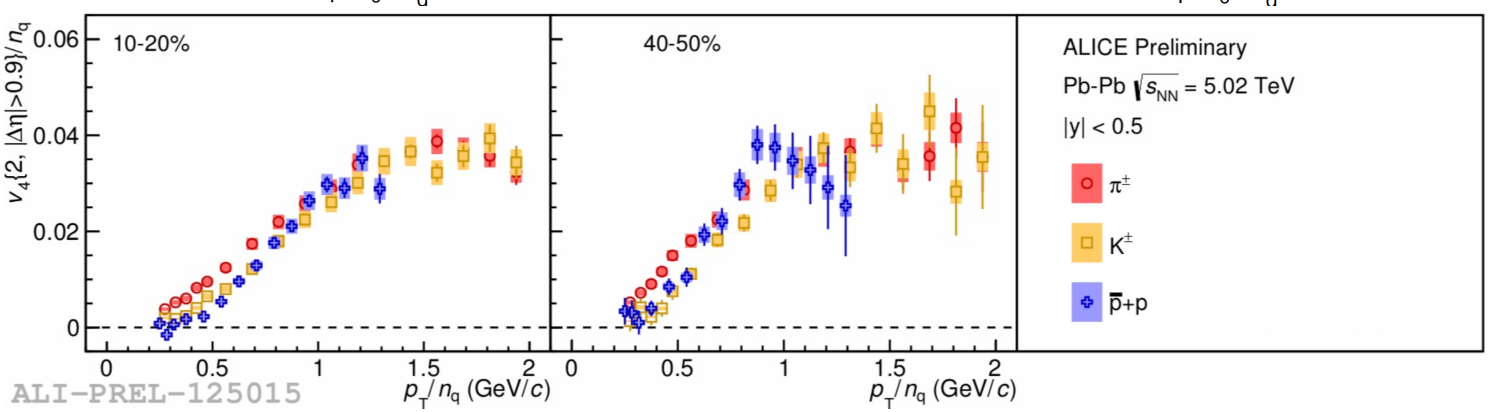
Elliptic Flow at LHC

•Pb + Pb 5.02 TeV

•**ALICE:** ICHEP 2018, ATHIC 2018



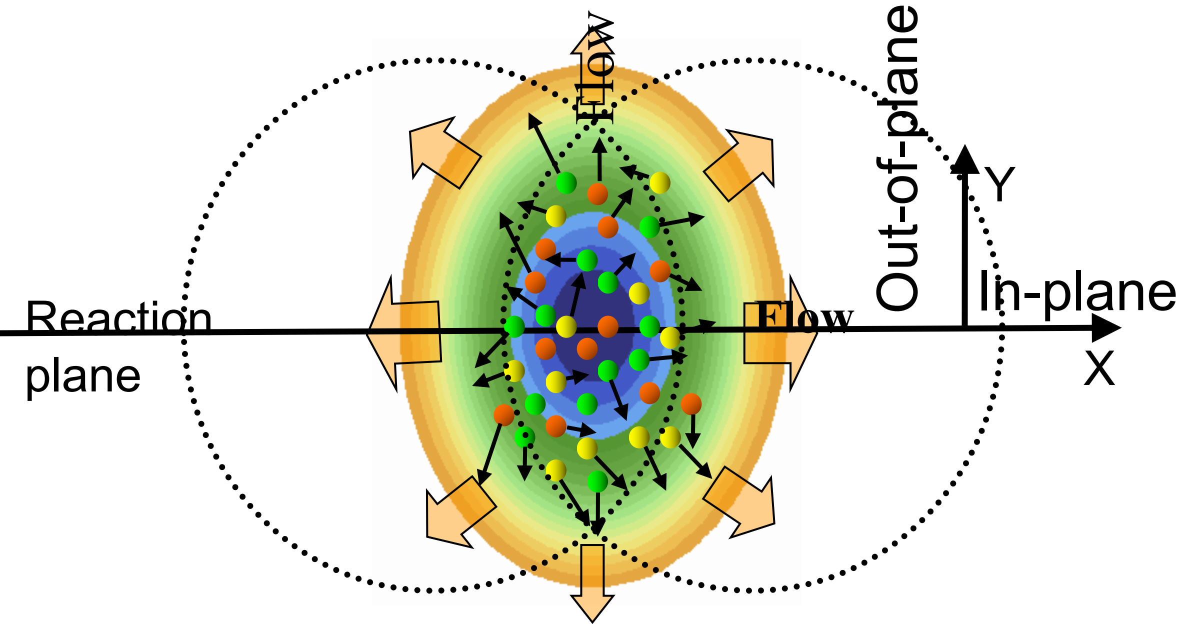


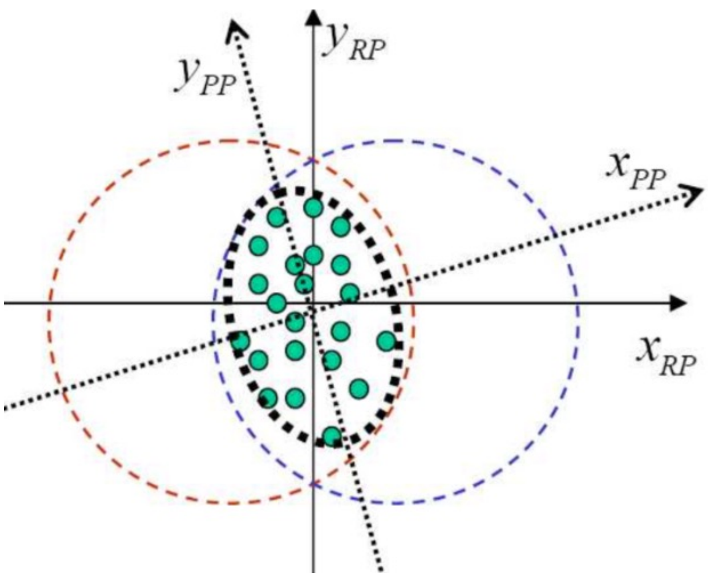


ALICE QM2017

- ➢ Mass ordering is observed for p_T<2GeV
- ➢ Approximate partical type scaling for p_T>2.5GeV/c

Flow Fluctuations





Reaction plane defined by impact parameter and beam direction

X_{PP}: Participant Plane, maximises spatial anisotropy ε_n

Ψ_n: Event plane, maximises anisotropy v_n

Flow Fluctuations

By using multi-particle correlations to estimate flow we are actually estimating the averages of various powers of flow

$$\langle\langle 2\rangle\rangle = \langle v_n^2\rangle, \qquad \langle\langle 4\rangle\rangle = \langle v_n^4\rangle, \qquad \langle\langle 6\rangle\rangle = \langle v_n^6\rangle,$$

But what we are after is: $\langle v\rangle$

take a random variable x with mean μ_x and spread σ_x .The the expectation value of some function of a random variable *x*, *E*[*h*(*x*)], is to leading order given by

$$\langle h(x)\rangle \equiv E[h(x)] = h(\mu_x) + \frac{\sigma_x^2}{2} h''(\mu_x)$$

using this for the flow results:

$$\langle v^2\rangle = \langle v\rangle^2 + \sigma_v^2 , \quad \langle v^4\rangle = \langle v\rangle^4 + 6\sigma_v^2 \langle v\rangle^2$$

$$\langle v^6\rangle = \langle v\rangle^6 + 15\sigma_v^2 \langle v\rangle^4 \cdots$$

Flow Fluctuations

flow estimates from cumulants can be written as:

$$v\{2\} = \langle v^2 \rangle^{1/2}$$
$$v\{4\} = (-\langle v^4 \rangle + 2\langle v^2 \rangle^2)^{1/4}$$
$$v\{6\} = \left[\frac{1}{4}(\langle v^6 \rangle - 9\langle v^2 \rangle\langle v^4 \rangle + 12\langle v^2 \rangle^3)\right]^{1/6}$$

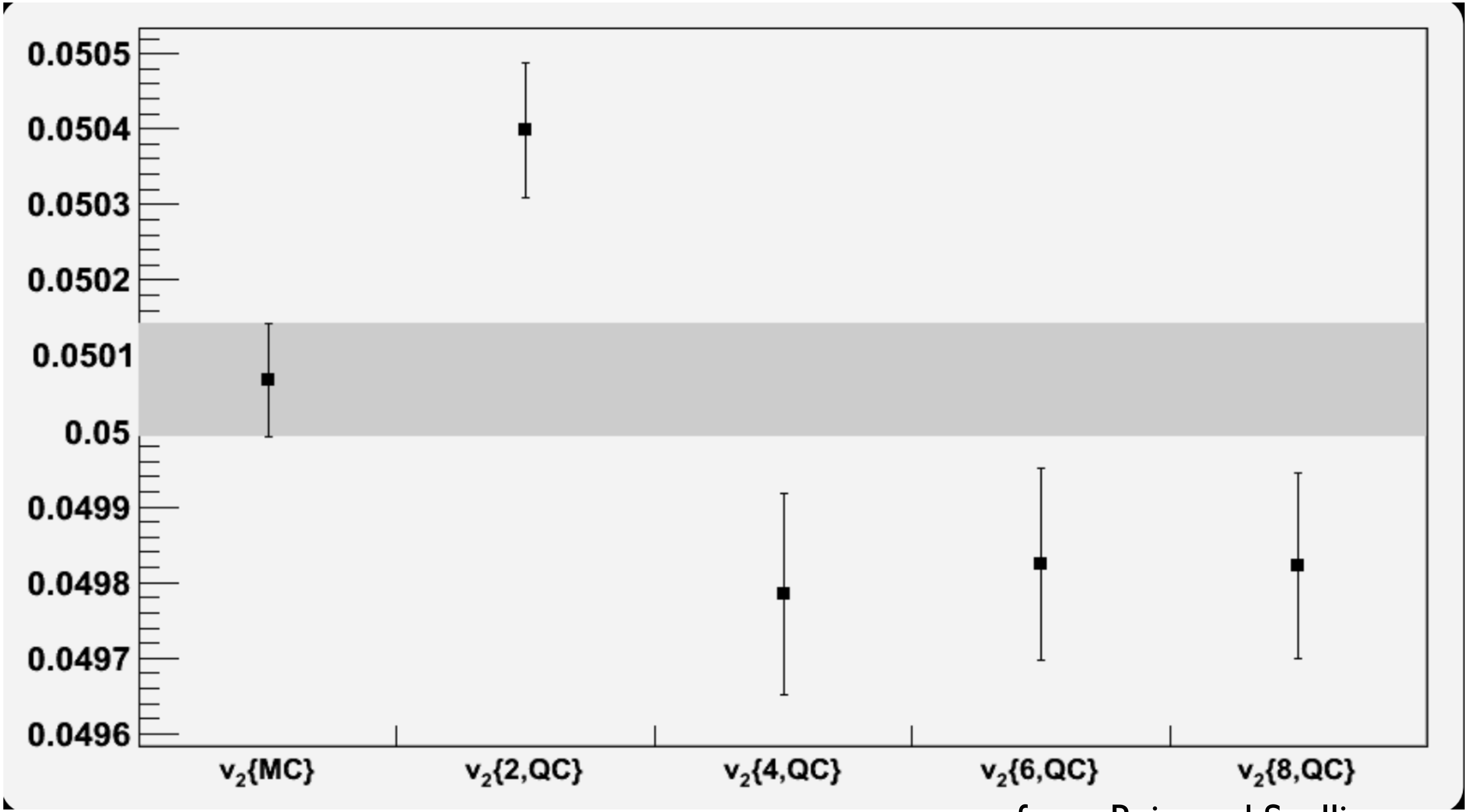
Use: $\sigma_v \ll \langle v \rangle$

take up to order σ^2

$$v\{2\} = \langle v \rangle + \frac{1}{2}\frac{\sigma_v^2}{2\langle v \rangle}$$
$$v\{4\} = \langle v \rangle - \frac{1}{2}\frac{\sigma_v^2}{2\langle v \rangle}$$
$$v\{6\} = \langle v \rangle - \frac{1}{2}\frac{\sigma_v^2}{2\langle v \rangle}$$

Flow Fluctuations

Example: input $v_2 = 0.05 \pm 0.005$ (Gaussian), $M = 500$, $N = 2 \times 10^5$

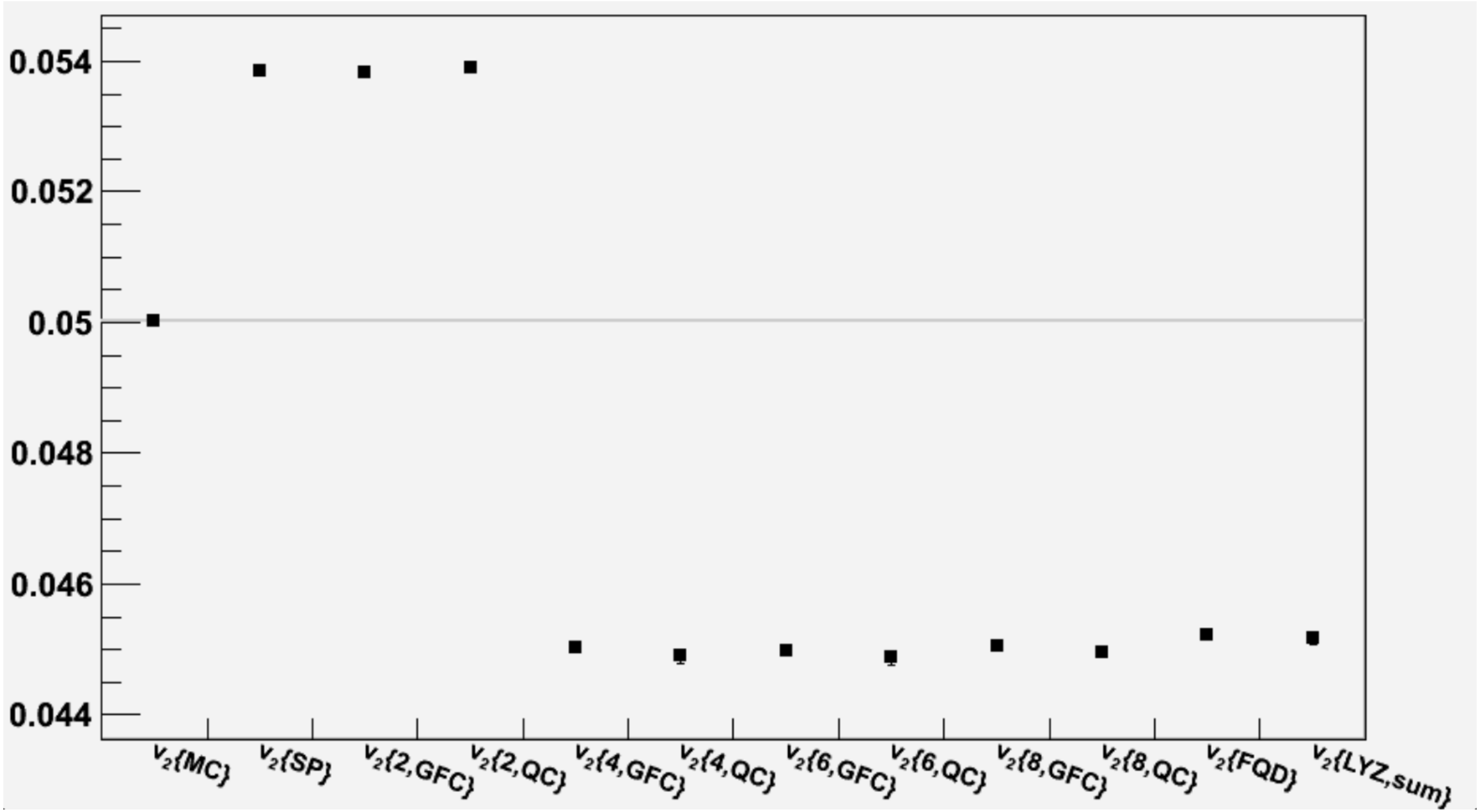


from: Raimond Snellings

Gaussian fluctuation behave as predicted!

Flow Fluctuations

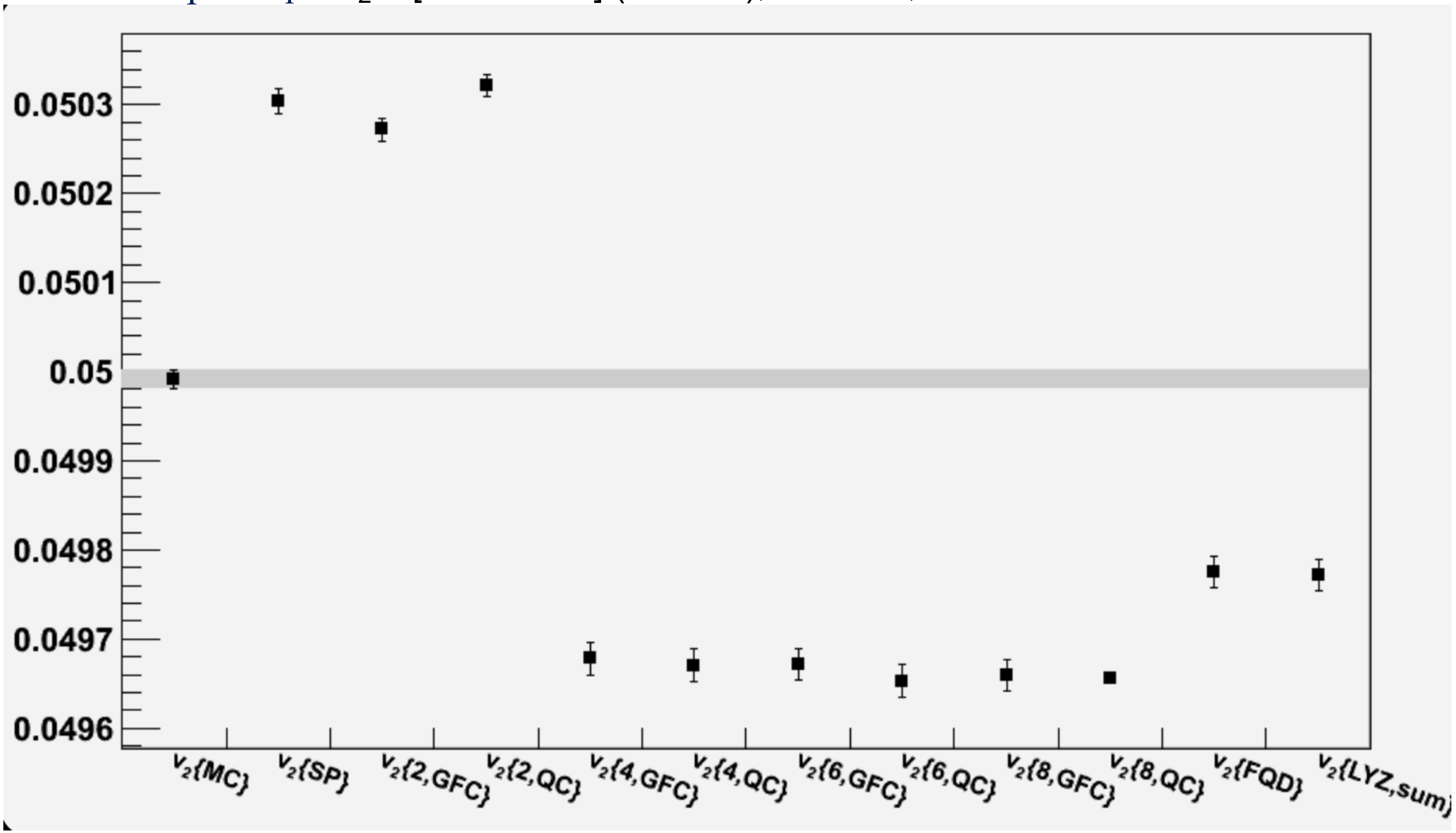
Example: input $v_2 = 0.05 \pm 0.005$ (Gaussian), $M = 500$, $N = 2 \times 10^6$



from: Raimond Snellings

Flow Fluctuations

Example: input v_2 = [0.04 - 0.06] (uniform), M = 500, $N = 1 \times 10^7$

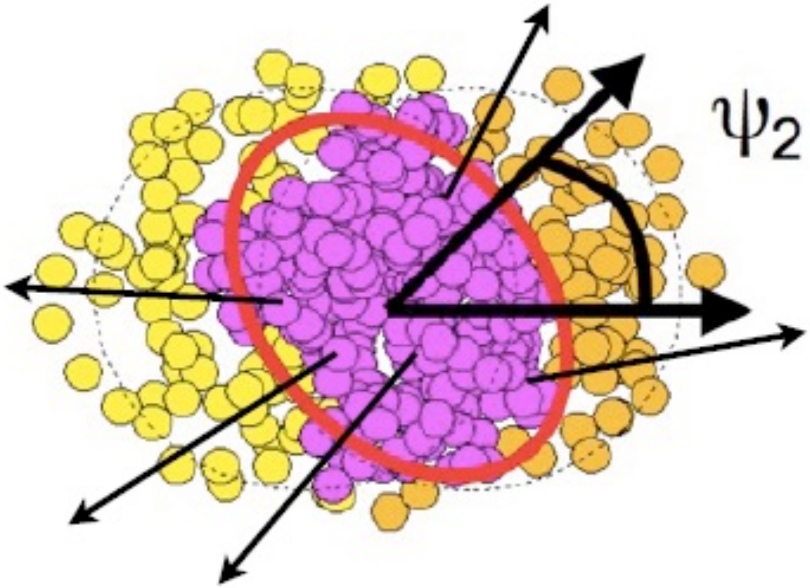


from: Raimond Snellings

with higher statistics uniform fluctuations show sensitivity to details fluctuations!

Participant eccentricity

Event plane may be different from the reaction plane.



$$\epsilon_{\rm part} = \frac{\sqrt{(\sigma_y^2-\sigma_x^2)^2+4\sigma_{xy}^2}}{\sigma_y^2+\sigma_x^2}$$

$$v_2 \propto \epsilon$$

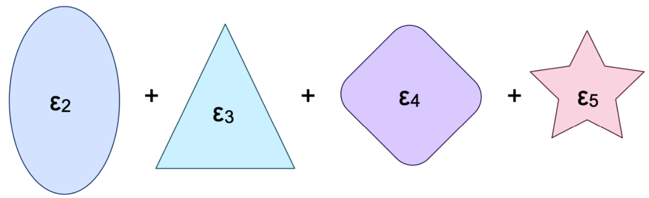
Can be nonzero even at vanishing impact parameter due to fluctuations.

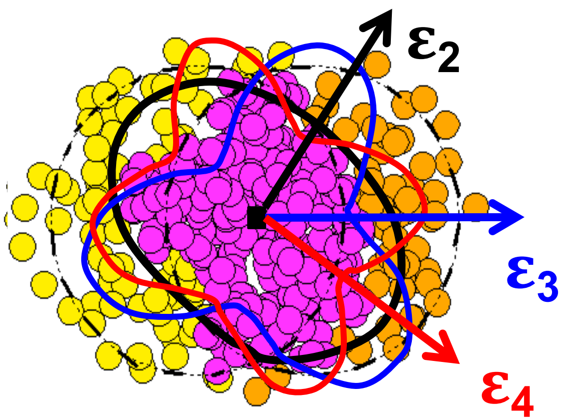
Important because high-multiplicity events mostly come from central collisions.

AA → fluctuation of nucleons
pp → fluctuation of small-x gluons

Harmonics in hydro-picture

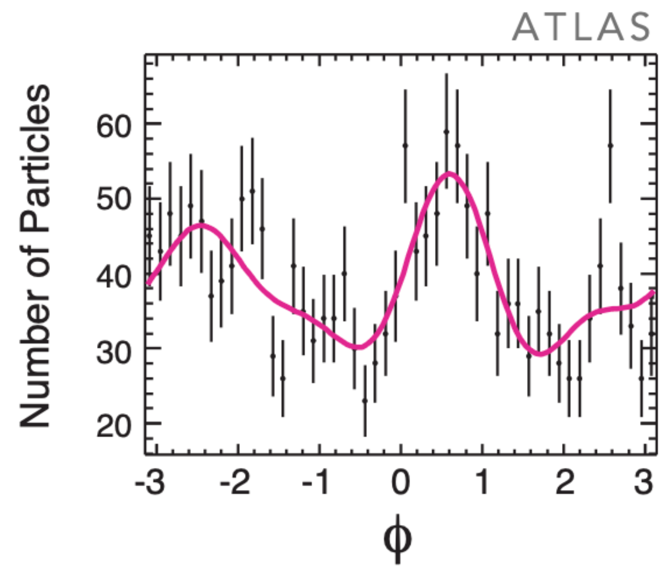
Initial state





Hydro-response

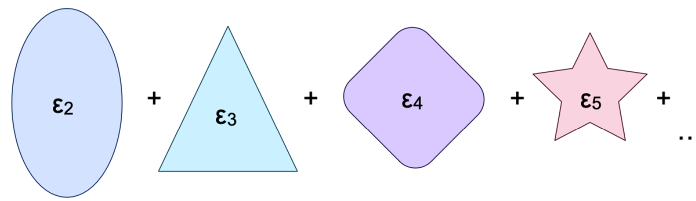
Space-time dynamics

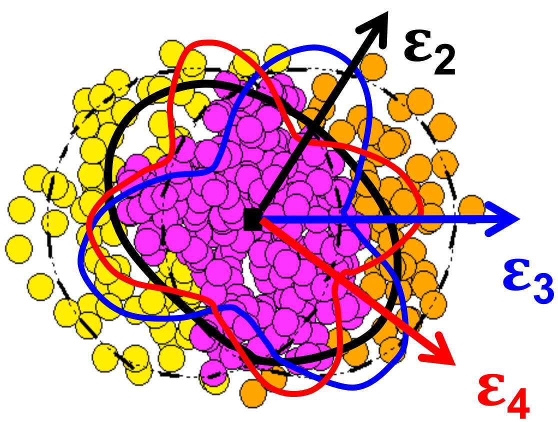


$$\frac{dN}{d\phi} \propto 1 + 2(v_1 \cos\varphi + v_2 \cos 2\varphi + v_3 \cos 3\varphi + v_4 \cos 4\varphi)$$

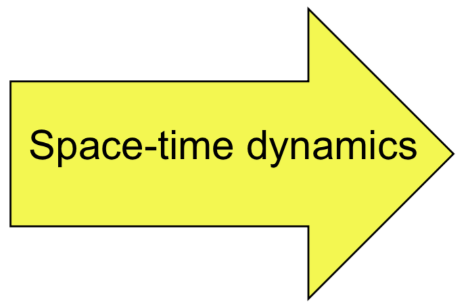
Harmonics in hydro-picture

Initial state

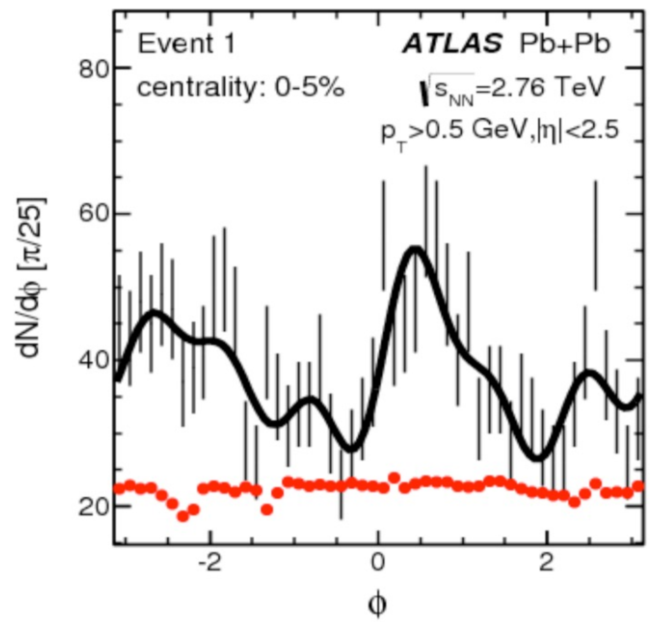




Hydro-response



Particle flow

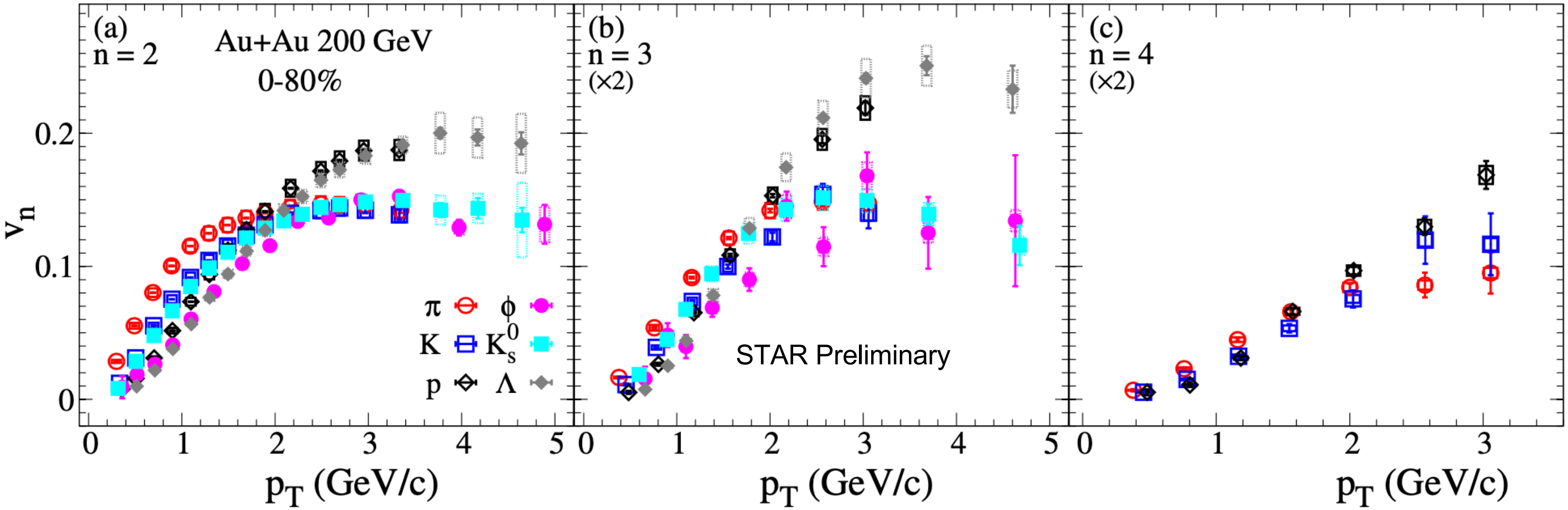


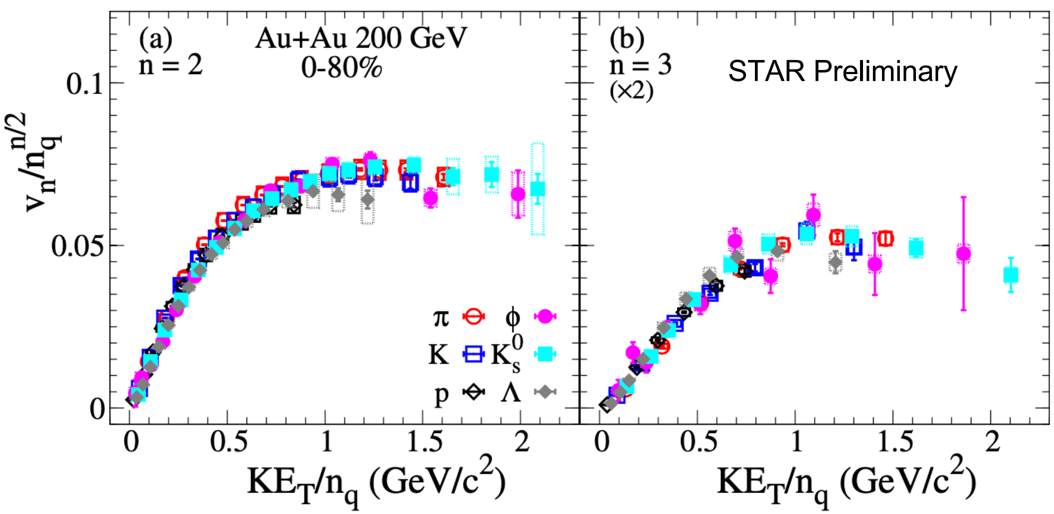
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$

$$\tan(n\Psi_n) = \frac{\langle r^n \sin n\phi \rangle}{\langle r^n \cos n\phi \rangle}$$

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos(\phi - \psi_n)$$

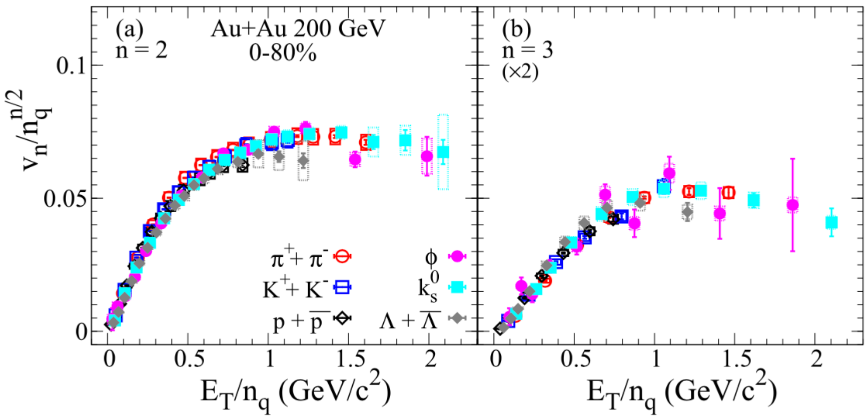
高阶流：200 GeV

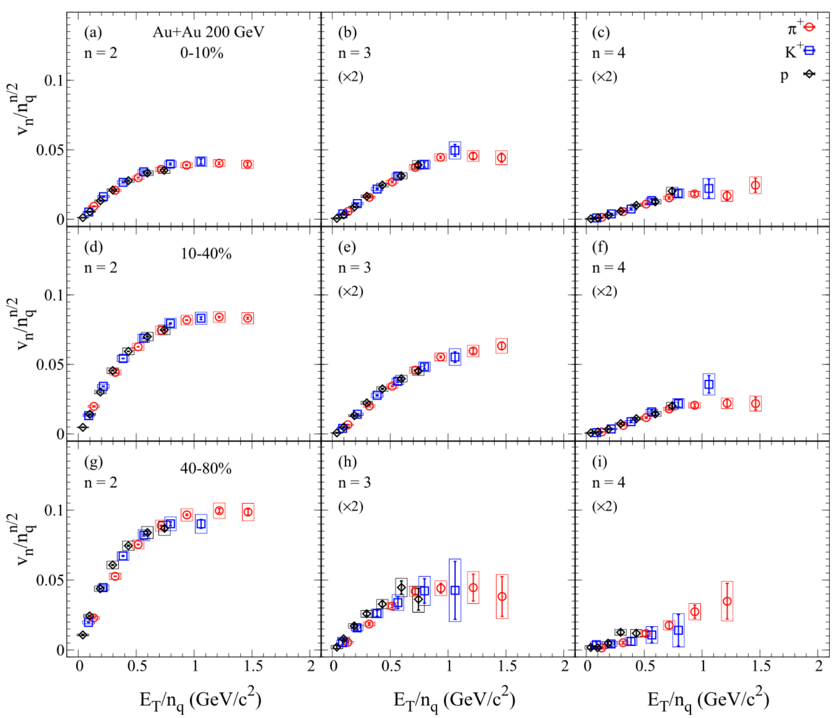




- 高阶流（v_3和v_4）同样符合部分子态集体运动的物理图像

Higher-order Flow in 200 GeV





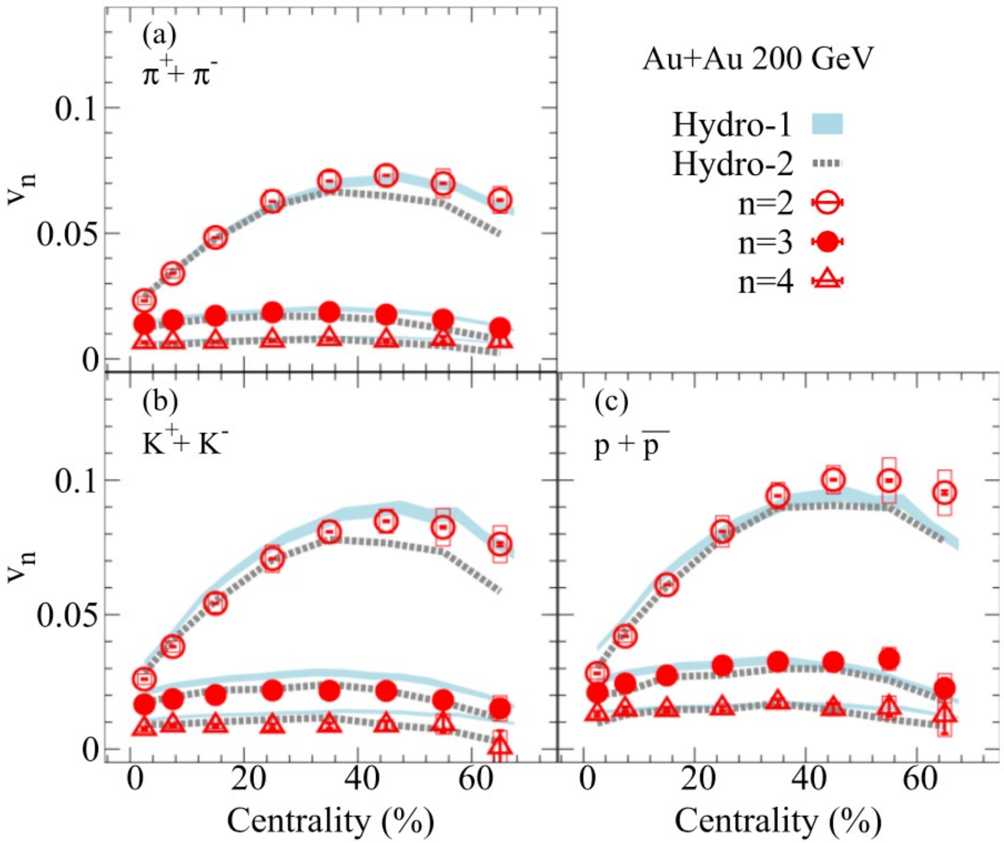
RHIC top energy

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

Partonic collectivity

STAR: Phys. Rev. C.105, 064911 (2022)
R. Lacey, J. Phys. G, Nucl. Part. Phys. 38 (2011) 124048.

Higher-order Flow in 200 GeV



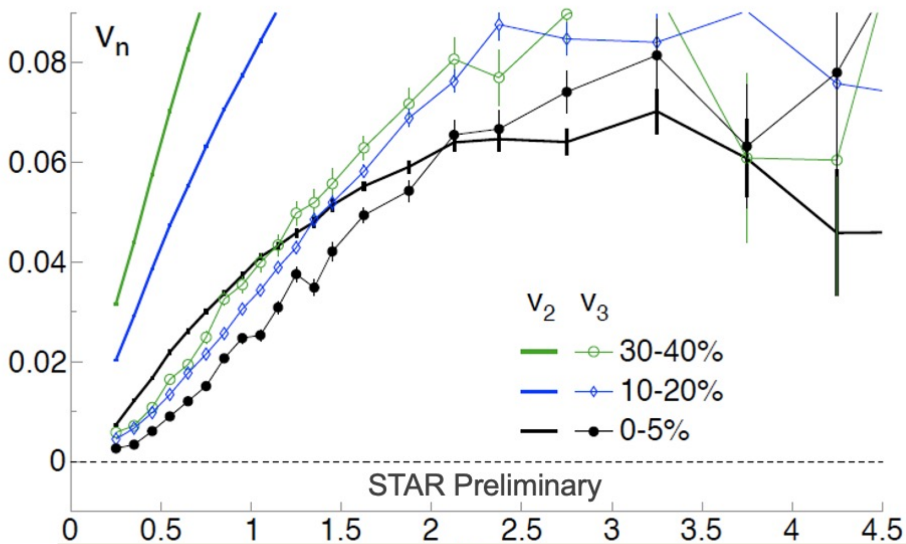
the v_n values decrease with increasing harmonic order. reflects the increase of viscous effects with increasing harmonic order

$$\ln(v_n/\varepsilon_n) \propto -n^2 \left\langle \frac{\eta}{s}(T) \right\rangle \langle N_{ch} \rangle^{-1/3}$$

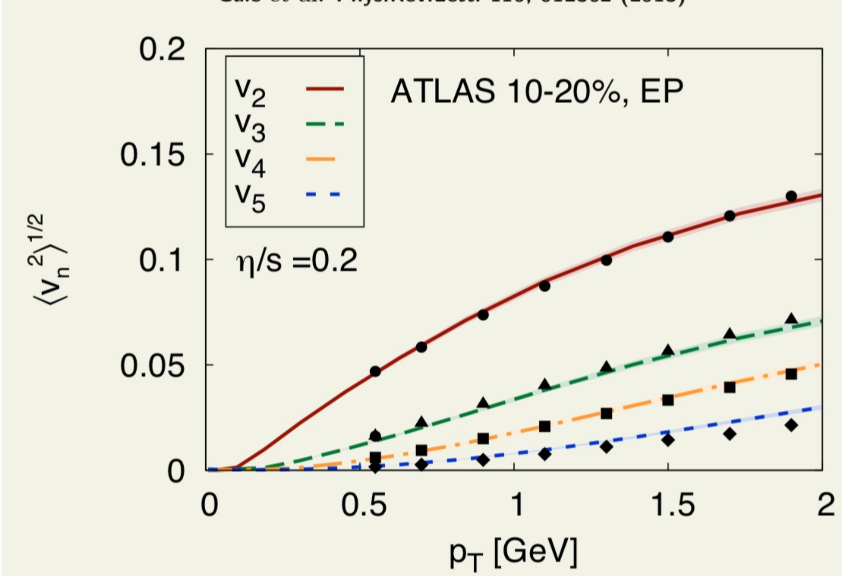
The weakening centrality dependence for higher flow is caused by the dominating geometry fluctuations.

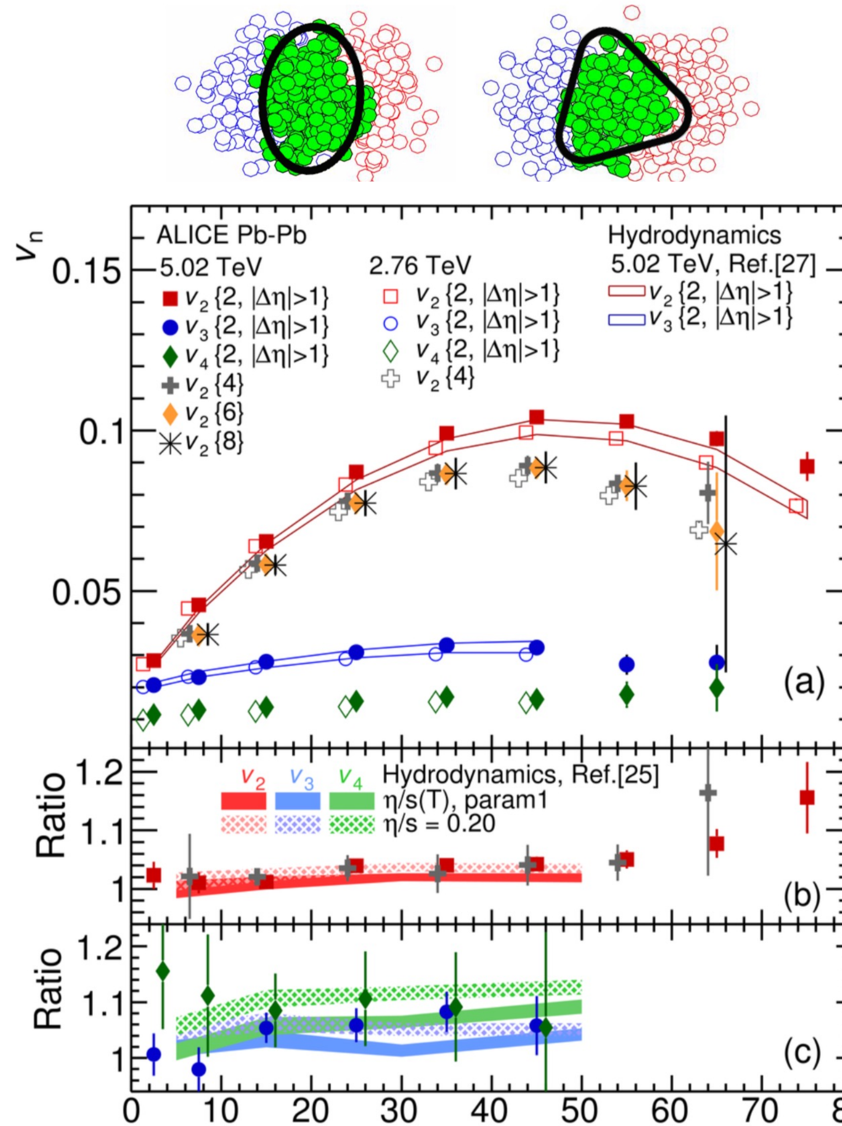
STAR: Phys. Rev. C.105, 064911 (2022)

The centrality dependence of v_n



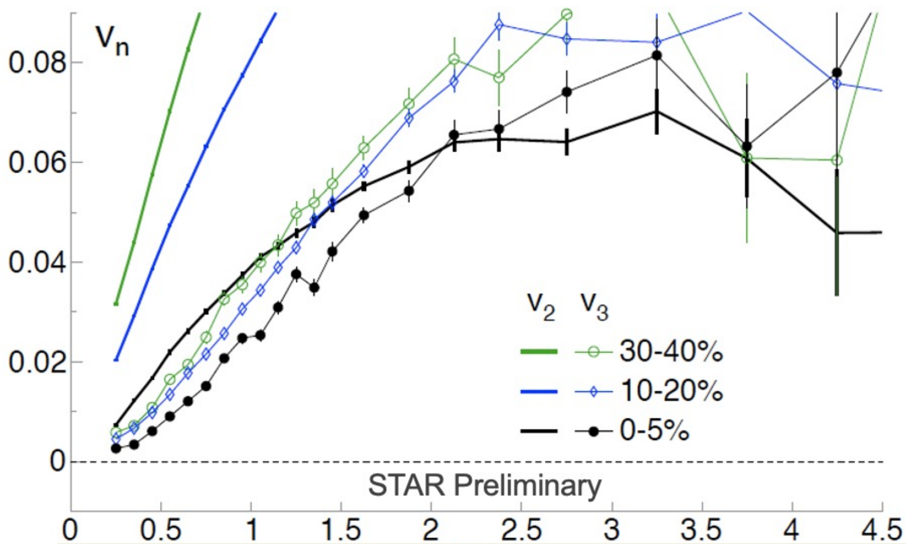
Gale *et al.* Phys.Rev.Lett. 110, 012302 (2013)



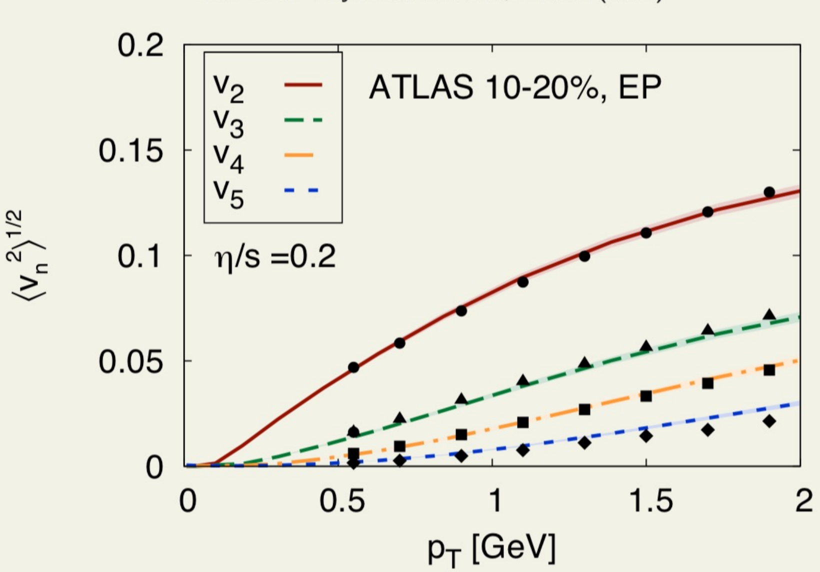


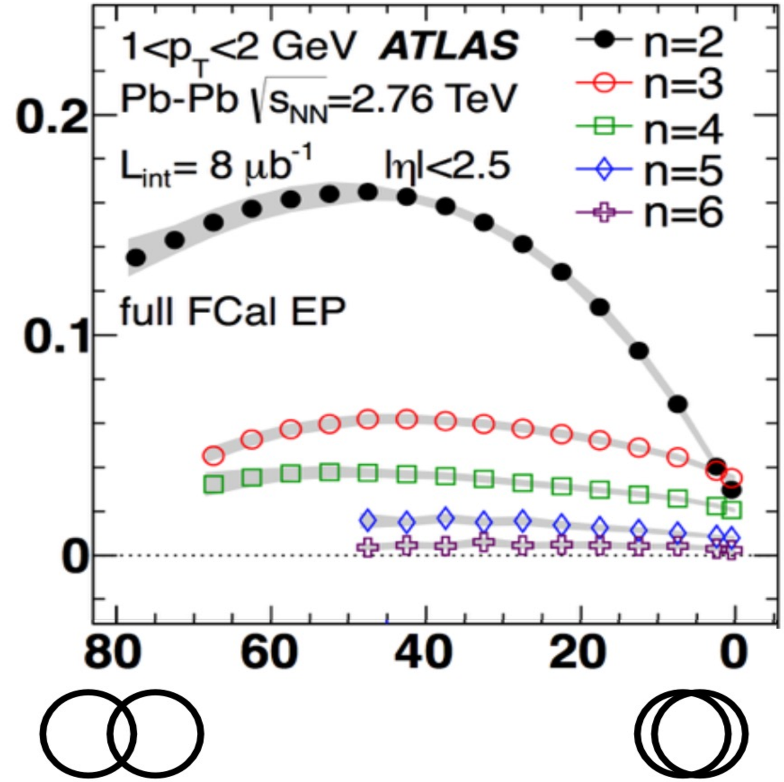
Phys. Rev. Lett. 116 (2016) 132302

The centrality dependence of vn



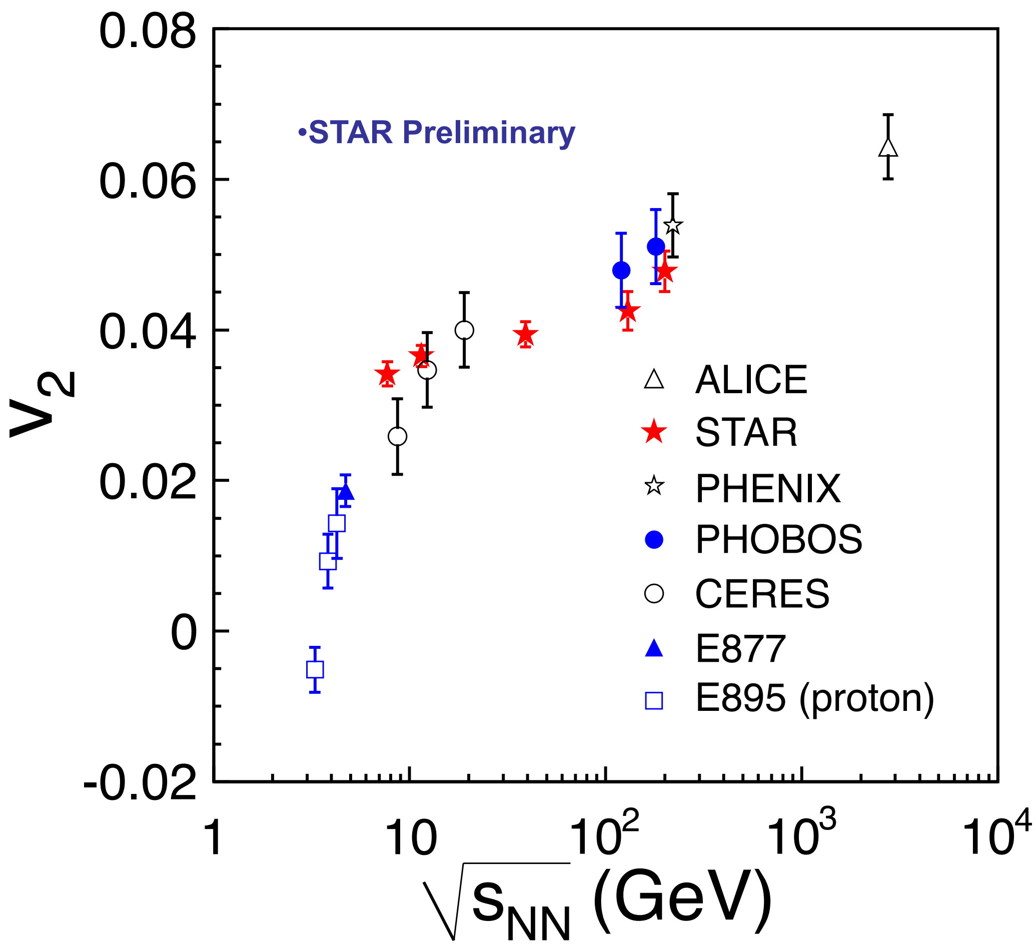
Gale *et al.* Phys.Rev.Lett. 110, 012302 (2013)





- Steep decrease of v_2 for central collisions: reflects the elliptic geometry of the overlap area
- Mild decrease of v3 : reflects the initial triangularity, due to fluctuations
- For peripheral collisions, both v_2 and v_3 decrease: 1/R viscous suppression becomes large.

Energy Dependence

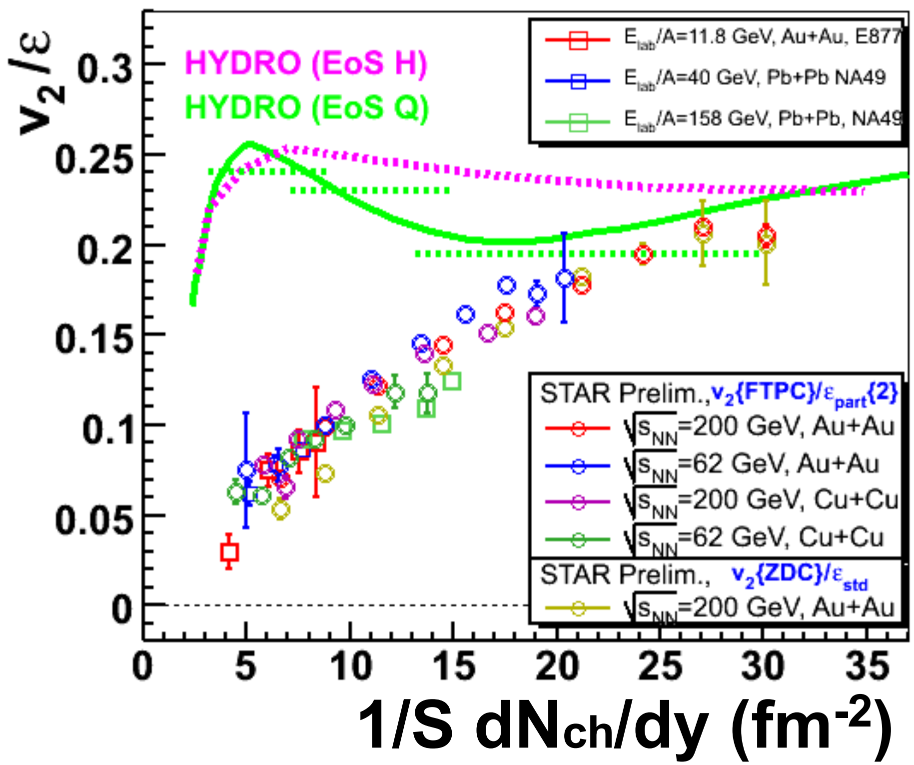


- STAR, ALICE: $v_2\{4\}$ results
  Centrality: 20-30%
- An increasing trend is observed for p_T integrated v_2 from AGS to LHC
- Above AGS energies the measured elliptic flow is underpredicted by hadronic cascade models like RQMD

•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

Towards Ideal Hydro Limit

S. A. Voloshin (STAR) : J. Phys. G**34**, S883 (2007)



re-scattering probability among constituents

H. Heiselberg, A.-M. Levy, PRC**59**, 2716 (1999)
S. A. Voloshin, A. M. Poskanzer, PLB**474**, 27 (2000)

Low density limit (LDL)

$$\frac{v_2}{\varepsilon} \propto \frac{1}{S}\frac{dN}{dy} \quad (\lambda \geq R)$$

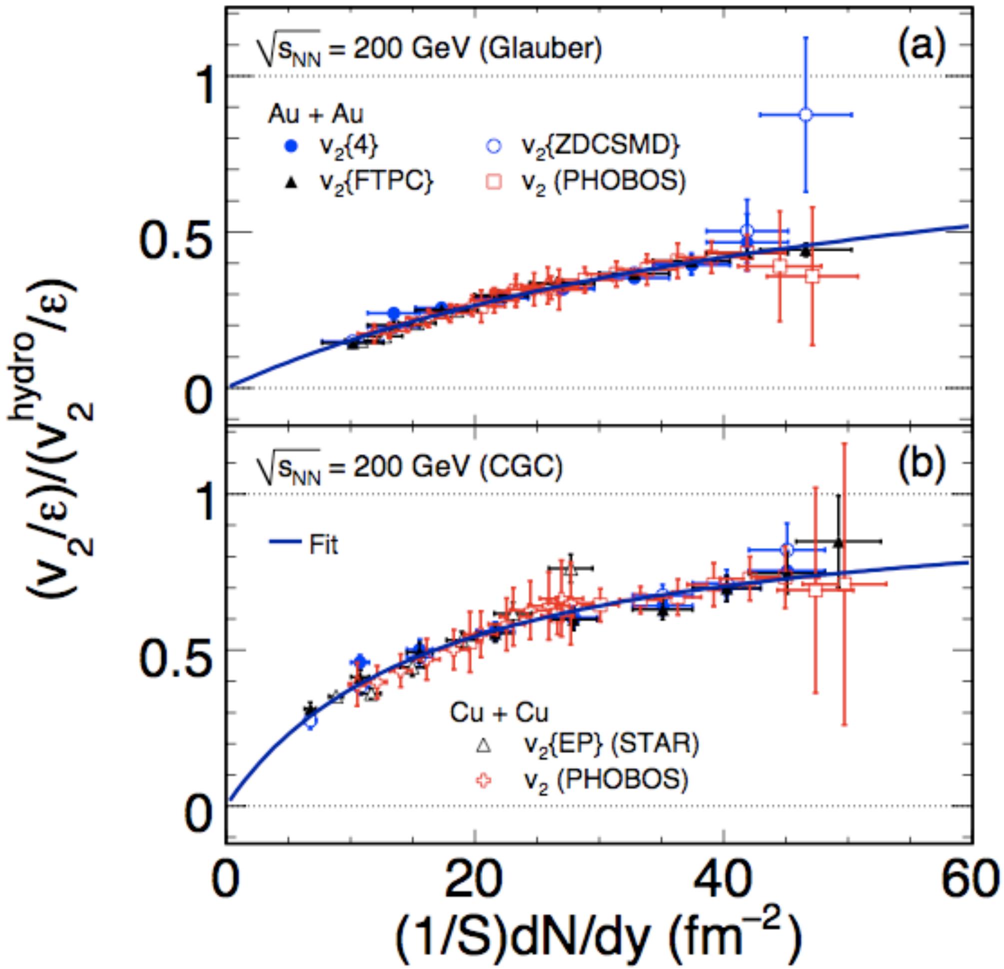
Hydro limit

$$\frac{v_2}{\varepsilon} \propto \text{const.} \quad (\lambda \to 0)$$

$$S = \pi\sqrt{\langle x^2\rangle\langle y^2\rangle}$$

- ➢ v_2/ε increase from AGS to RHIC.
- ➢ Has v_2/ε reached ideal hydro limit ?

Ideal Hydro Limit



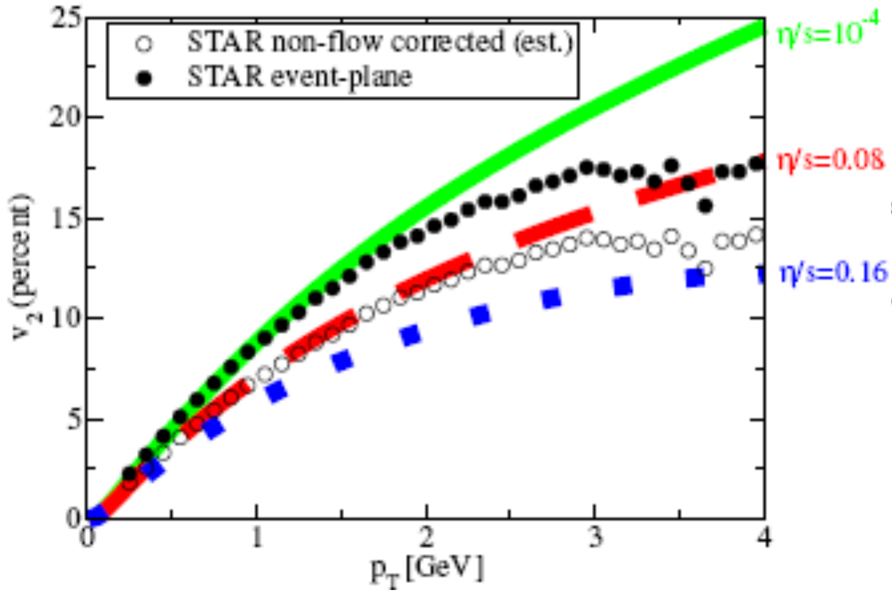
- The system is still away from ideal hydro limit: 30-50%
- Model dependent on initial eccentricity!
- Viscosity? Incomplete thermalization?

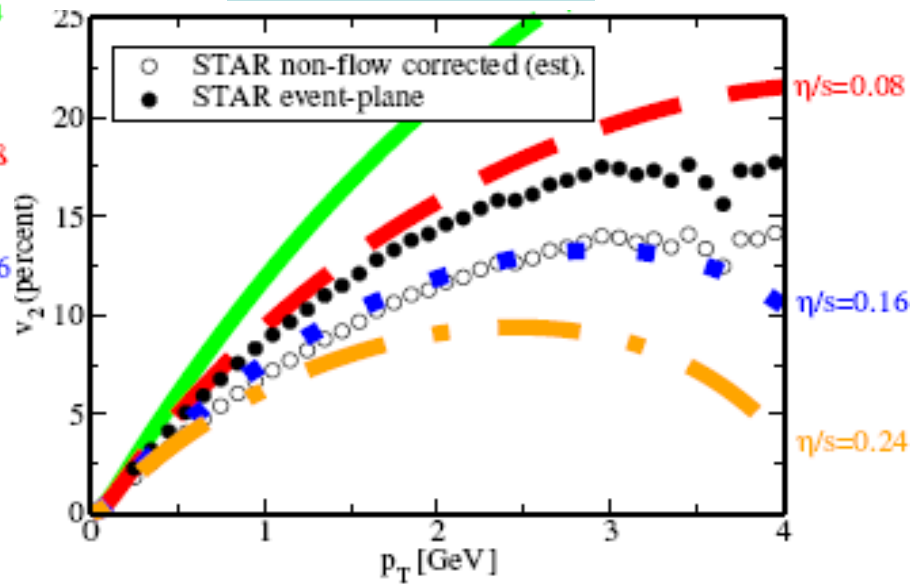
Comparison to Viscous Hydro

Glauber

AuAu@200

CGC

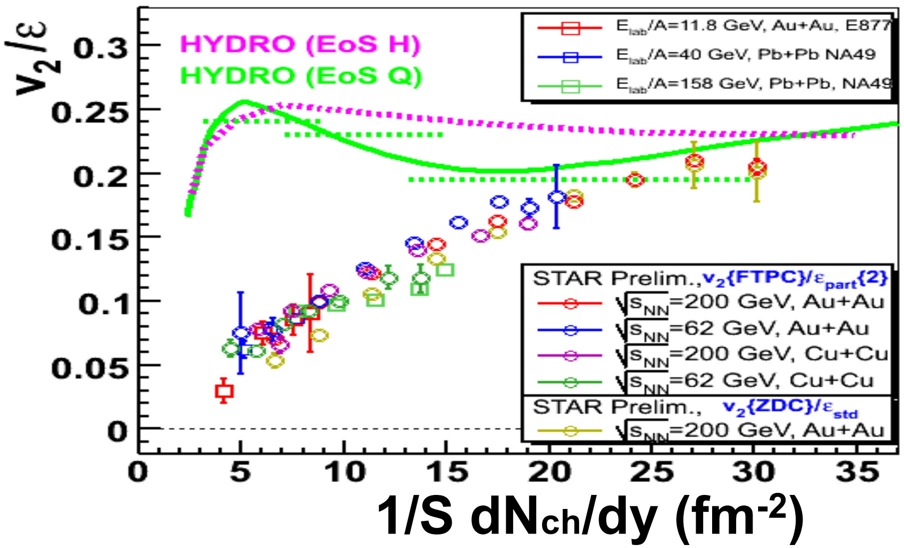




[1]P. Romatschke and U. Romatschke, Phys.Rev.Lett.99:172301, 2007 (arXiv:0706.1522)
[2]M. Luzum and P. Romatschke, Phys. Rev. C 78, 034915, 2008 (arXiv:0804.4015)

- Glauber vs.CGC ~ a factor of 2 difference on the extracted value of η/s
  - ➔ Strongly depends on the initial eccentricity model.

Perfect Liquid at RHIC

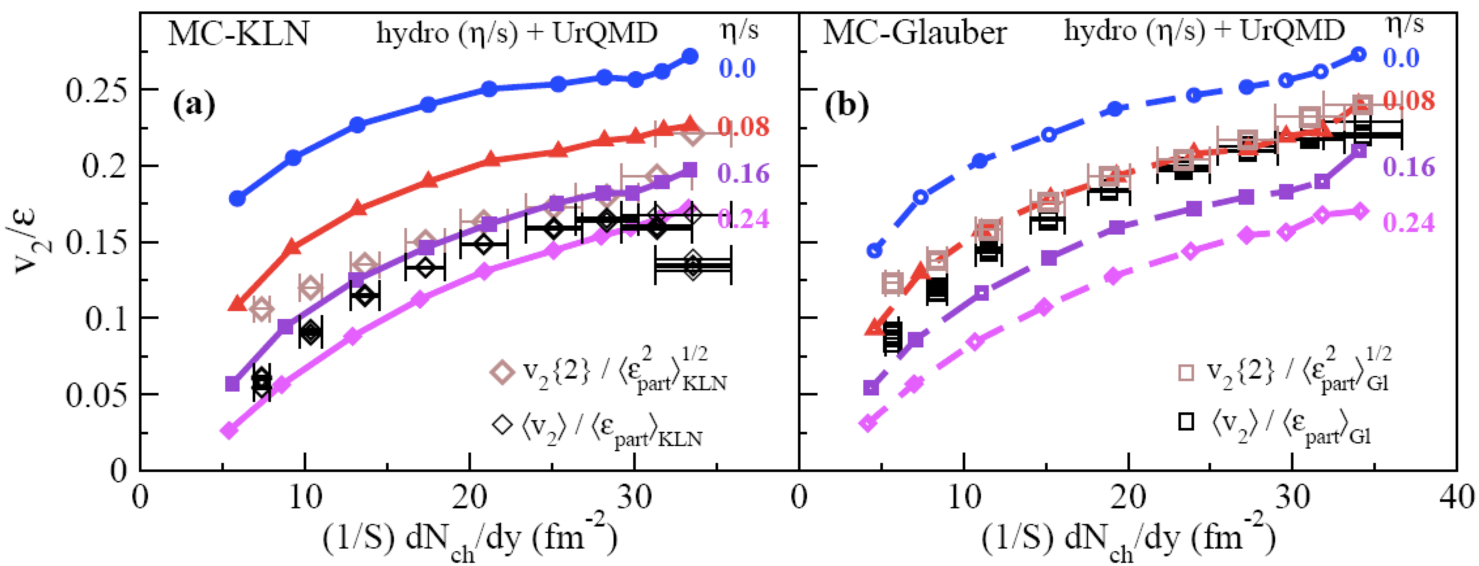


v_2/ε approaches the limit of ideal hydrodynamics

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

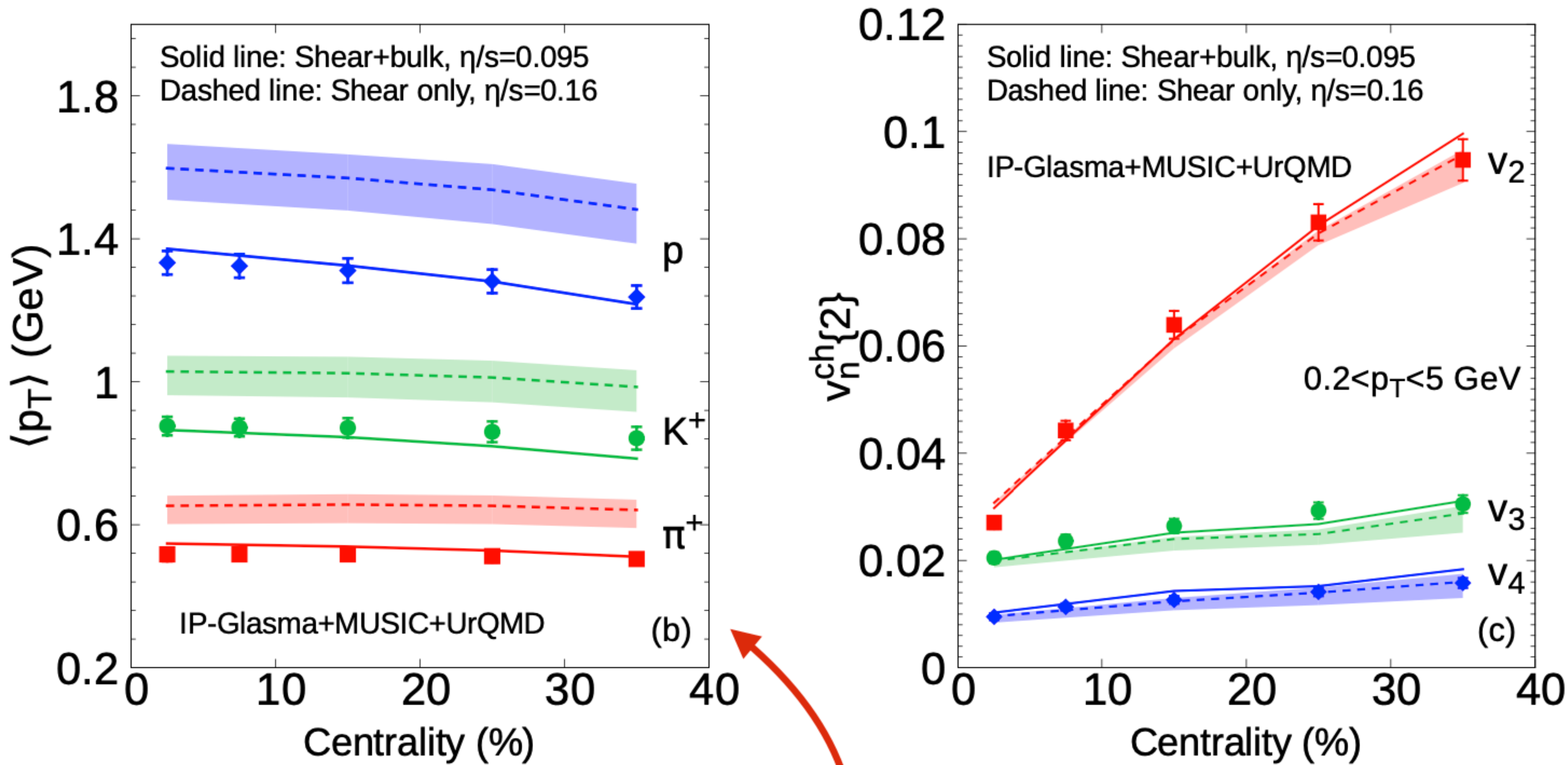
Model uncertainty dominated by initial eccentricity ε

Model: Song *et al. arXiv:1011.2783*



Effect of bulk viscosity

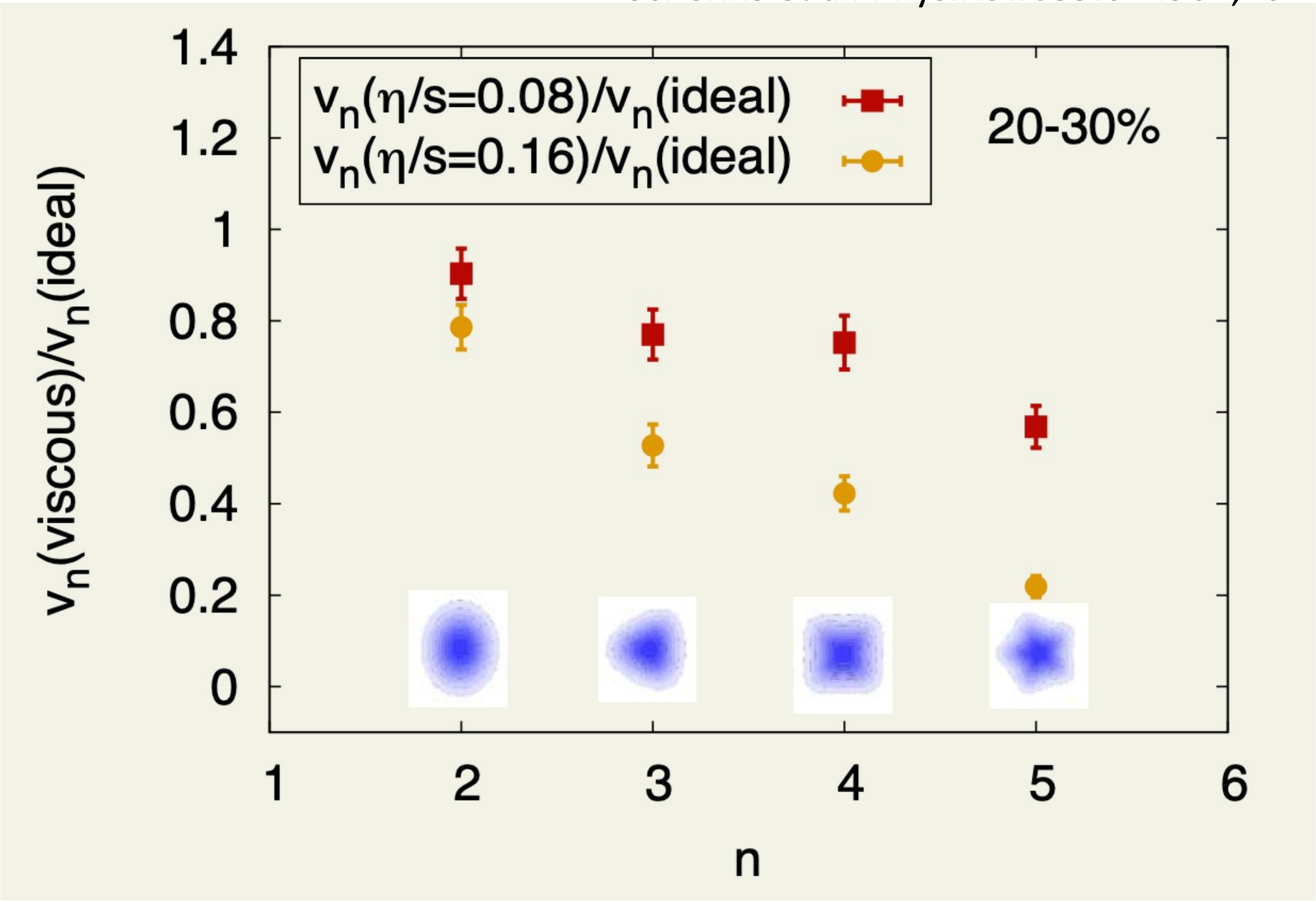
S. Ryu, J. -F. Paquet, C. Shen, G.S. Denicol, B. Schenke, S. Jeon, C. Gale, arXiv:1502.01675 (2015)



Main effect of bulk viscosity:
Slow down expansion - reduce mean transverse momentum

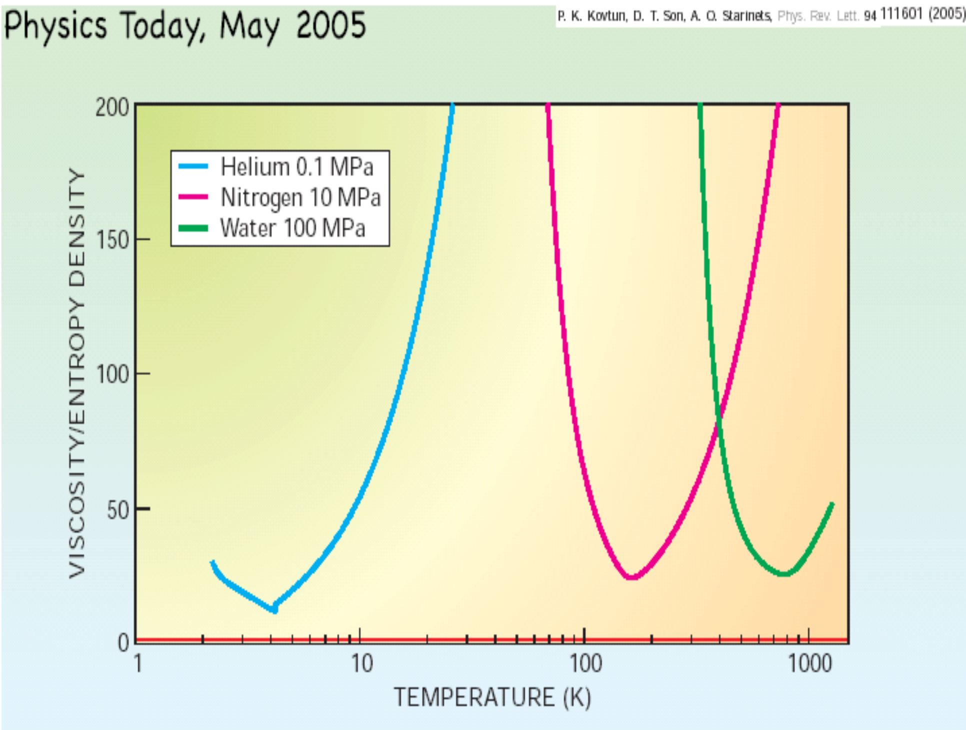
Sensitivity to η/s

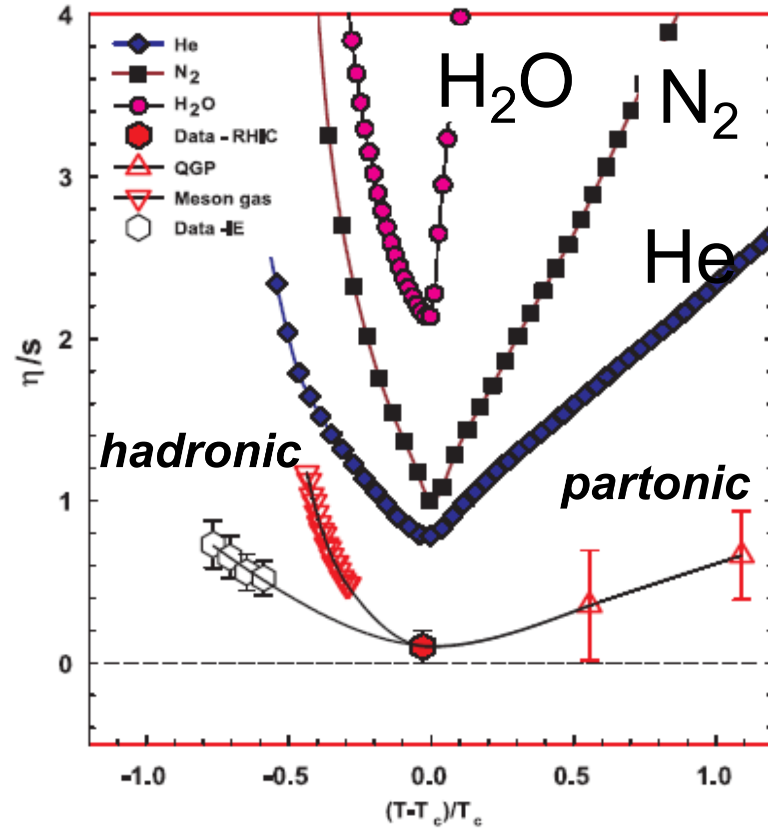
Schenke et al. Phys.Rev.C85:024901,2012



higher coefficients are suppressed more by dissipation

Viscosity and the Perfect Fluid





1) $\eta/s \geq 1/4\pi$

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

2) $\boldsymbol{\eta/s}$(QCD matter) < $\boldsymbol{\eta/s}$(QED matter)

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

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."

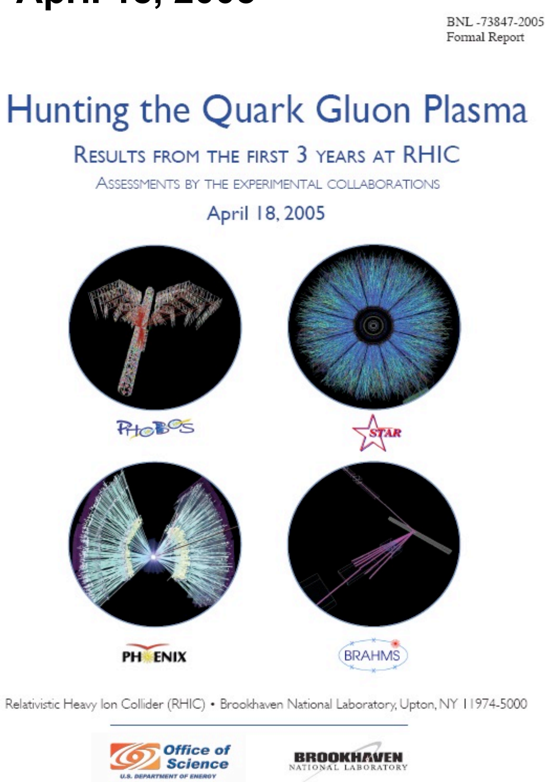
弱相互作用的夸克和胶子等离子体的概念还有待于实验的证实

sQGP at RHIC

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005


BNL -73847-2005
Formal Report

Hunting the Quark Gluon Plasma

RESULTS FROM THE FIRST 3 YEARS AT RHIC

ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005

Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

Office of Science U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

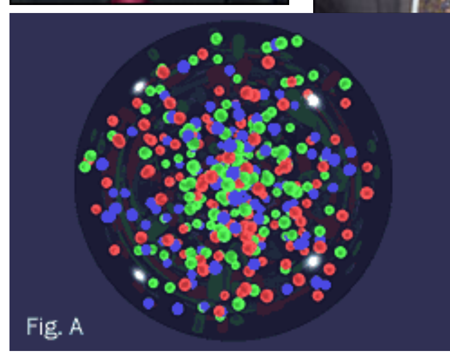


Fig. A

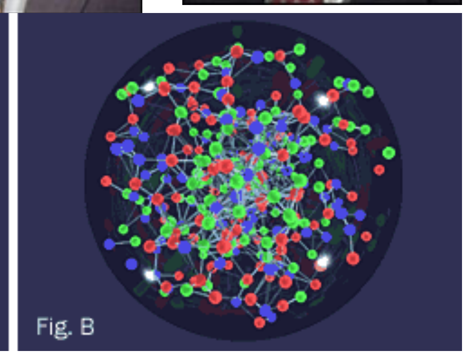


Fig. B

In the press

Science

Iran Daily April 20, 2005 4

Early Universe Liquid-Like

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have pervaded the first microseconds of existence, AP reported.

By revising physicists' concept of the early universe, the new discovery offers opportunities to better learn how subatomic particles interact at the most fundamental level. It may also reveal intriguing parallels between gravity and the force that holds atomic nuclei together, physicists said Monday at a Tampa, Fla., meeting of the American Physical Society.

"There are a lot of exciting questions," said Sam Aronson, associate director for high energy and nuclear physics at Brookhaven National Laboratory, which is located on Long Island about 65 miles east of New York city.

Between 2000 and 2003 the lab's Relativistic Heavy Ion Collider, known as RHIC, repeatedly smashed the nuclei of gold atoms together with such force that their energy briefly generated trillion-degree temperatures. Physicists think of the collider as a time machine, because those extreme temperature conditions last prevailed in the universe less than 100 millionths of a second after the big bang.

Everything was so hot then that quarks and gluons, which are now almost inextricably bound into the protons and neutrons inside atomic nuclei, were thought to have flown around like BBs in a blender.

But by reproducing the conditions of the early universe, RHIC has shown that unconstrained quarks and gluons don't fly away in all directions so much as squirt out in streams.

"The matter that we've formed behaves like a very nearly perfect liquid," Aronson said.

When physicists talk about a perfect liquid, they don't mean the best glass of champagne they ever tasted. The word "perfect" refers to the liquid's viscosity, a friction-like property that affects a fluid's ability to flow and the resistance to objects trying to swim through it. Honey has a high viscosity; water's viscosity is low. A perfect liquid has no viscosity at all, which is impossible in reality but useful for theoretical discussions.

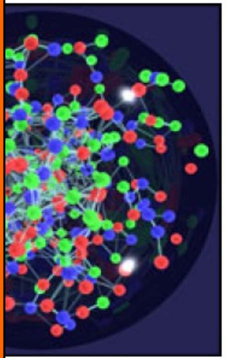
Theoretical physicists have recently proposed that material swallowed by black holes might also have extremely low viscosity. That notion, based on a branch of mathematical physics known as string theory, has led some physicists to hypothesize that there might be a deeper connection between what happens in a black hole and what goes on when two gold nuclei collide at RHIC.

New State o ... e'

Physicists ...
Laboratory annou...
created what appe...
out of the building...
and gluons. The r...
findings--which co...
composition of the...
big bang--today in...
American Physica...

There are four col...
PHENIX, PHOBO...
Brookhaven's Rela...
(RHIC). All of them... interacting beams of gold ions smash into one another at great velocities, resulting in thousands of subatomic collisions every second. When the researchers analyzed the patterns of the atoms' trajectories after these collisions, they found that the particles produced in the collisions tended to move collectively, much like a school of fish does. Brookhaven's associate laboratory director for high energy and nuclear physics, Sam Aronson, remarks that "the degree of collective interaction, rapid thermalization and extremely low viscosity of the matter being formed at RHIC make this the most nearly perfect liquid ever observed."

When physicist talk about a perfect liquid, they don't mean the best glass of champagne they ever tasted. The word "perfect" refers to the liquid's viscosity

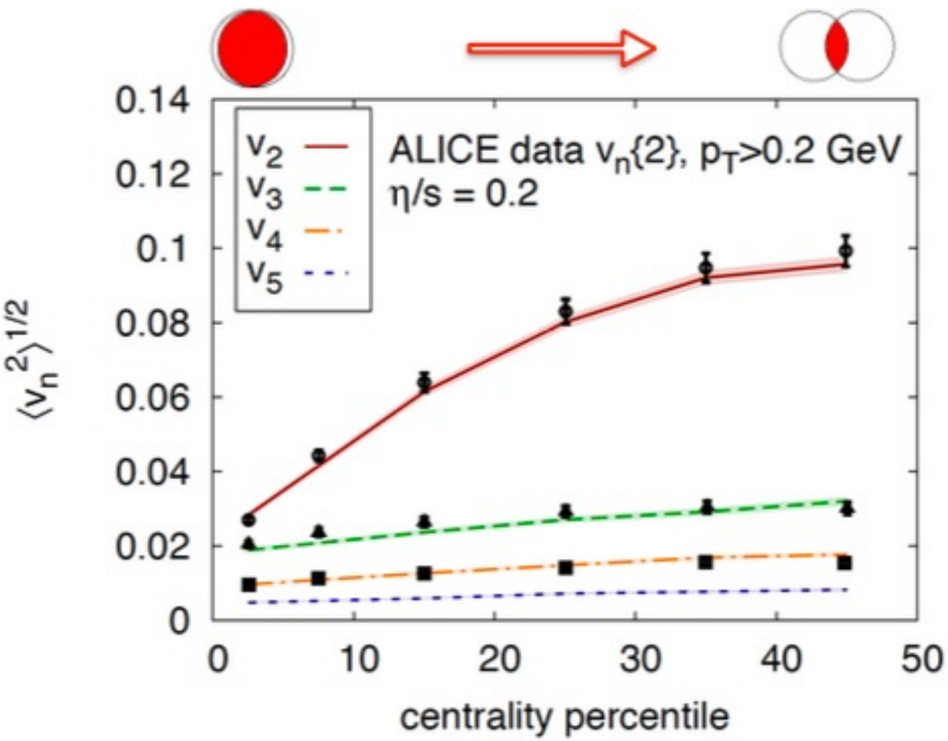


The impression is of matter that is more strongly interacting than predicted

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

Constraint from higher harmonic flow



ALICE PRL 107, 032301 (2011)

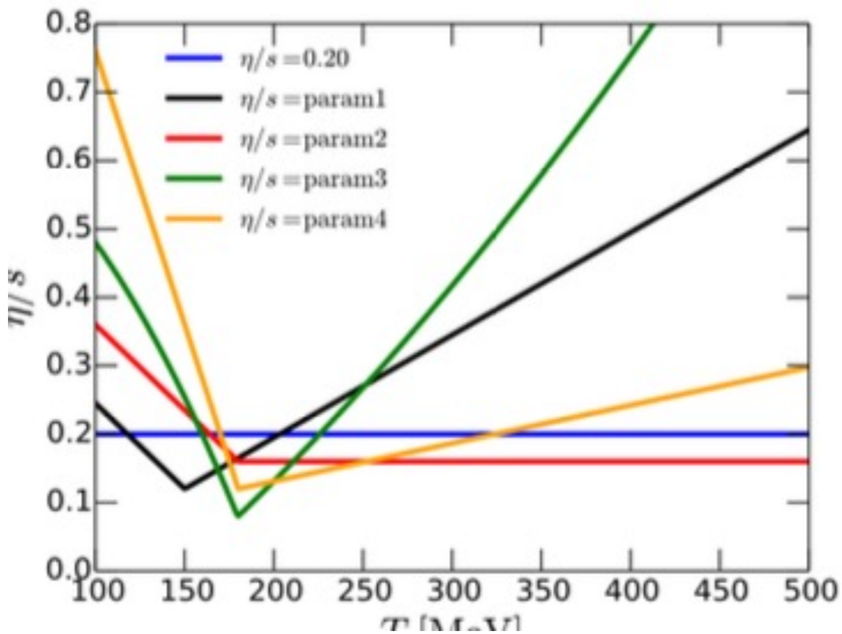
IP-Glasma:
PRL 110, 012302

ALICE published high precision measurements of charged particle v_n

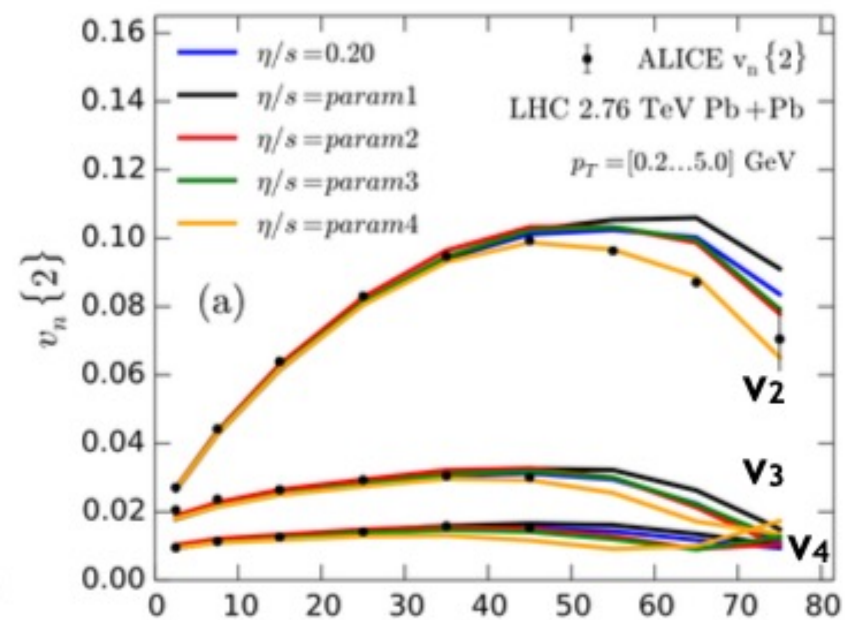
- v_2, v_3 and v_4 are nicely described by hydrodynamic calculations with IP-Glasma initial condition & $\eta/s = 0.20$.
- Neither Glauber & $\eta/s = 0.08$ or CGC&$\eta/s = 0.16$ describe v_n simultaneously.

Constraint from higher harmonic flow

EKRT: H. Niemi et. al, PRC 93, 024907 (2016)



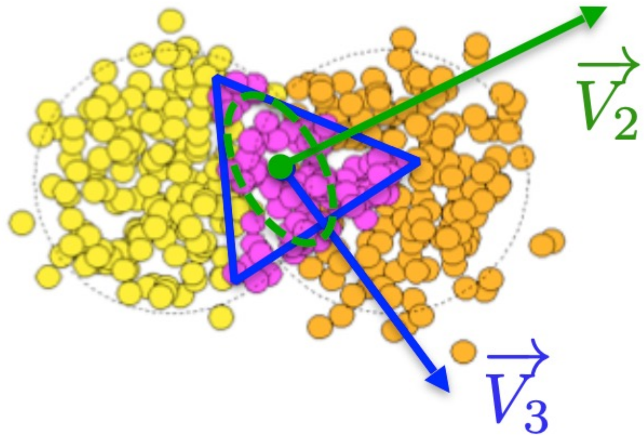
ALICE PRL 107, 032301 (2011)



v_n measurements are also quantitatively described by hydrodynamic calculations using EKRT initial conditions and η/s(T)

- weak sensitivity to details of η/s(T)
- not easy to discriminate which set is the best

Correlations of V_m and V_n



$$\overrightarrow{V_m} = v_m e^{-im\Psi_m}$$
$$\overrightarrow{V_n} = v_n\, e^{-in\Psi_n}$$

What are the correlations between v_n and v_m ?
will these correlations provide information in addition to individual v_n?

A linear correlation coefficient $c(v_m, v_n)$ was proposed to study the correlations between v_m and v_n:

Symmetric cumulant

New observable:

$$\langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle_c$$
$$=\langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle-\langle\langle\cos[m(\varphi_1-\varphi_2)]\rangle\rangle\,\langle\langle\cos[n(\varphi_1-\varphi_2)]\rangle\rangle$$
$$=\langle v_m^2 v_n^2\rangle-\langle v_m^2\rangle\langle v_n^2\rangle\,.$$

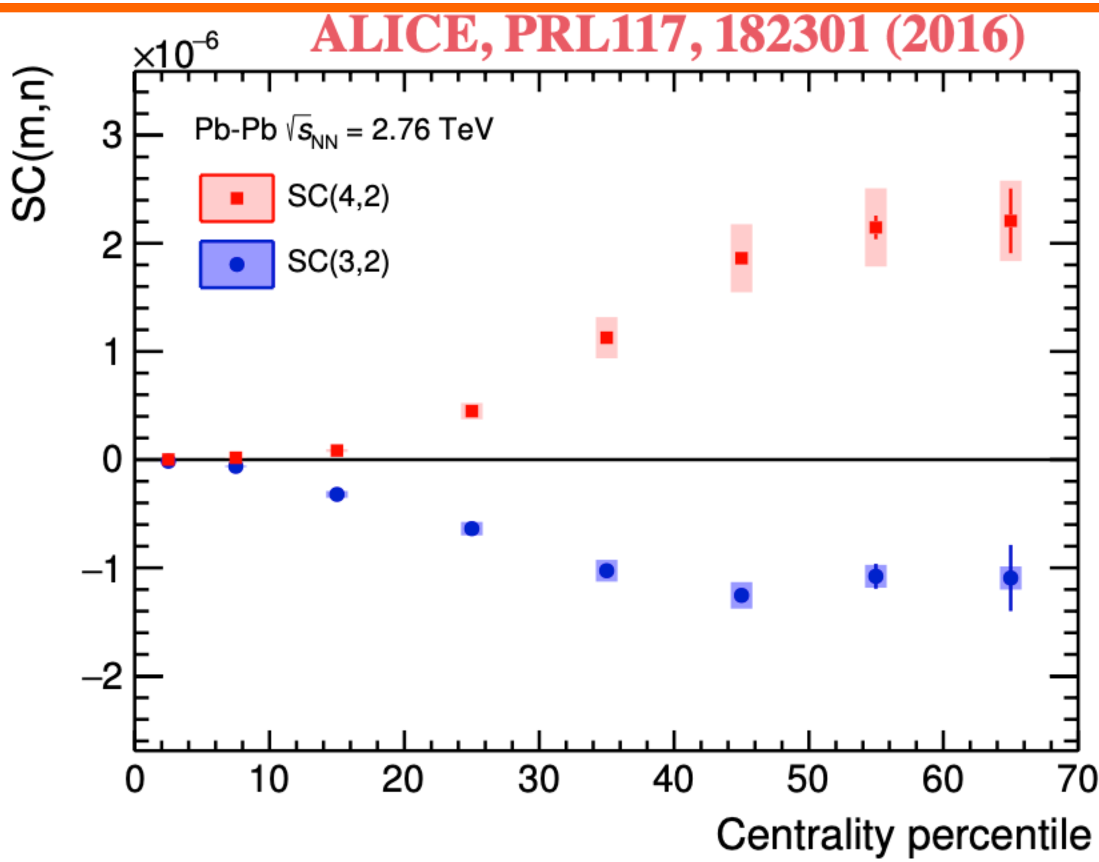
A. Bilandzic, C. H. Christensen, K. Gulbrandsen, A. Hansen, Y. Zhou**PRC 89, 064904 (2014)**

By construction not sensitive to:

- non-flow effects, due to usage of 4-particle cumulant
- inter-correlations of various symmetry planes (ψ_n and ψ_m correlations)

It is non-zero if the event-by-event amplitude fluctuations of v_n and v_m are (anti-)correlated.

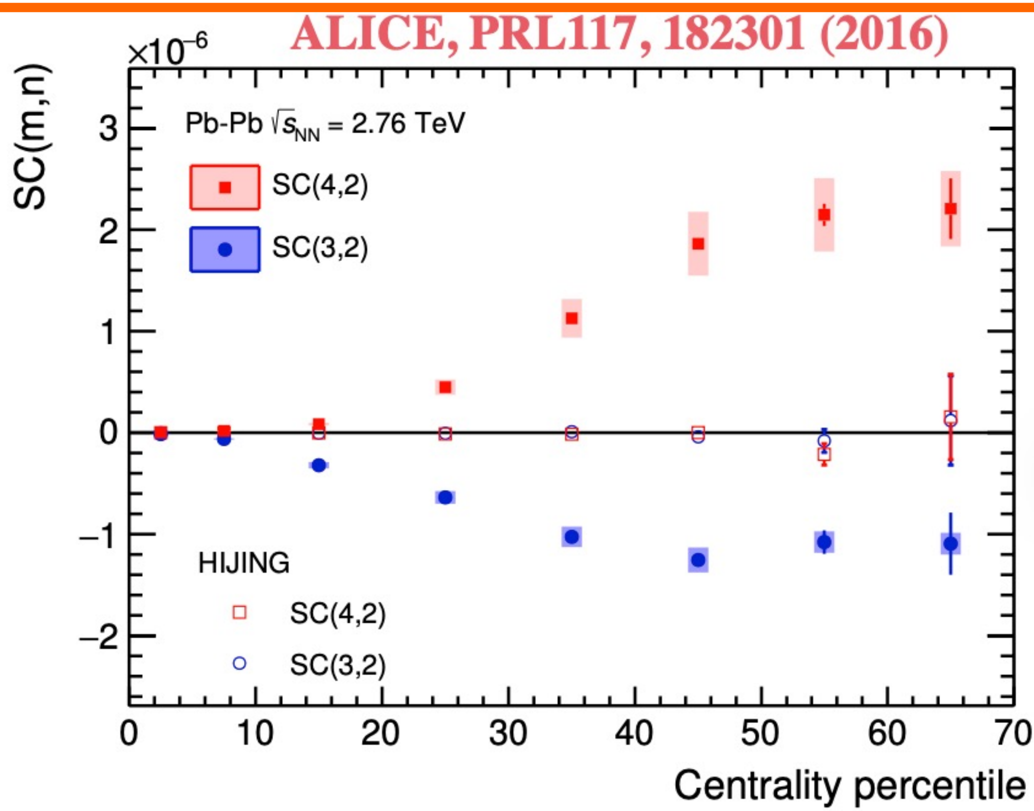
Centrality dependence of SC(m,n)



The positive values of SC(4,2) and negative SC(3,2) are observed for allcentralities.

- suggests a correlation between v_2 and v_4, and an anti-correlations between v_2 and v_3.
- indicates finding $v_2 > \langle v_2 \rangle$ in an event enhances the probability of finding $v_4 > \langle v_4 \rangle$ and finding $v_3 < \langle v_3 \rangle$ in that event.

Non-flow contributions?



$$SC(m,n) = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

SC(m,n) calculations from HIJING (a MC model w/o flow)

❖ It is found that and in HIJING, but SC(m,n) are compatible with zero

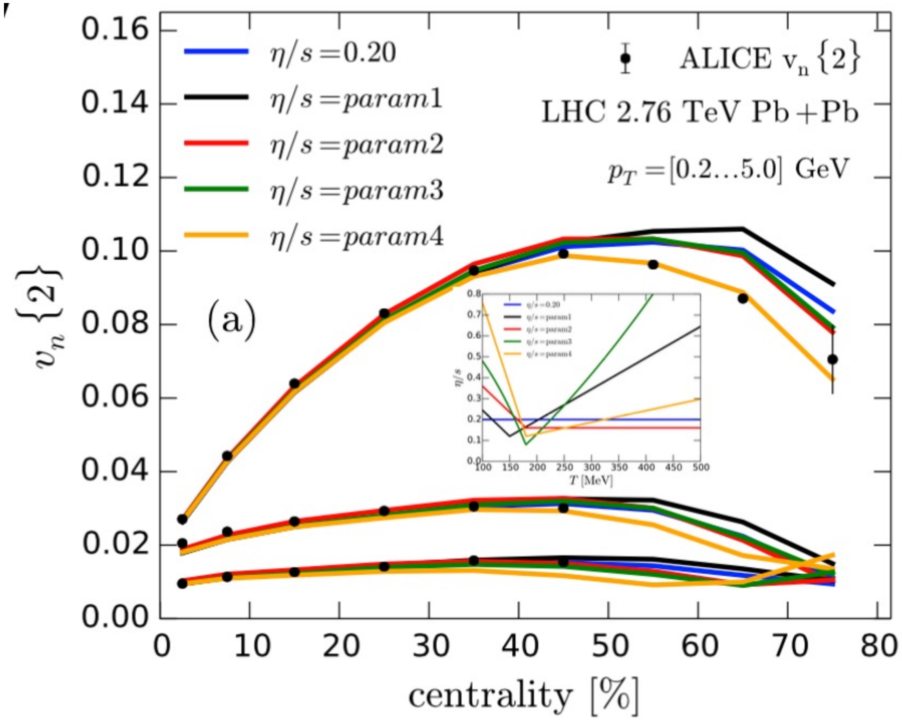
-> suggests SC measurements are nearly insensitive to non-flow effects.

- non-zero values of SC measurements cannot be explained by non-flow effects

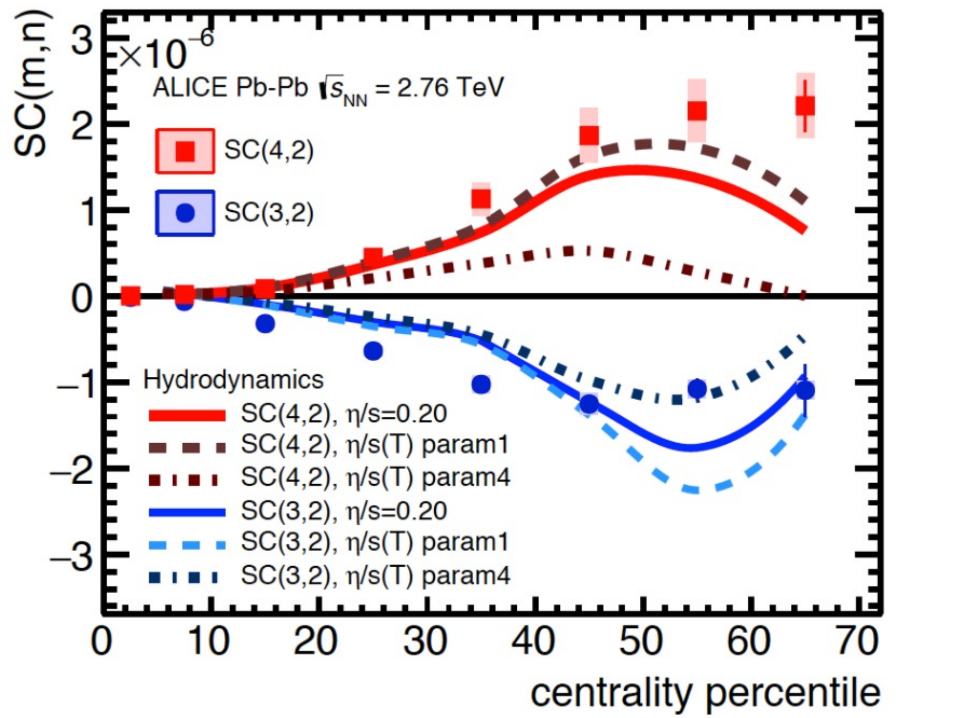
Comparisons to hydrodynamics

EKRT: H. Niemi et. al, PRC 93, 024907 (2016)

ALICE PRL107, 032301



ALICE, PRL117, 182301 (2016)



Comparison of SC measurements to hydrodynamic calculations

- Although hydro describes the v_n fairly well, it fails to describe simultaneously SC(4,2) and SC(3,2).
- SC measurements provide stronger constraints on the η/s in hydro than individual v_n measurements alone.

Summary III

(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})

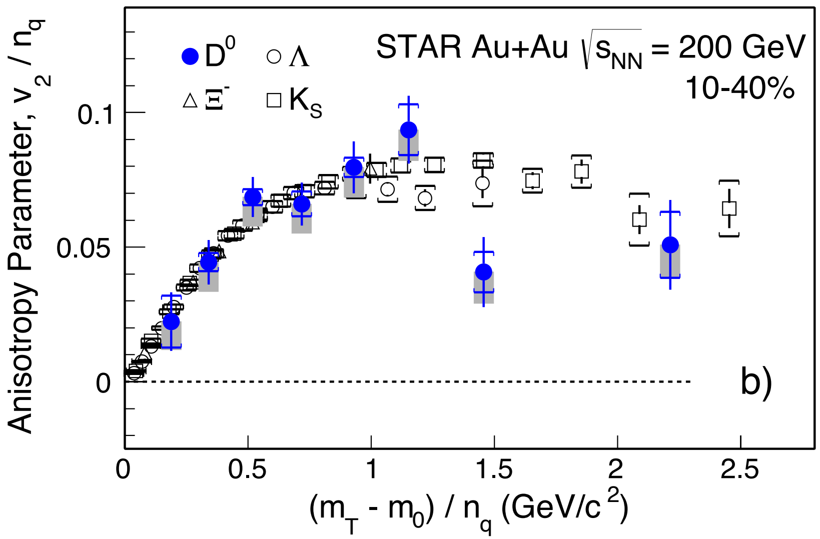
3) The matter behavior like a ***quantum liquid*** with small ***η/s***

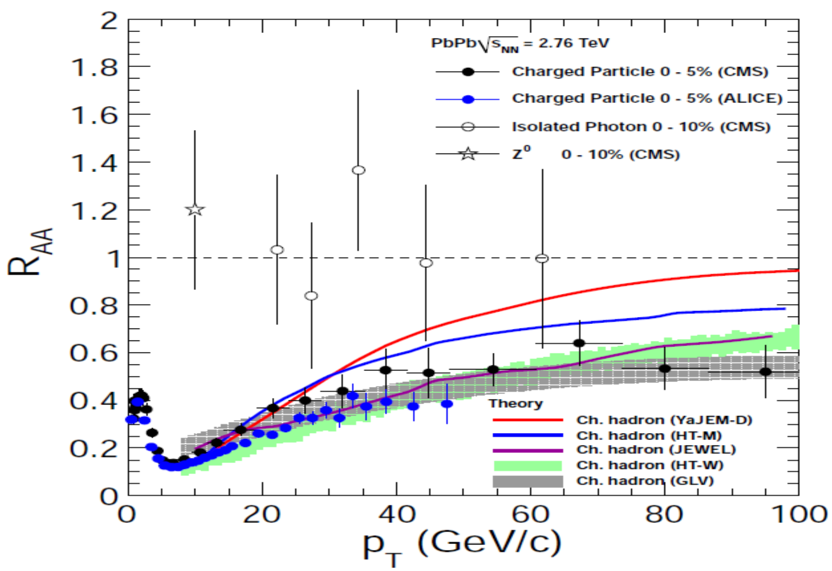
Search for QCD cretical point and phase boundary

Outline

- Introduction
- Perfect Liquid at RHIC
- Criticality
- Summary and Outlook

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

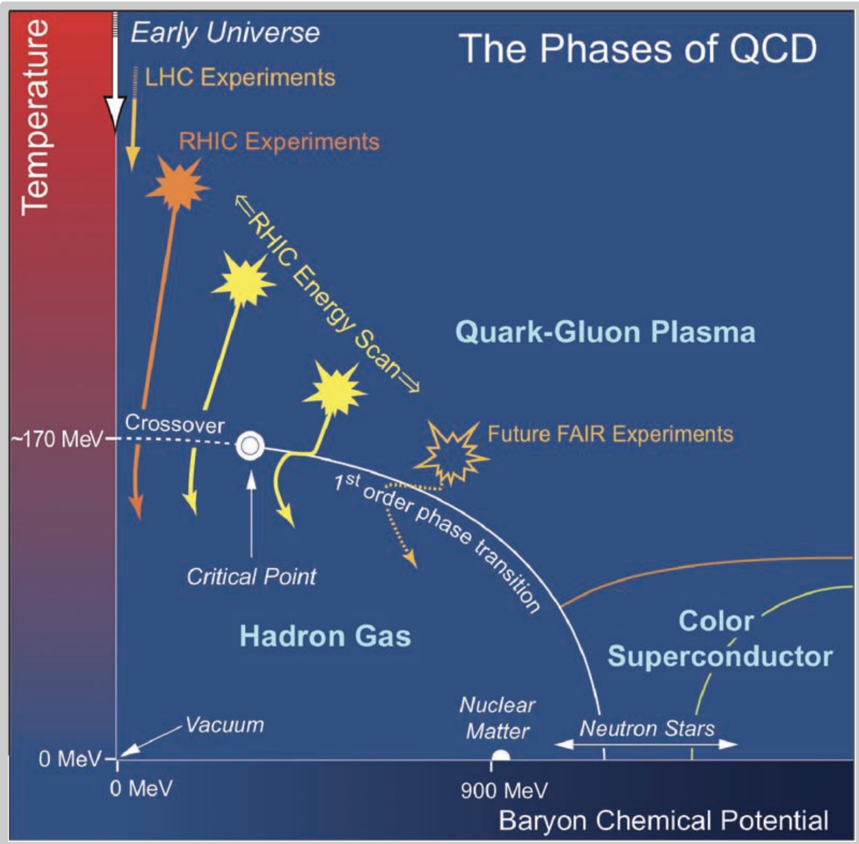
重离子碰撞的研究任务：

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

QCD相图的研究



Study QCD Phase Structure

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

Observables:

1st order phase transition
(1) Azimuthally sensitive HBT
(2) Directed flow v_1

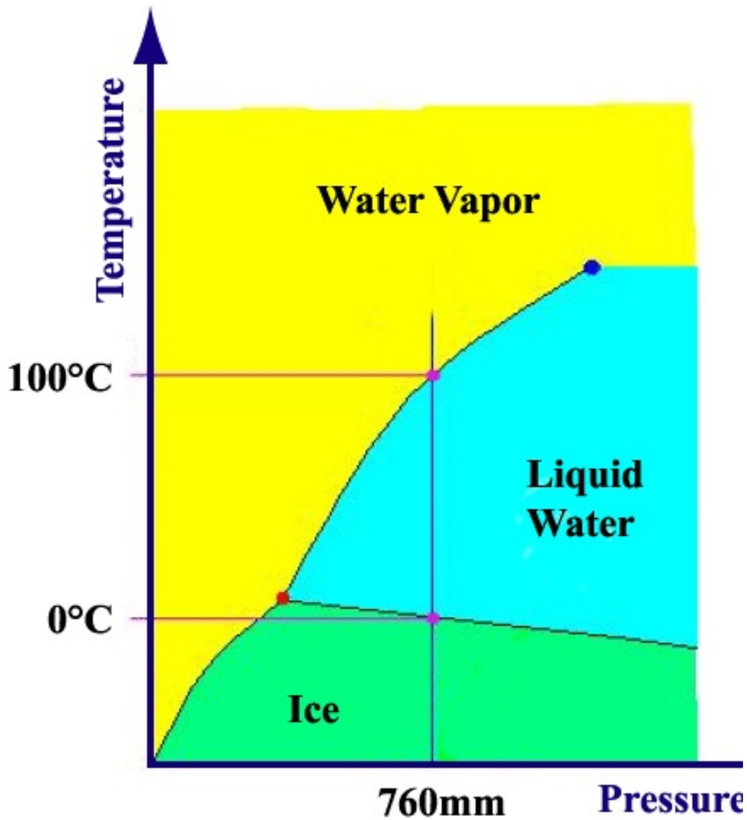
Partonic vs. hadronic dof
(3) R_{AA}: N.M.F.
(4) Charge separation
(5) v_2 - NCQ scaling

Critical point, correl. length
(6) Fluctuations

Chiral symmetry restoration
(7) Di-lepton production

•**BES-I: $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39GeV**

相图



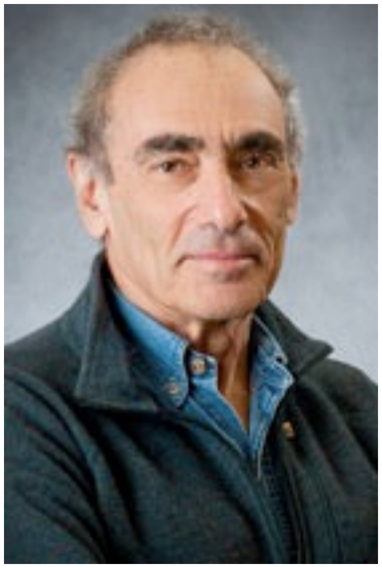
显示对于确定自由度的系统，在给定的外部条件下，物质如何自组织的规律。

H_2O

固态	T < 0度	冰
液态	0<T<100	水
气态	T> 100	气态

等离子体态：

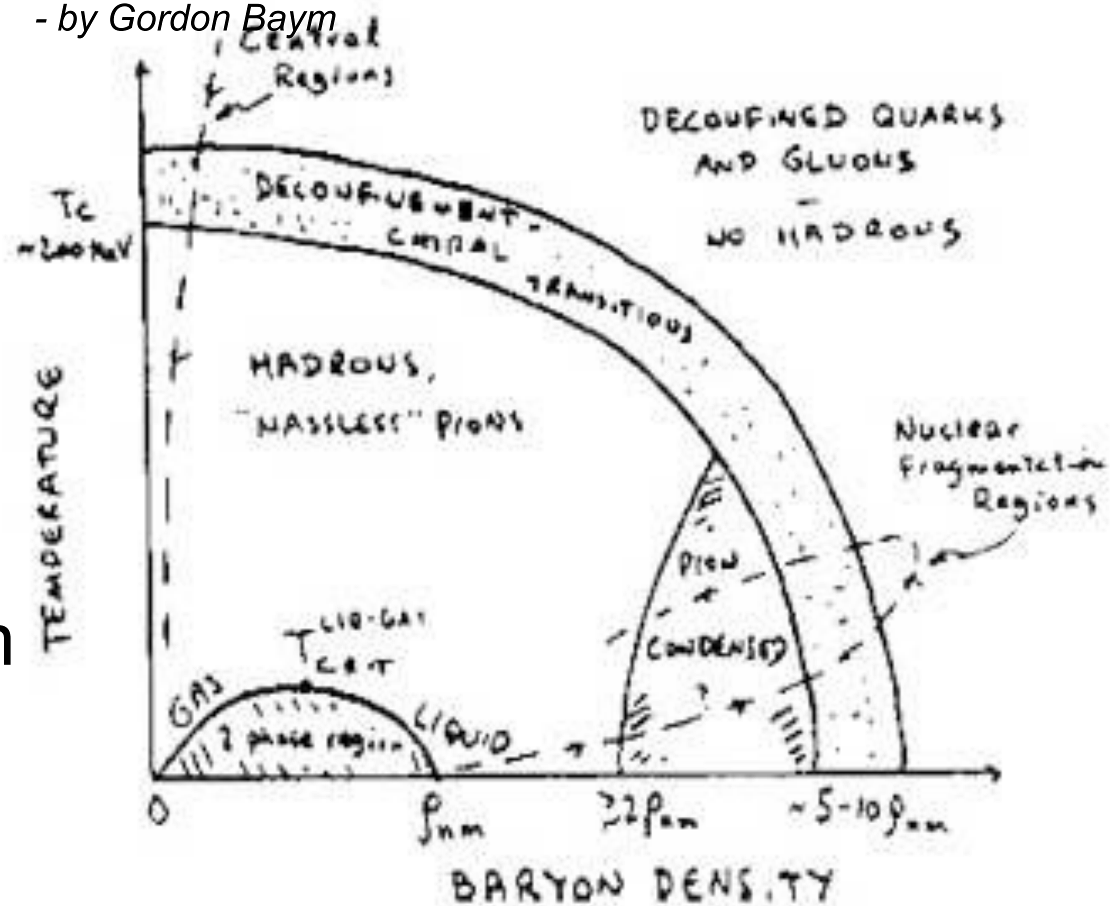
QCD Phase Diagram (1983)



Gordon Baym

1983 US Long Range Plan

- by Gordon Baym



QCD Phase Diagram

1983: "an extended ***quark-gluon plasma*** within which the quarks are deconfined and move independently"
夸克-胶子等离子体，其中夸克被定义并独立运动"

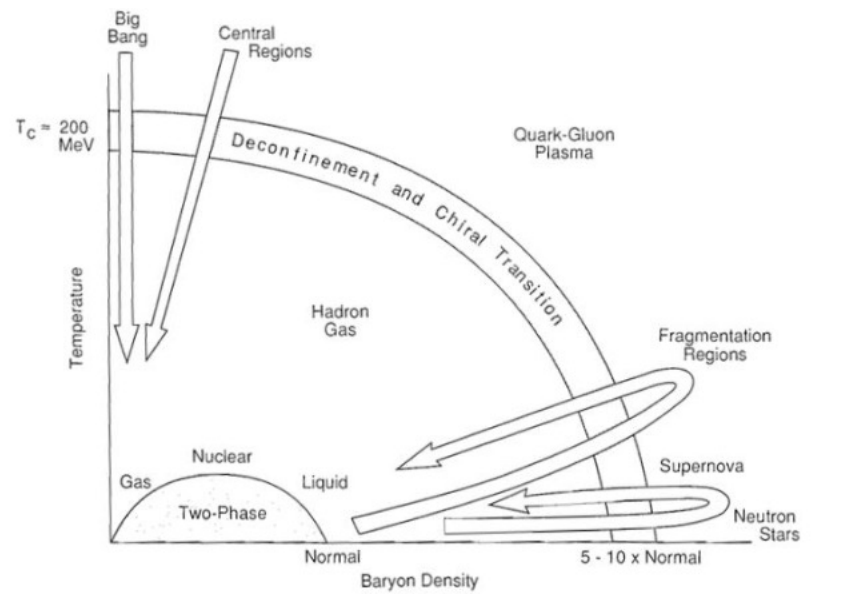


Figure 24: Expected phases of nuclear matter at various temperatures and baryon (or nucleon) densities, showing the "hadronic phase," including a gas-liquid phase-transition region, and the transition region to deconfined quarks and gluons. The dashed lines illustrate trajectories in this phase diagram that can be explored in ultrarelativistic heavy-ion collisions.

1989: "quark-gluon plasma, in which hadrons dissolve into a plasma of quarks and gluons, which are then free to move over a large volume."
"夸克-胶子等离子体，其中强子溶解成夸克和胶子的等离子体，然后在很大的体积上自由移动

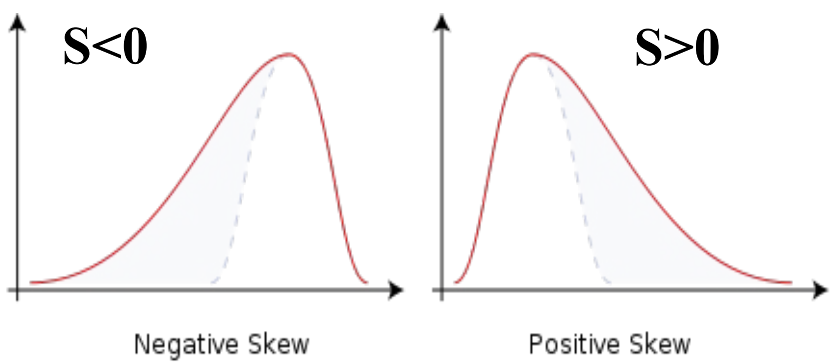
2000: "Quarks and gluons would then freely roam within the volume of the fireball created by the collision." 夸克和胶子将在由碰撞 产生的火球内自由漫游

Higher Moments : Sensitive to the Correlation Length

Skewness:

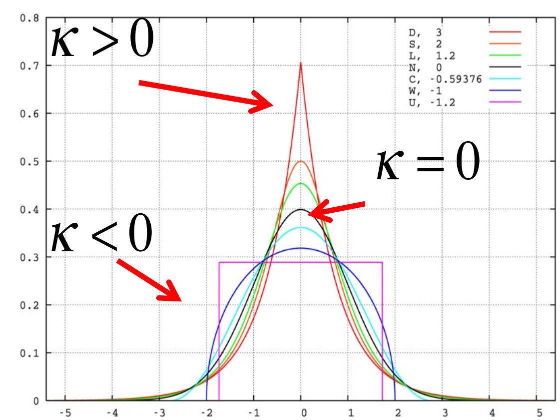
C_n: n^{th} order cumulants

$$S = \frac{C_{3,N}}{(C_{2,N})^{3/2}} = \frac{<(N-<N>)^3>}{\sigma^3}$$



Kurtosis:

$$\kappa = \frac{C_{4,N}}{(C_{2,N})^2} = \frac{<(N-<N>)^4>}{\sigma^4} - 3$$



- Ideal probe of non-gaussian fluctuations.
- Sensitive to the correlation length (ξ).

$< (\delta N)^2 > \sim \xi^2$ $\quad < (\delta N)^3 > \sim \xi^{4.5}$

$< (\delta N)^4 > - 3 < (\delta N)^2 >^2 \sim \xi^7$

Search for CP in Heavy Ion Collisions (ξ~2-3 fm)

•M. A. Stephanov,
•Phys. Rev. Lett. 102, 032301 (2009);
•Phys. Rev. Lett. 107, 052301 (2011);

Higher Moments (II): Related to the Susceptibility

Theory: Lattice QCD, HRG… ⇔ Experiment: Heavy Ion Collisions

Pressure:
$$\frac{p}{T^4} = \frac{1}{VT^3}\ln Z(V,T,\mu_B,\mu_Q,\mu_S)$$

Susceptibility:
$$\chi_q^{(n)} = \frac{1}{T^4}\frac{\partial^n}{\partial(\mu_q/T)^n}P\left(\frac{T}{T_C},\frac{\mu_q}{T}\right)\Big|_{T/T_C},$$

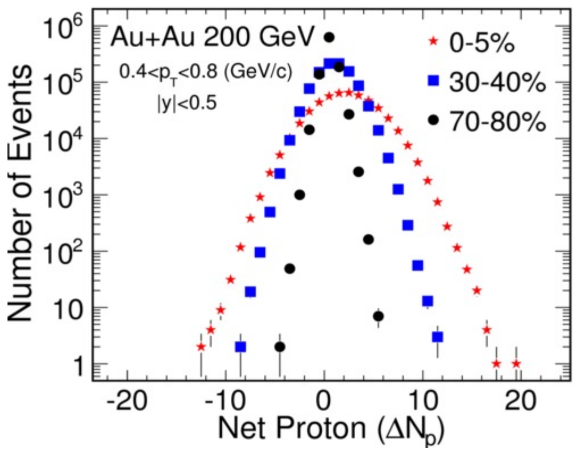
$q = B,Q,S$ **(Conserved Quantum Number)**

$$\chi_q^{(1)} = \frac{1}{VT^3}\langle \delta N_q\rangle, \chi_q^{(2)} = \frac{1}{VT^3}\langle (\delta N_q)^2\rangle$$
$$\chi_q^{(3)} = \frac{1}{VT^3}\langle (\delta N_q)^3\rangle$$
$$\chi_q^{(4)} = \frac{1}{VT^3}\left(\langle (\delta N_q)^4\rangle - 3\langle (\delta N_q)^2\rangle^2\right)$$

$$\langle(\delta N)^2\rangle \approx \xi^2,\ \langle(\delta N)^3\rangle \approx \xi^{4.5},\ \langle(\delta N)^4\rangle \approx \xi^7$$

Bazavov et al . PRL109, 192302 (2012)
F. Karsch et al, PLB 695, 136 (2011).
arXiv: 1203.0784; S. Borsanyi et al, JHEP1201,138(2011);

STAR Experiment: *PRL105, 22303(2010).*



- **Susceptibility ⇔ Moments**

$$\kappa\sigma^2 \sim \frac{\chi^{(4)}}{\chi^{(2)}}, S\sigma \sim \frac{\chi^{(3)}}{\chi^{(2)}}, \frac{\sigma^2}{M} \sim \frac{\chi^{(2)}}{\chi^{(1)}}$$

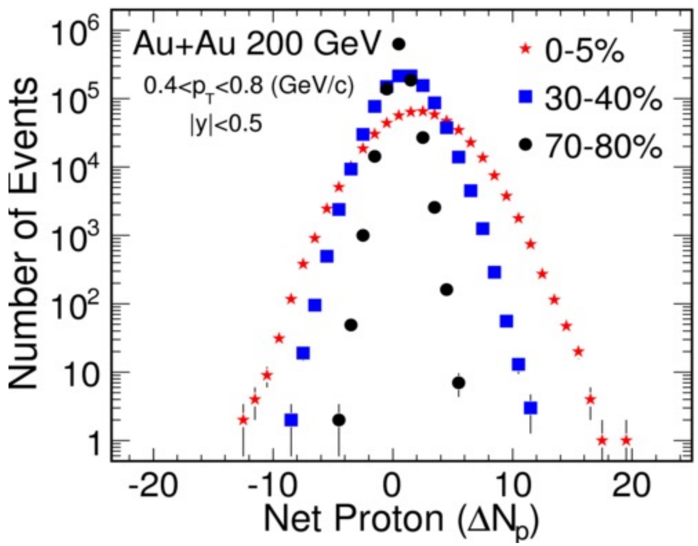
- Study Phase Transition and Bulk properties of QCD matter.

R.V. Gavai and S. Gupta, *PLB 696, 459 (2011).*
S. Gupta, et al., *Science, 332, 1525(2011).*
Y. Hatta, et al, *PRL. 91, 102003 (2003).*

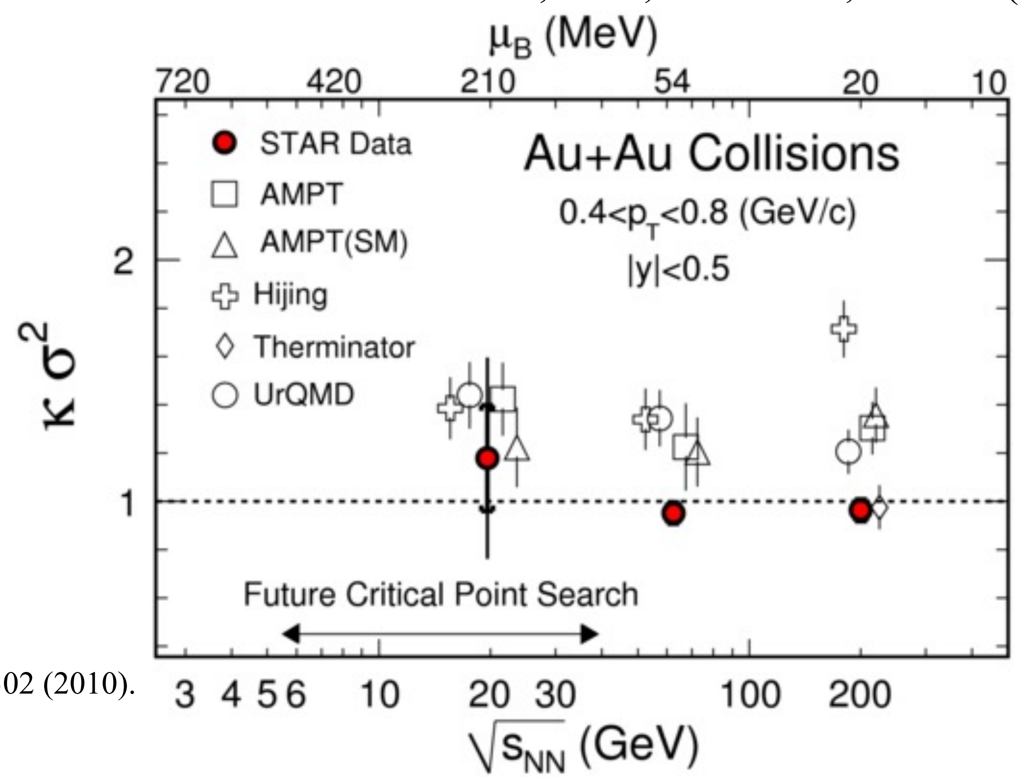
Observable: Higher Moments of Net-proton Distributions

Net-proton fluctuations can reflect the diverges of baryon number fluctuations at CP and can be used to search for the CP.

•Y. Hatta, et al., P.R.L. 91, 102003 (2003).

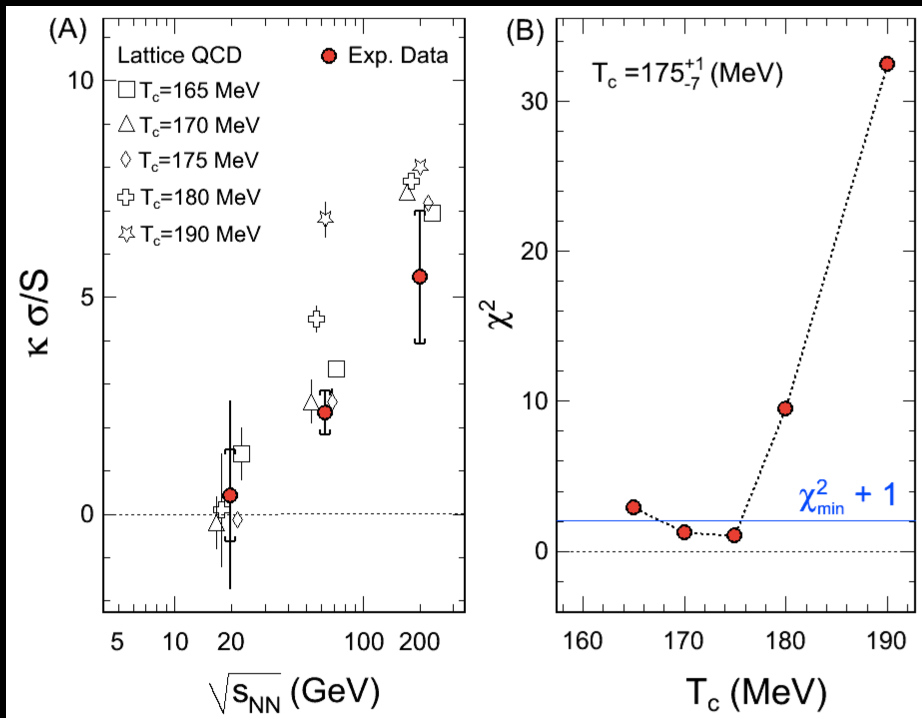


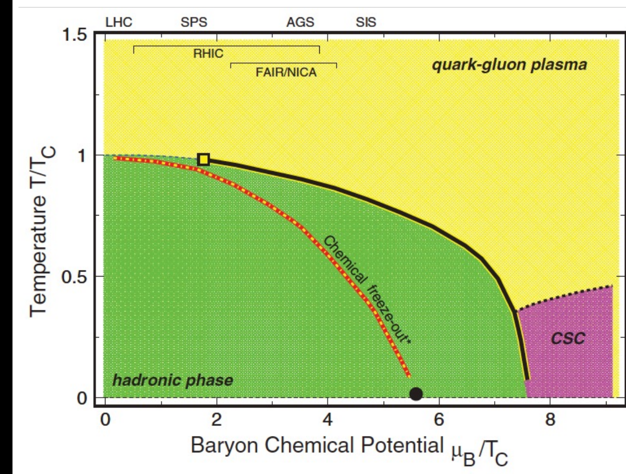
STAR: Physical Review Letters 105, 022302 (2010).



- First measurement of the higher moments of net-proton distributions at RHIC.
- High order fluctuation results consistent with thermalization.
- There has no evidence for the existence of QCD critical point with μ_B <200 MeV.

Scale of Hot/Dense Matter on LGT





Tc :量子色动力学(QCD)相图的标度

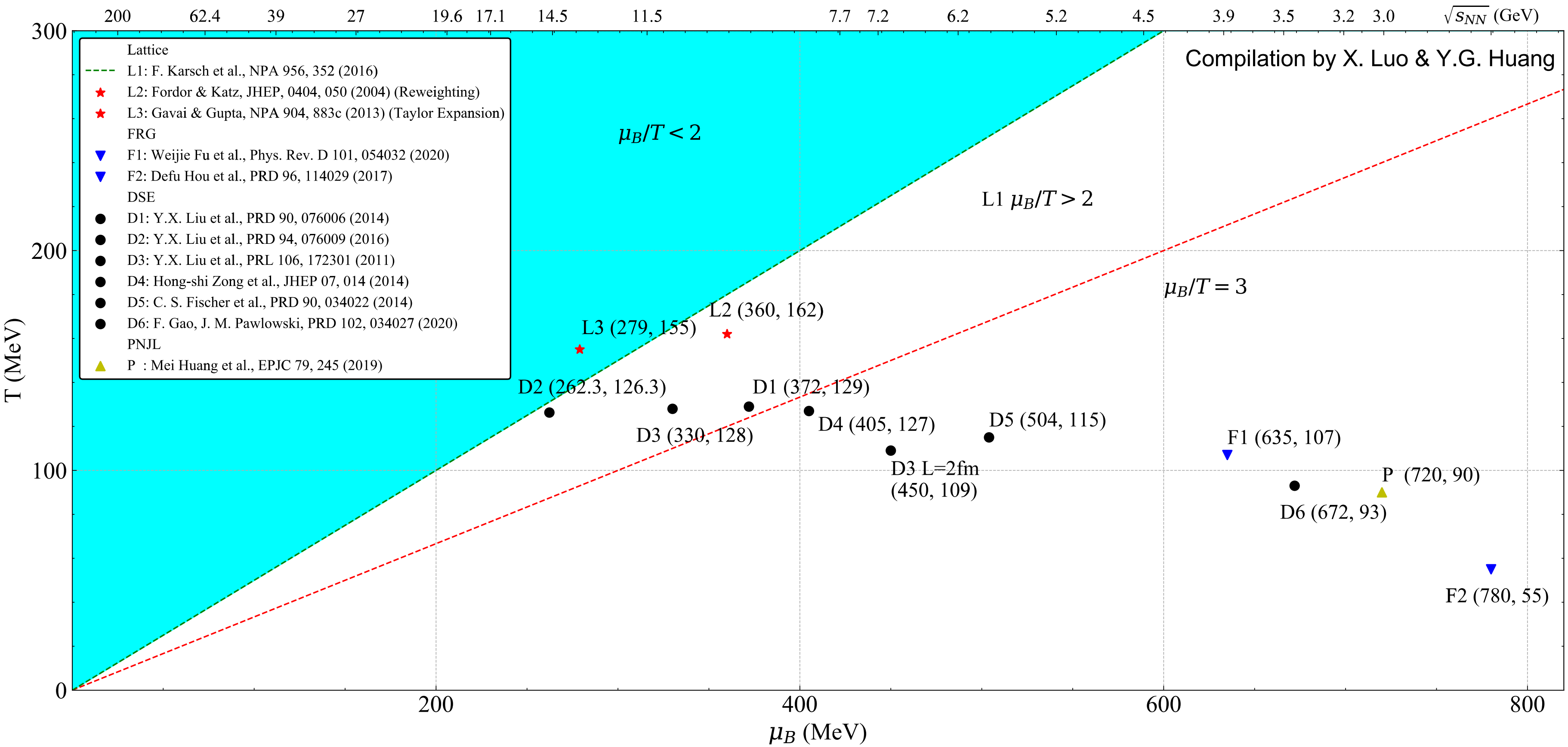
1) Central collisions at RHIC, the high moments measurements are consistent with thermal equilibrium assumption

2) Scale of LGT, determined with the data, is***:*** ***T_C=175$^{+1}_{-7}$*** (MeV)

STAR, ***PRL****105, 22303(2010);* S. Gupta, X.F. Luo, B. Mohanty, H.G. Ritter, NX, ***Science****, 332, 1525(2011);* F. Karsch and K. Redlich, ***PLB****695, 136(2011);* R.V. Gavai and S. Gupta, ***PLB****696, 459(2011).*

临界点位置：理论模型计算

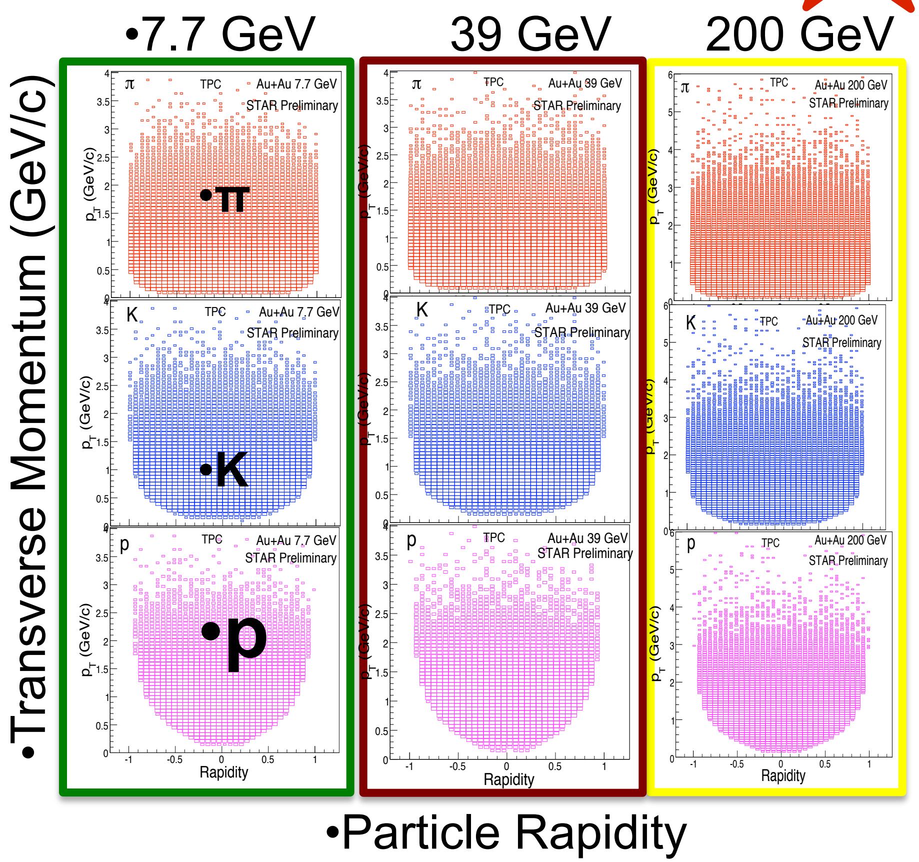
Preliminary collection from Lattice, DSE, FRG and PNJL (2004-2020)



理论上确定QCD相变临界点的位置有较大的不确定性。

RHIC BES-I 数据样本

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year
200	350	2010
62.4	67	2010
39	39	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	4	2010



1) 不同碰撞能量最大的数据样本

2) STAR: 大并且均匀接收度, 良好的粒子鉴别能力

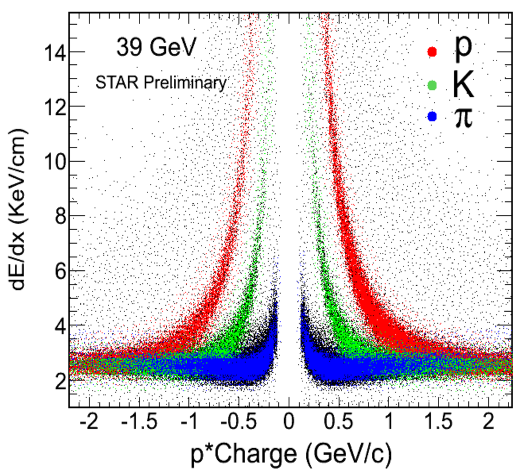
- 为开展临界点的寻找和状态方程的研究提供了可能

Data Analysis

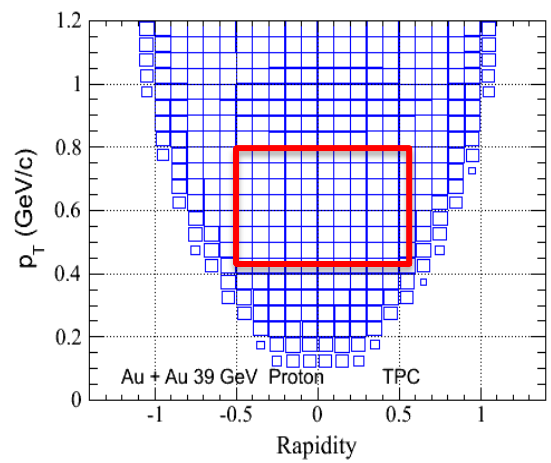
Energy (GeV)	7.7	11.5	19.6	27	39	62.4	200
Statistics (Million)	~3	~6.6	~15	~30	~87	~47	~242
Year	2010	2010	2011	2011	2010	2010	2010

➢ PID : Energy loss (dE/dx) in Time Projection Chamber of STAR detector is used to identify protons with high purity within $0.4<p_T<0.8$ (GeV/c) and at mid-rapidity $|y|<0.5$.

STAR TPC dE/dx PID

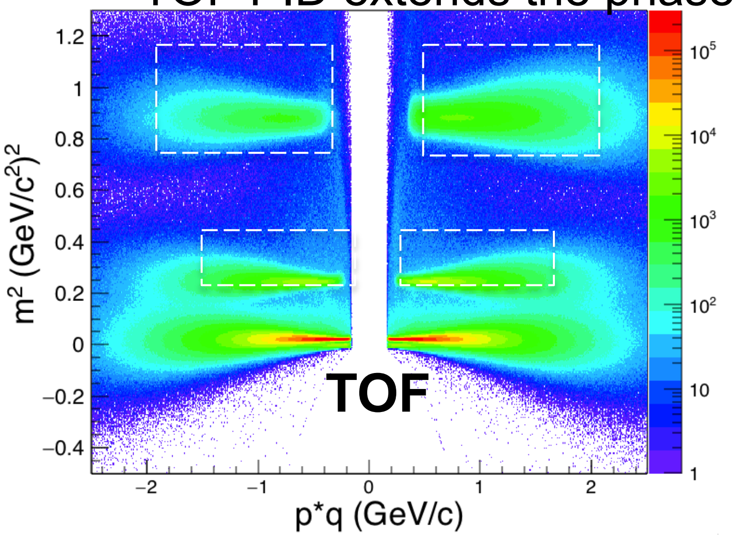


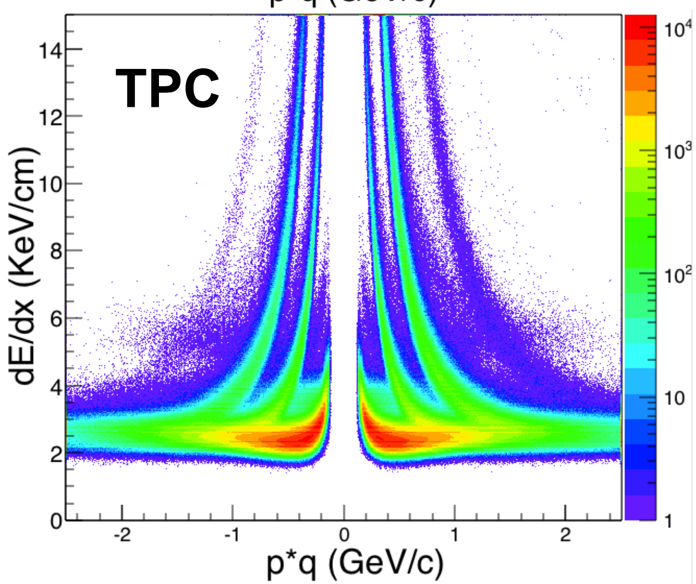
Proton Phase Space

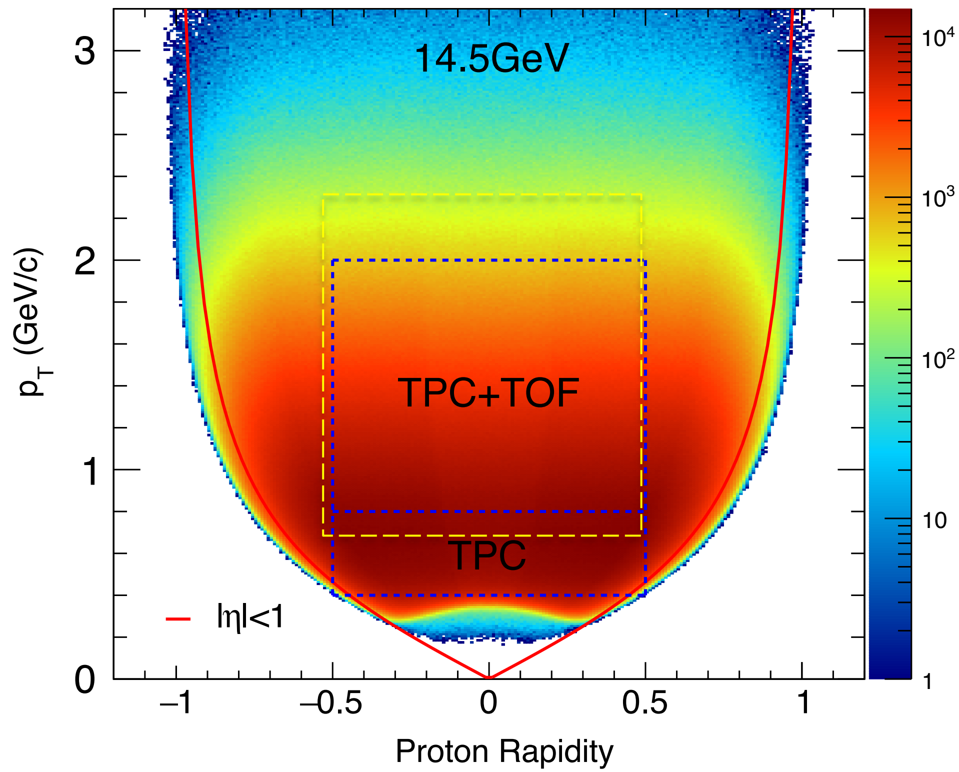


Proton Identification with TOF

Published net-proton results: Only TPC used for proton/anti-proton PID. TOF PID extends the phase space coverage.







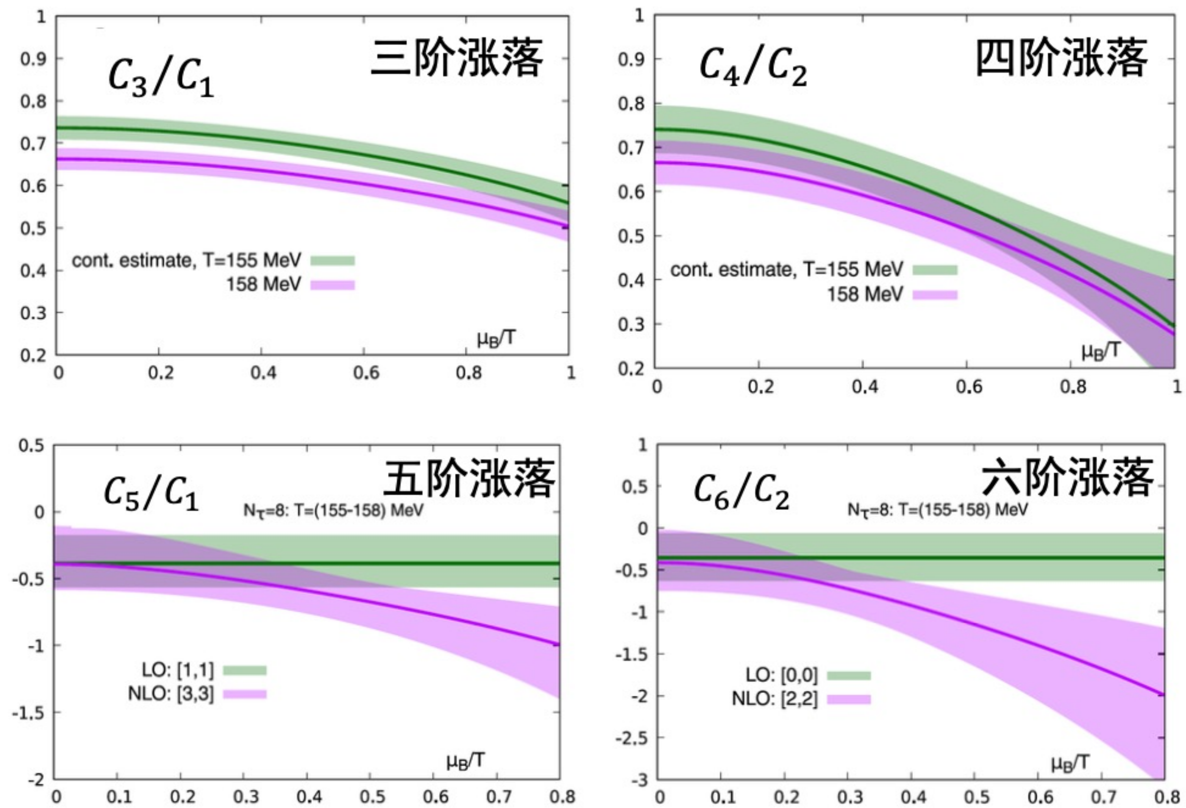
Acceptance: $|y| \leq 0.5$, $0.4 \leq p_T \leq 2$ GeV/c

Efficiency corrections:

TPC ($0.4 \leq p_T \leq 0.8$ GeV/c): **$\varepsilon_{TPC} \sim 0.8$**

TPC+TOF ($0.8 \leq p_T \leq 2$ GeV/c): **$\varepsilon_{TPC}*\varepsilon_{TOF} \sim 0.5$**

高温低密区的平滑过渡



格点 (HotQCD合作组), Phys. Rev. D 101, 074502 (2020)

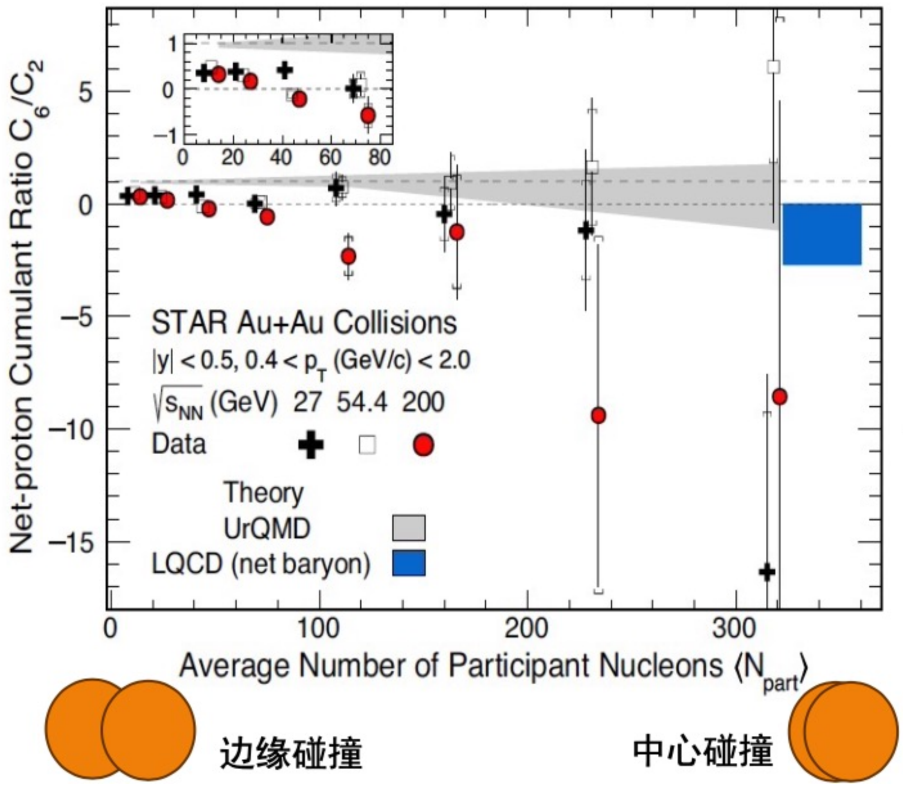
格点 QCD计算表明在低重子密度区为相转变为平滑过渡且净重子数涨落具有两个特性

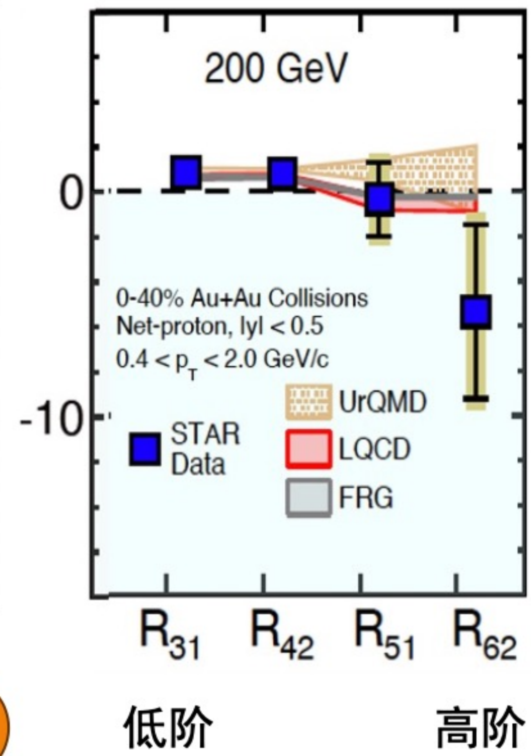
- 高阶符号为负
- 排序(Ordering) $\frac{C_3}{C_1} > \frac{C_4}{C_2} > \frac{C_5}{C_1} > \frac{C_6}{C_2}$

高温低密区的平滑过渡

200 GeV 金核-金核碰撞

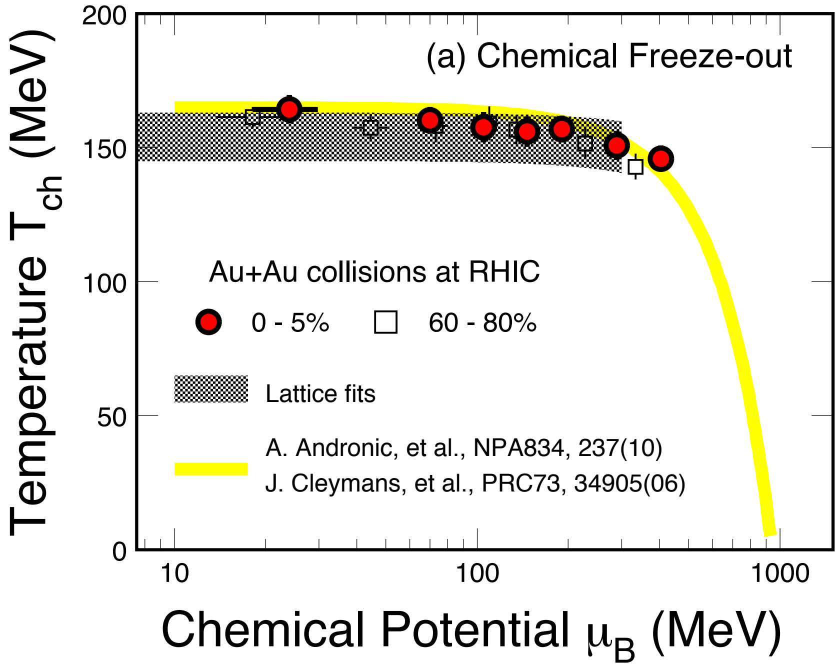
STAR Phys. Rev. Lett. 127, 262301 (2021)　　STAR Phys. Rev. Lett. 130, 082301 (2023)

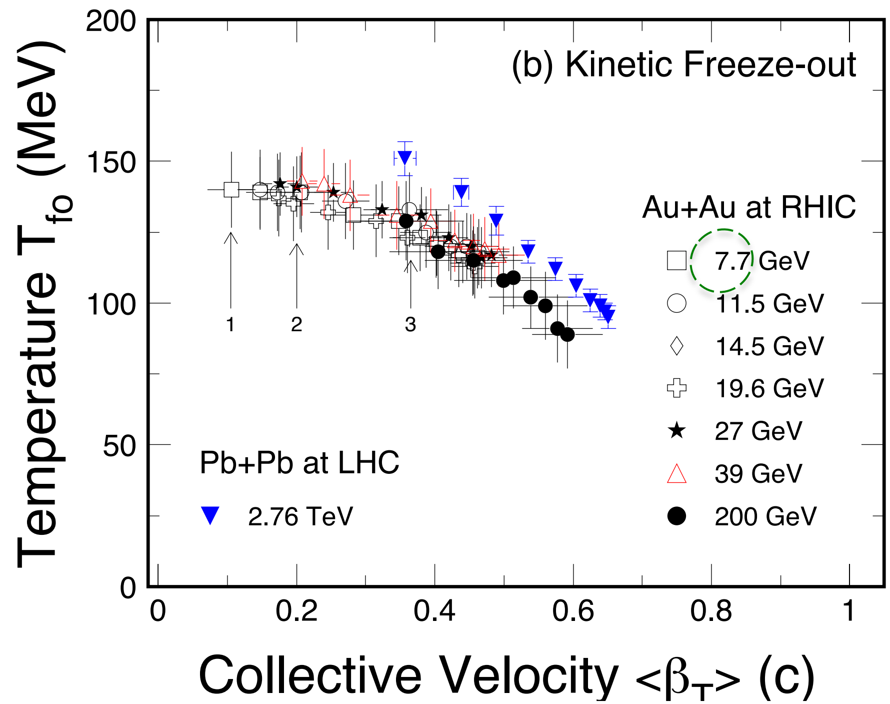




首次观测到净质子数六阶涨落从边缘到中心碰撞逐渐趋于负值，且在中心 碰撞中观测到从低阶到高阶的排序，与格点QCD的平滑过渡计算结果一致

Bulk Properties at Freeze-outs





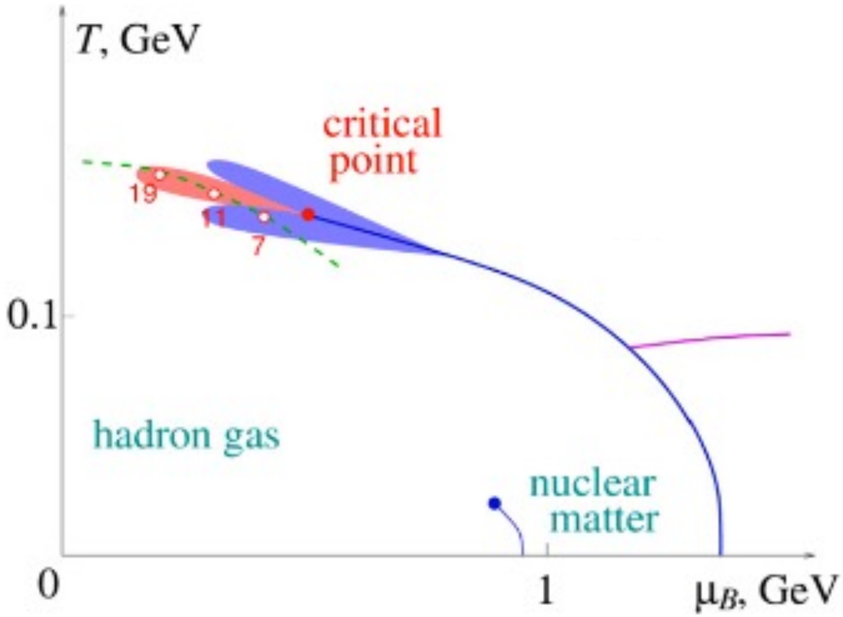
- ALICE: PRL109, 252301(12); PRC88, 044910(2013).
- STAR: NPA757, 102(05); X.L. Zhu, NPA931, c1098(14); L. Kumar, NPA931, c1114(14)
- S. Mukherjee: Private communications. August, 2012

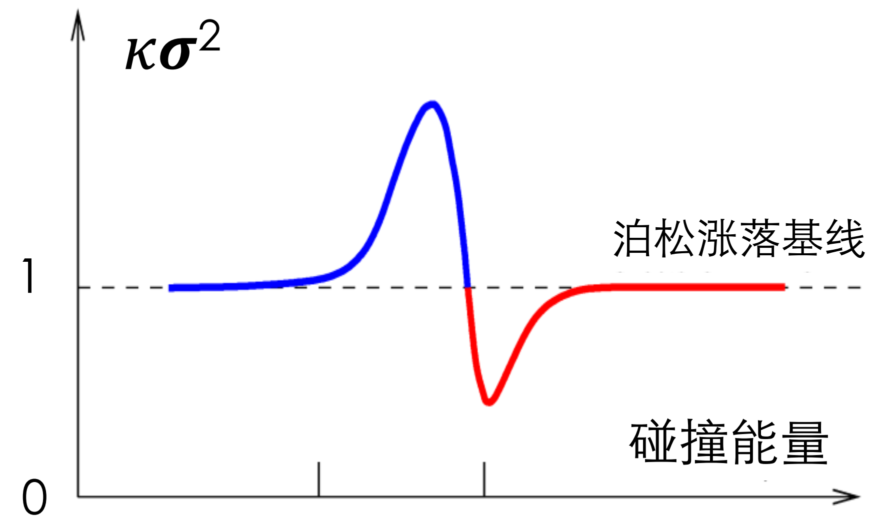
Chemical Freeze-out: (GCE)
- Weak temperature dependence
- Centrality dependence μ_B!
- LGT calculations indicate Critical region above μ_B **~ 300 MeV?**

Kinetic Freeze-out:
- Central collisions => lower value of T_{fo} and larger collectivity β_T
- **Stronger collectivity at higher energy, even for peripheral collisions**

模型预言：QCD临界点信号

假设：体积无穷大以及静态系统





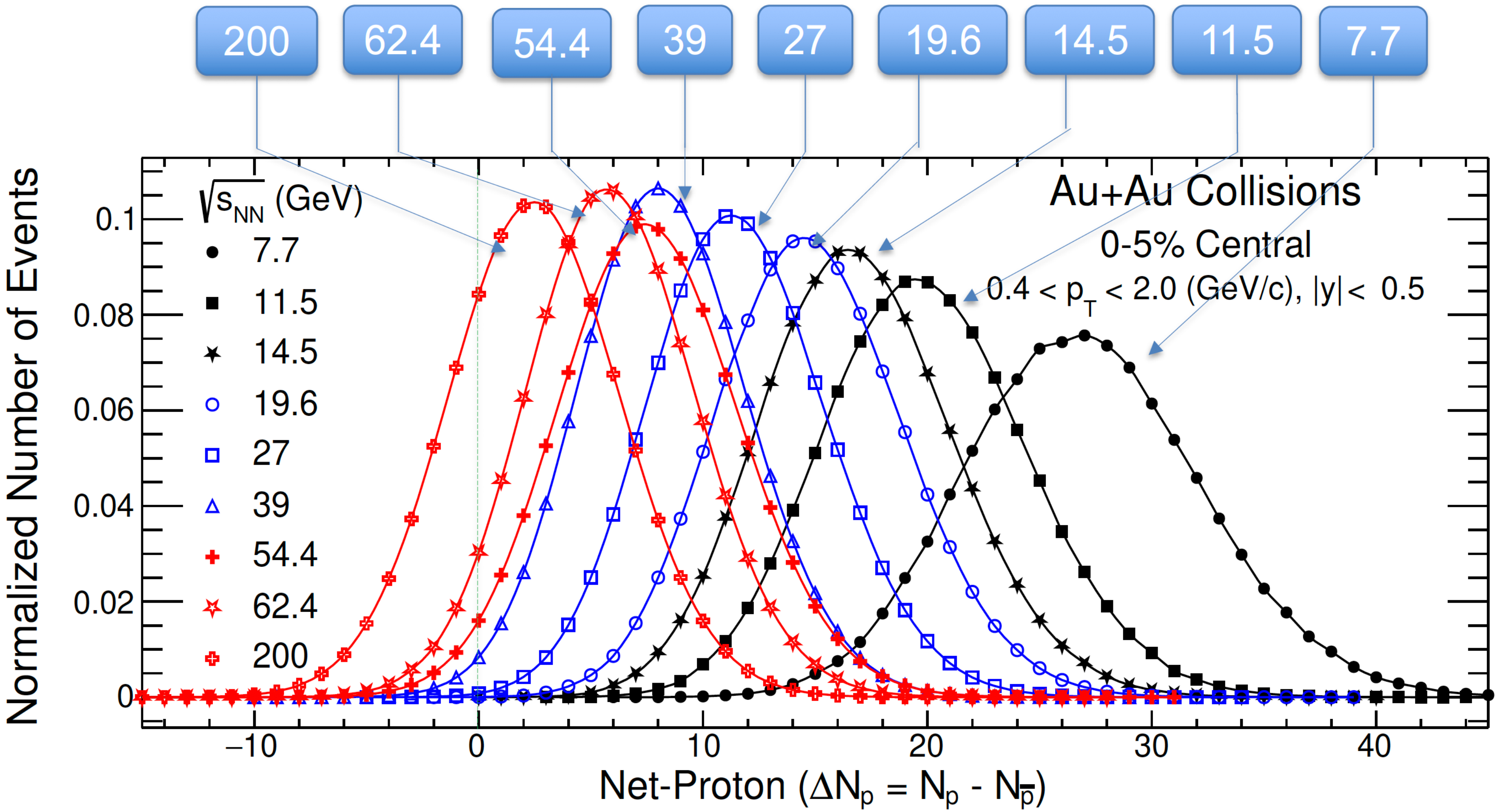
M. Stephanov, PRL107, 052301 (2011); J. Phys. G 38, 124147 (2011).
Schaefer et al., PRD 85, 034027 (2012); W. Fu et al., PRD 94, 116020 (2016).
J.W. Chen, J. Deng, et al., PRD 93, 034037 (2016). PRD 95,014038 (2017).
W. K. Fan, X. Luo, H.S. Zong, IJMPA 32, 1750061 (2017);
G. Shao et al., EPJC 78, 138 (2018) ; Z. Li et al., EPJC 79, 245 (2019).
A. Bzdak et al., Phys. Rep. 853, 1(2020). D. Mroczek et al, arXiv: 2008.04022.

需要注意：非平衡效应以及有限时间/尺度效应

M. Asakawa, M. Kitazawa, B. Müller, PRC 101, 034913 (2020).
S Mukherjee, R. Venugopalan, Y Yin, PRL 117, 222301 (2016).
S. Wu, Z. Wu, H. Song, PRC 99, 064902 (2019).

理论预言改变碰撞能量，系统穿过临界区，观测量将受到负(红色区域)和正(蓝色区域)的贡献。对能量依赖将显示出非单调依赖行为。

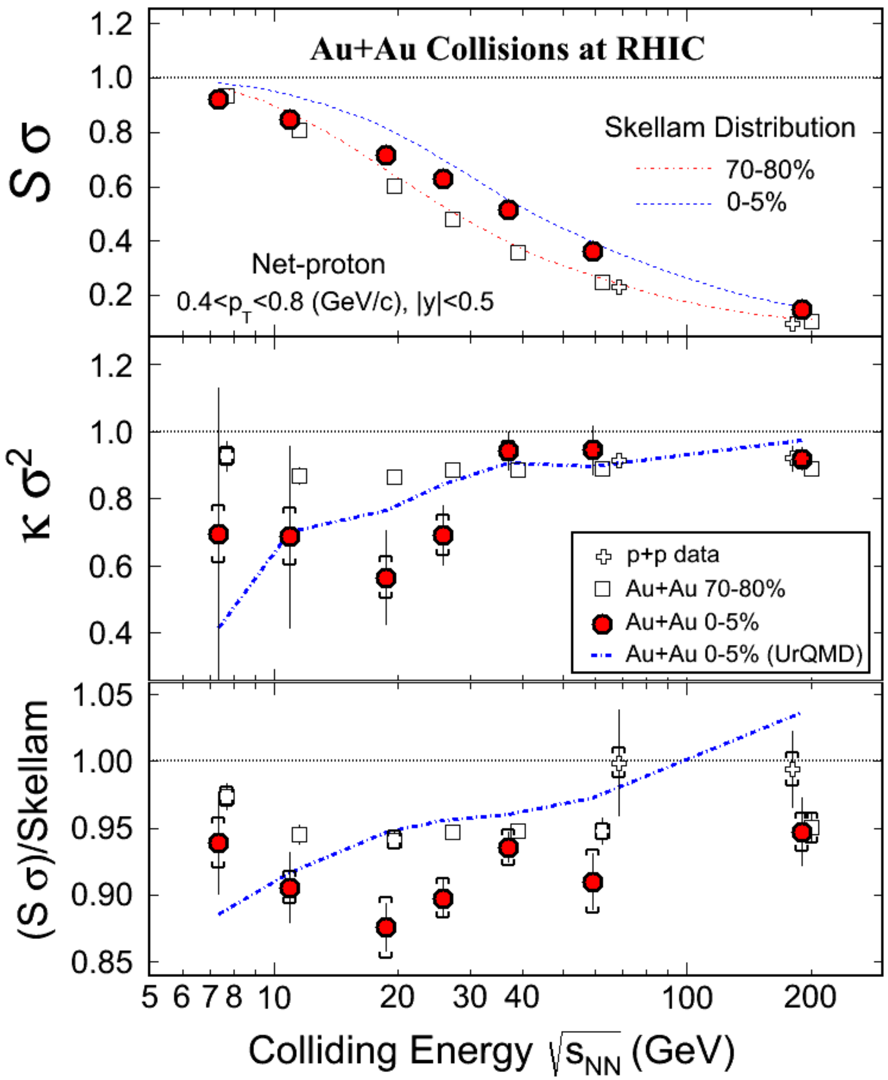
Raw Event-by-Event Net-Proton Distributions



STAR, Phys. Rev. Lett. 126, 092301 (2021)
STAR, Phys. Rev. C 104, 024902 (2021)

Mean values increase when decreasing energy:
Interplay between baryon stopping and pair production.

Energy Dependence of Moment Products



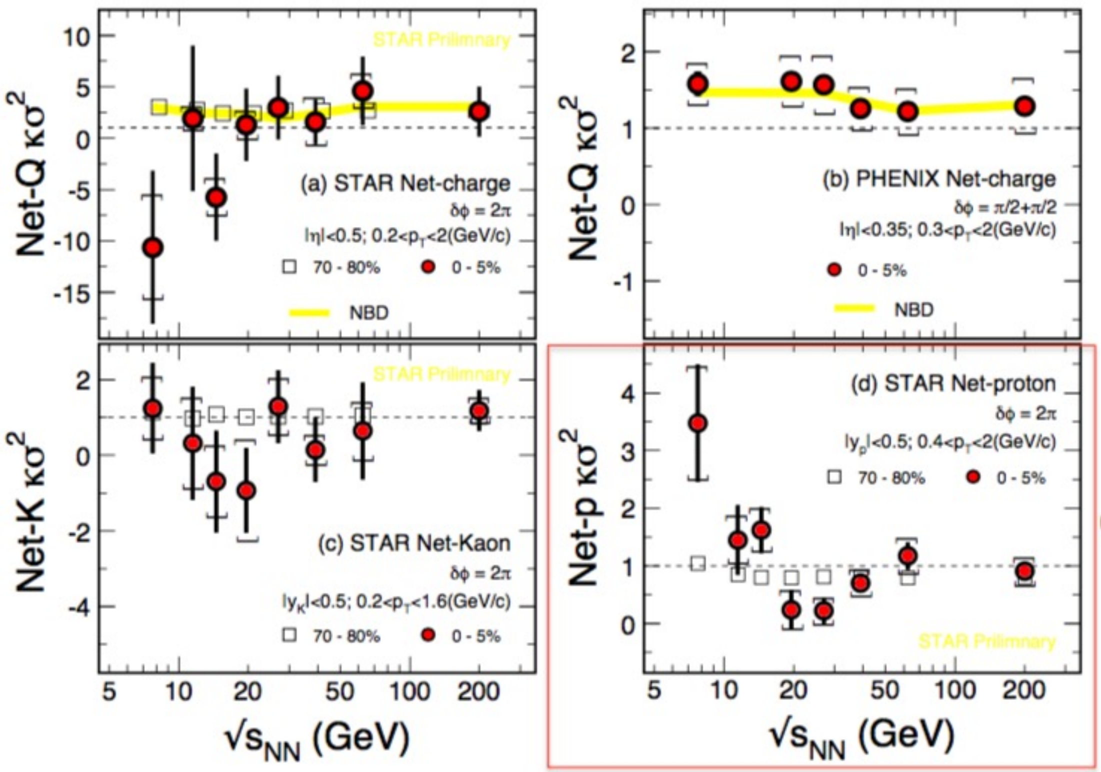
- Deviations below Skellam expectations are observed for all energies and centralities.
- UrQMD model show monotonic behavior for the moment products, in which non-CP physics, such as baryon conservation, hadronic scattering effects, are implemented.
- Higher statistics are needed in order to draw physics conclusion at lower beam energies.

Significance of Deviations from Skellam:

$$|\,Data - Skellam\,| / \sqrt{err_{stat}^{2} + err_{sys}^{2}}$$

Largest deviation for 19.6 and 27 GeV

STARBES I:净质子和净K介子高阶矩

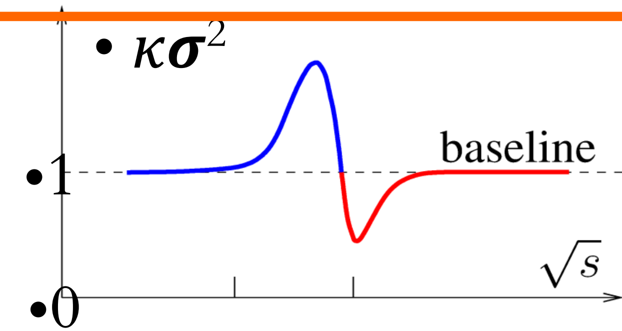


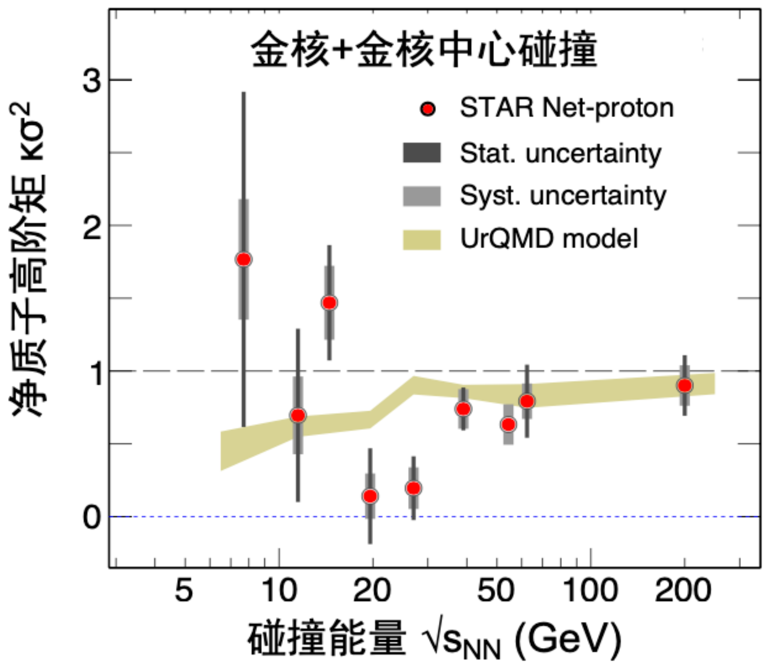
STAR: Phy. Rev. Lett. 112, 032302 (2014).
STAR: PoS CPOD2014 (2015) 019.
STAR, Phys. Lett. B 785, 551 (2018).

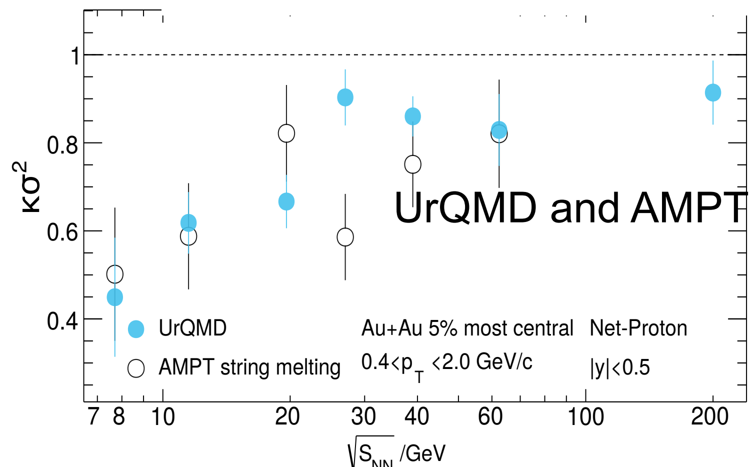
➢ 净质子数4阶涨落显示出对能量的明显的非单调依赖行为，系统进入临界区 ？

•BESI 中净质子数分布的高阶矩

$$\kappa\sigma^2 = \frac{\chi^{(4)}}{\chi^{(2)}} \propto \xi^5$$







STAR: PRL 126 (2021) 092301
STAR: PRC 104 (2021) 024902

•输运模型不能描述实验观测到的非单调能量依赖，特别是低能量上升且大于1的现象。

•J.Xu, S. Yu, F. Liu, X. Luo, Phys. Rev. C 94, 024901 (2016).
•S. He, X. Luo, S. Esumi, Y. Nara, N. Xu, Phys. Lett. B762, 296 (2016).
•S. He，X. Luo，Phys. Lett. B774, 623 (2017).

➢ 首次观测到净质子数4阶涨落显示出对能量的明显的非单调依赖行为，系统进入临界区？

•BESII：低能量点的精确测量

BES-I & II at RHIC (2010-2017, 2018-2021)

Collider mode Au+Au Collisions **FXT mode**

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	μ_B (MeV)	T_{CH} (MeV)
200	238	2010	25	166
62.4	46	2010	73	165
54.4	1200	2017	83	165
39	86	2010	112	164
27	30 (560)	2011/2018	156	162
19.6	**538** / 15	**2019**/2011	206	160
14.5	**325** / 13	**2019**/2014	264	156
11.5	**230** / 7	**2020**/2010	315	152
9.2	**160** / 0.3	**2020**/2008	355	140
7.7	**100** / 3	**2021**/2010	420	140
17.3	**250**	**2021**	230	158

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	μ_B (MeV)	T_{CH} (MeV)
7.7	50+112	2019+2020	420	140
6.2	118	2020	487	130
5.2	103	2020	541	121
4.5	108	2020	589	112
3.9	117	2020	633	102
3.5	116	2020	666	93
3.2	200	2019	699	86
3.0	259	2018	750	80
3.0	**2000**	**2021**	750	80

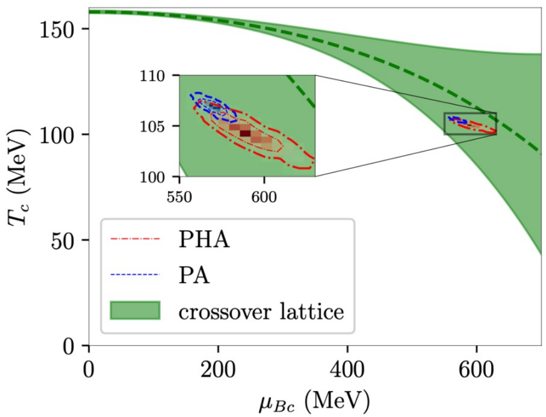
(μ_B, T_{CH}) : J. Cleymans et al., PR**C73**, 034905 (2006)

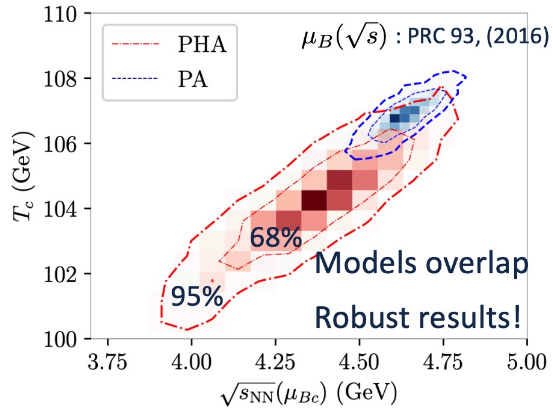
STAR, arXiv:1007.2613
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

- Most precise data to map the QCD phase diagram :

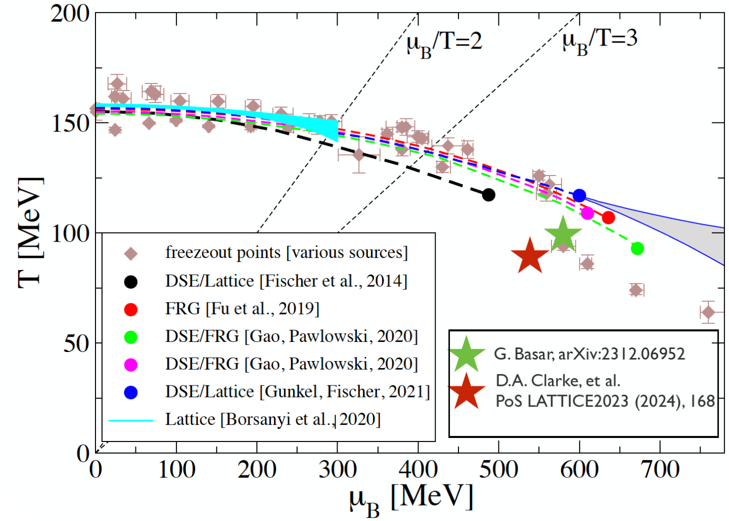
  $3 \leq \sqrt{s_{NN}} \leq 200$ GeV, $25 < \mu_B < 750$ MeV

Location of the QCD Critical Point : Theoretical Prediction





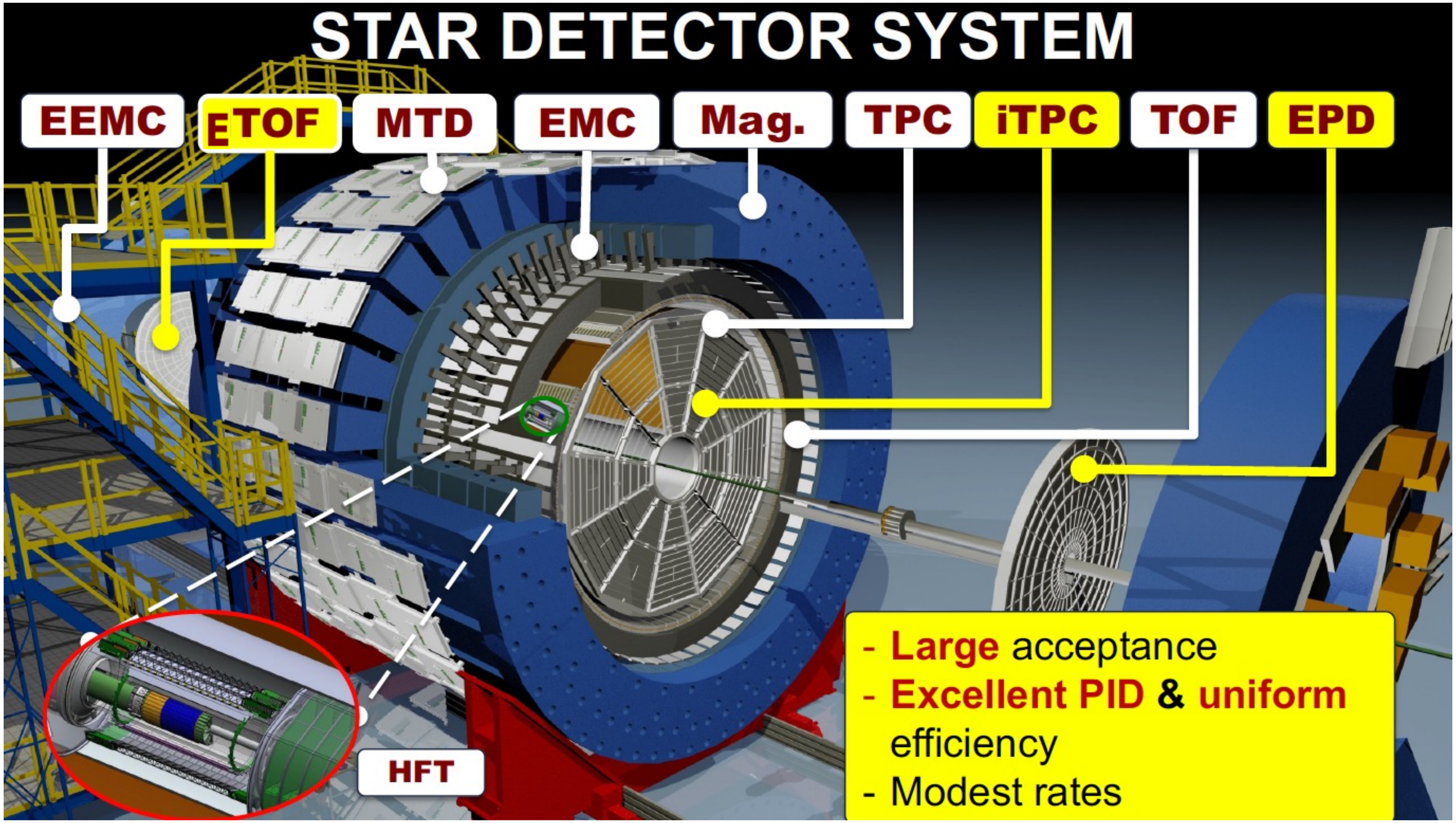
Holography+ Bayesian : Hippert et al., arXiv : 2309.00579



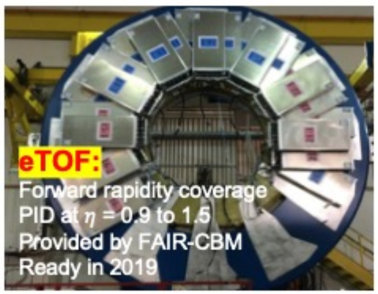
CPOD2024

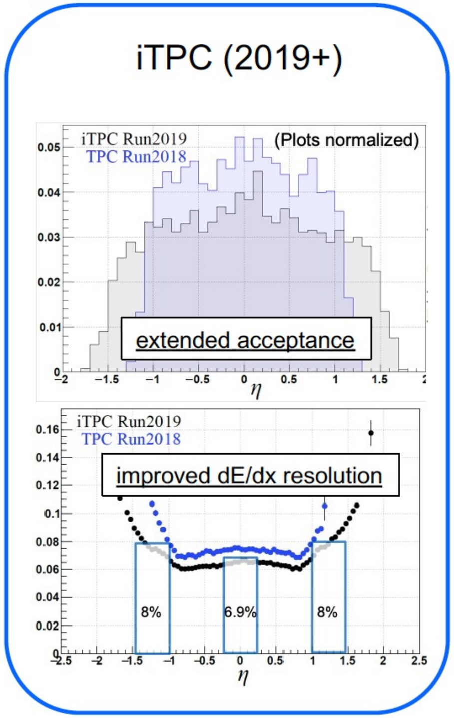
Method	μ_c (MeV)	T_c (MeV)
Holography + Bayesian	560 - 625	101 - 108
FRG/DSE	495 - 654	108 - 119
Lee-Yang edge singularities	500 - 600	100 - 105
Lattice QCD	$\mu_c/T_c > 3$	-
Summary	**495 - 654**	**100 - 119**

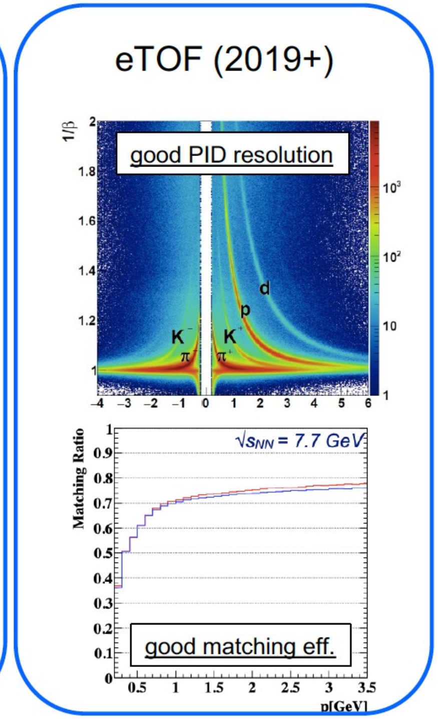
(μ_c, T_c) = (495 - 654, 100 - 119) MeV → $3.5 < \sqrt{s_{NN}} < 4.9$ GeV

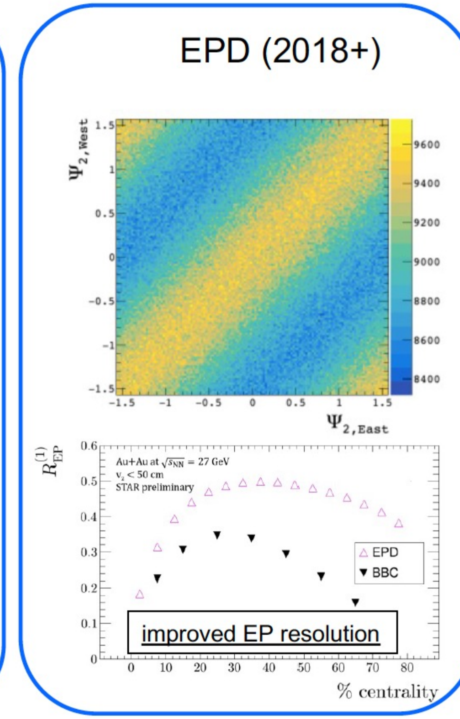

STAR DETECTOR SYSTEM
EEMC
ETOF
MTD
EMC
Mag.
TPC
iTPC
TOF
EPD
HFT
- Large acceptance
- Excellent PID & uniform efficiency
- Modest rates

Detector Upgrade and Performance in BES-II



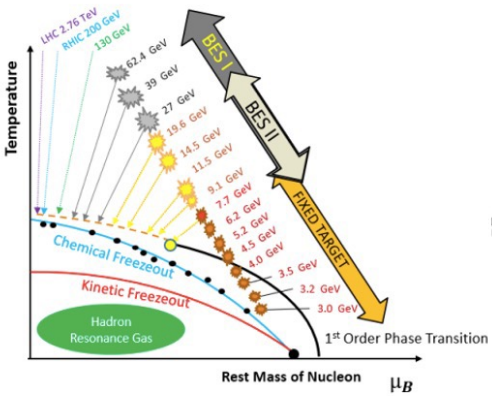




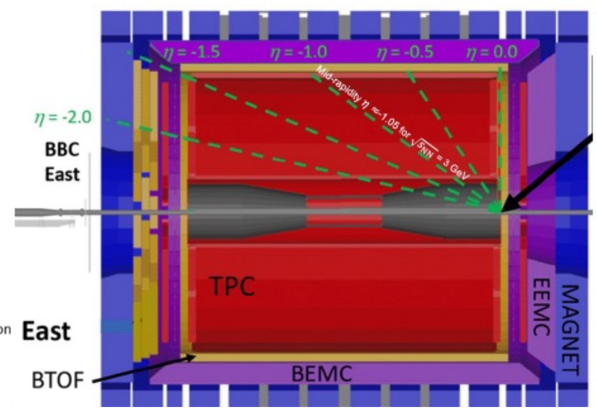


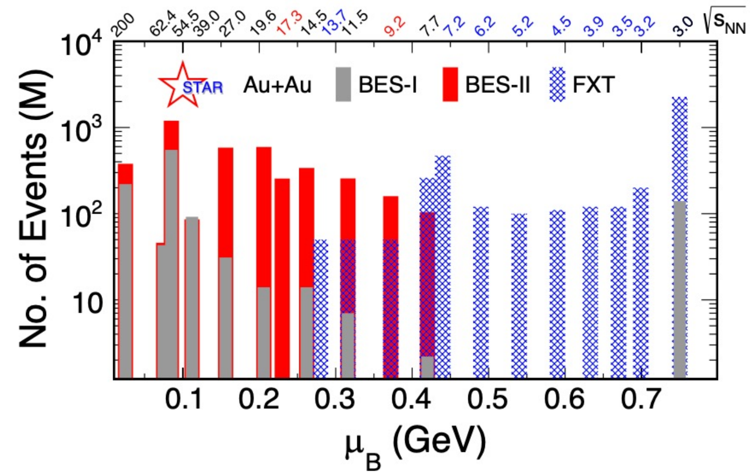
1) Enlarge rapidity acceptance
2) Improve particle identification
3) Enhance centrality/event plane resolution

RHIC Beam Energy Scan (BES) Program (2010-2021)



STAR Fixed Target Mode





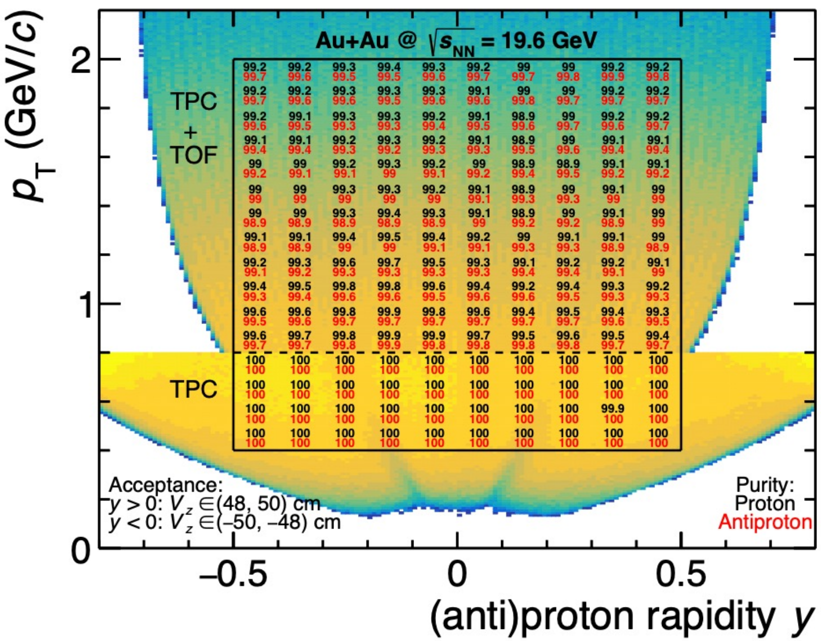
- x10-20 more statistics in BES-II compared to BES-I at collider energies
- BES-II: Collider energies (7.7 – 27 GeV), FXT energies (3.0 - 13.7 GeV)
- μ_B coverage : $25 < \mu_B < 750$ MeV

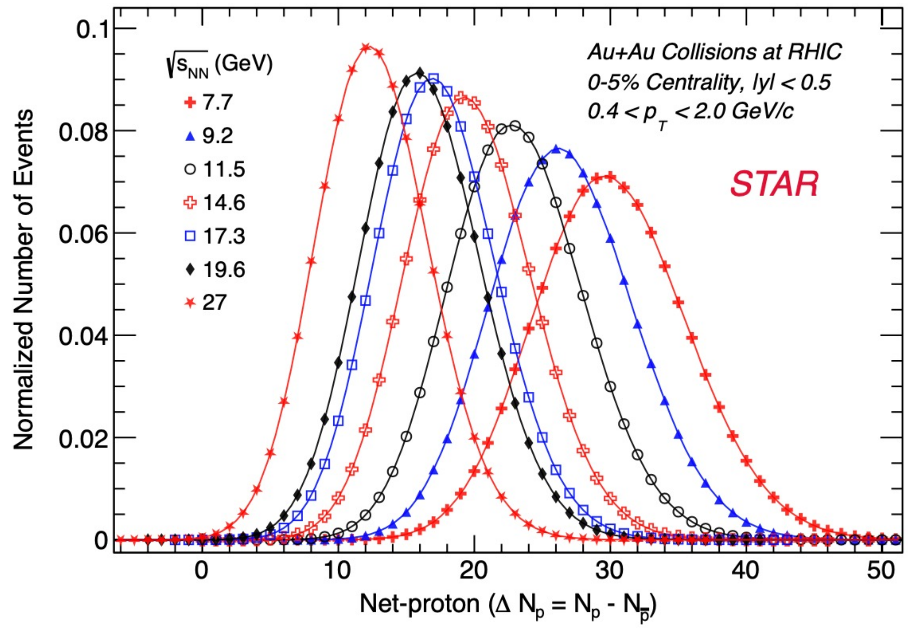
(Anti-)Proton Particle Identification and Net-Proton Distributions

- Identified protons in selected kinetic region are used for analysis:
  $0.4 < p_T < 2.0$ GeV/c and $|y| < 0.5$

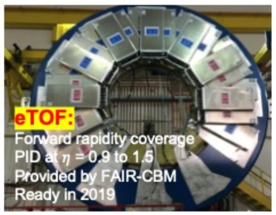
✓ Bin-by-bin proton/antiproton purity > **99%**

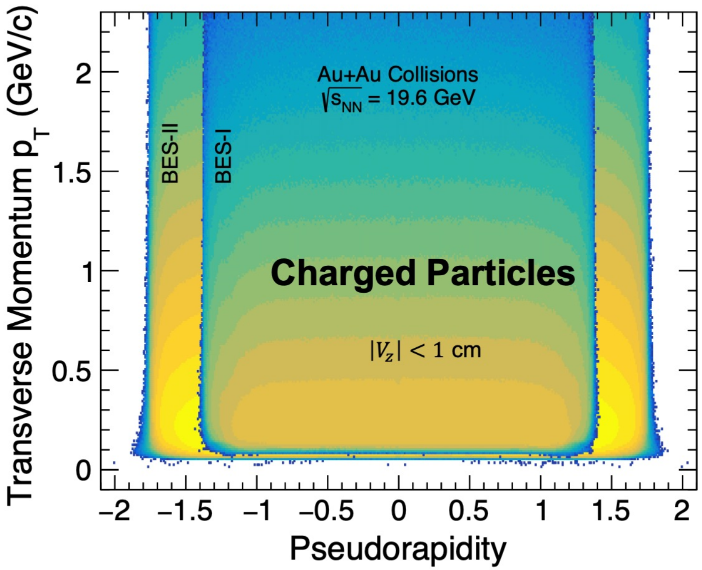
Stat. error $C_r \propto \frac{\sigma^r}{\sqrt{N}}$

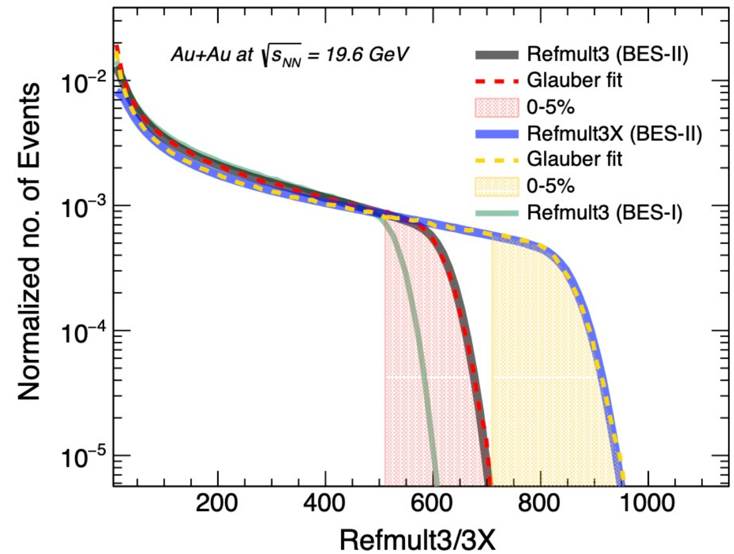




BES-II : Centrality Determination





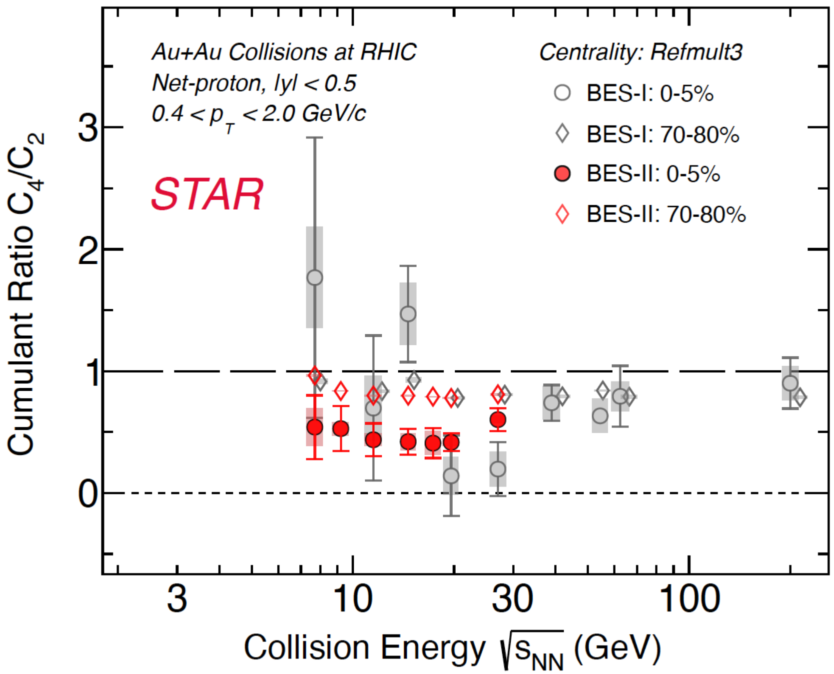


1. Multiplicity of charged particles except (anti-)protons is used for centrality determination

2. Larger acceptance and multiplicity lead to better centrality resolution:
   RefMult3X (BES-II, $|\eta|<1.6$) > RefMult3 (BES-II, $|\eta|<1$) > RefMult3 (BES-I, $|\eta|<1$)

w/ iTPC w/ iTPC w/o iTPC

Cumulant Ratios from BES-II and BES-I



Events used for net-proton fluctuation studies

$\sqrt{s_{NN}}$ (GeV)	Events BES-I (10^6)	Events BES-II (10^6)
7.7	3	**45**
9.2	-	**78**
11.5	7	**110**
14.5	20	**178**
17.3	-	**116**
19.6	15	**270**
27	30	**220**

Deviation between BES-II and BES-I data

$\sqrt{s_{NN}}$ (GeV)	0-5%	70-80%
7.7	1.0σ	0.9σ
11.5	0.4σ	1.3σ
14.6	2.2σ	2.5σ
19.6	0.7σ	0.0σ
27	1.4σ	0.2σ

STAR : **CPOD2024, SQM2024**

BES-II and BES-I results are consistent !

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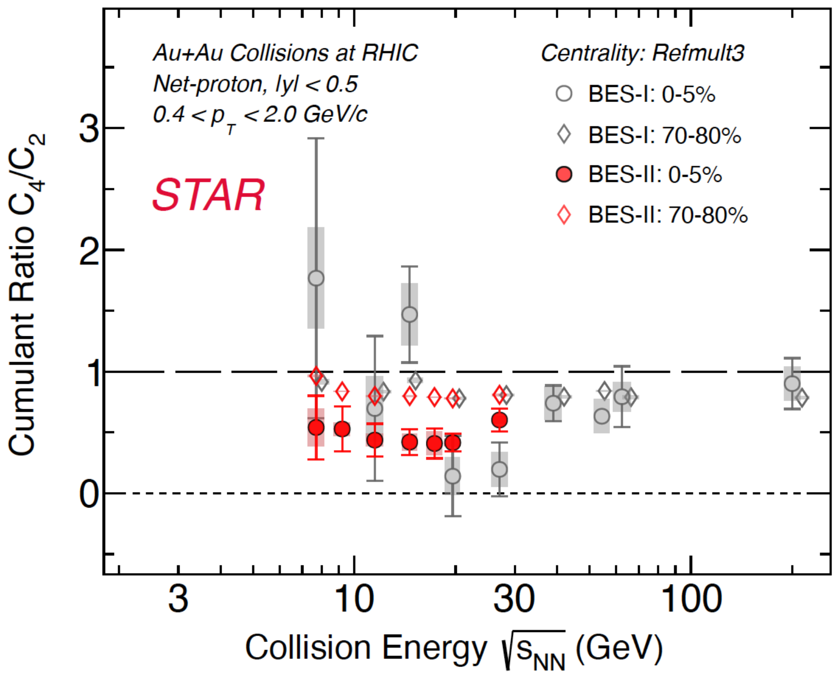

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Reduction factor (BES-II vs. BES-I) in uncertainties on 0-5%

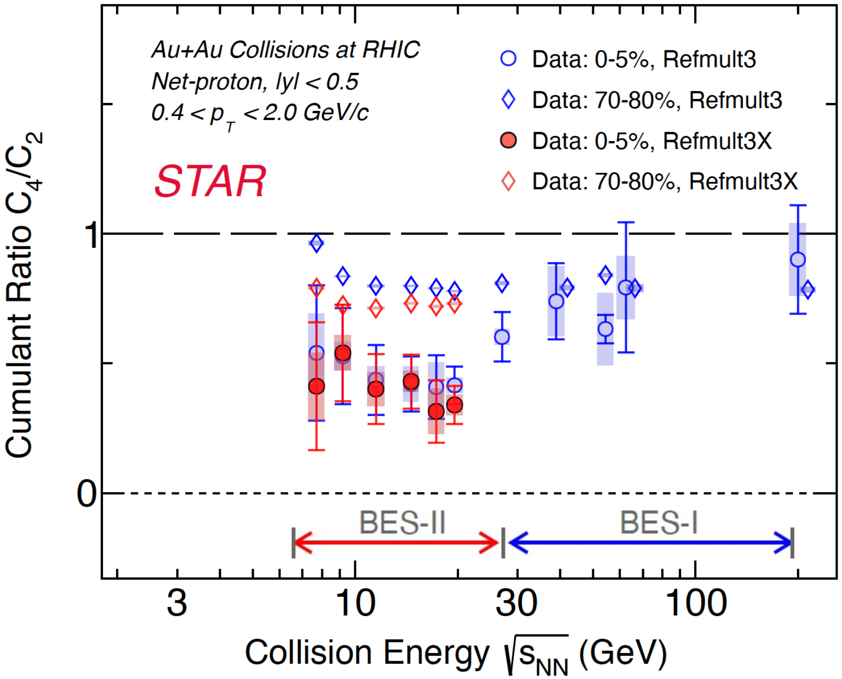
7.7 GeV		19.6 GeV	
stat. error	sys. error	stat. error	sys. error
4.7	3.2	4.5	4

BES-II and BES-I results are consistent !

STAR : **CPOD2024, SQM2024**

BES-II : Better statistical precision
Better control on systematics !

Cumulant Ratios from BES-II and BES-I



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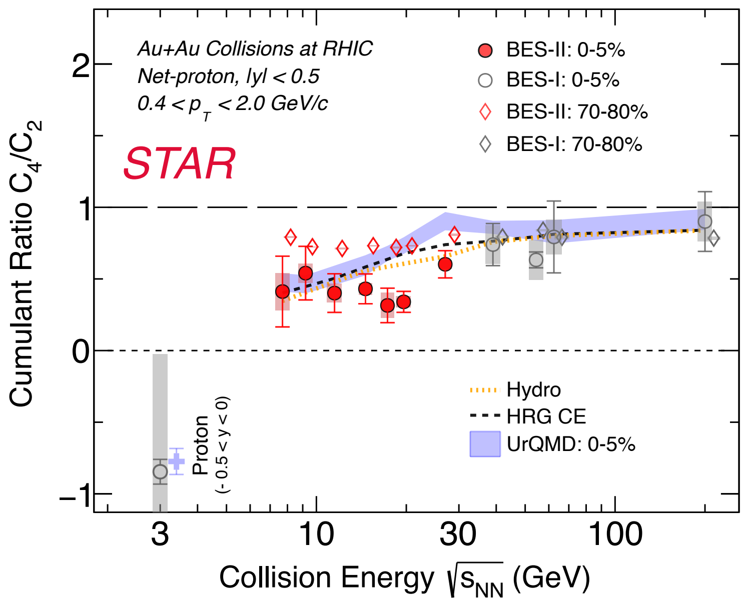
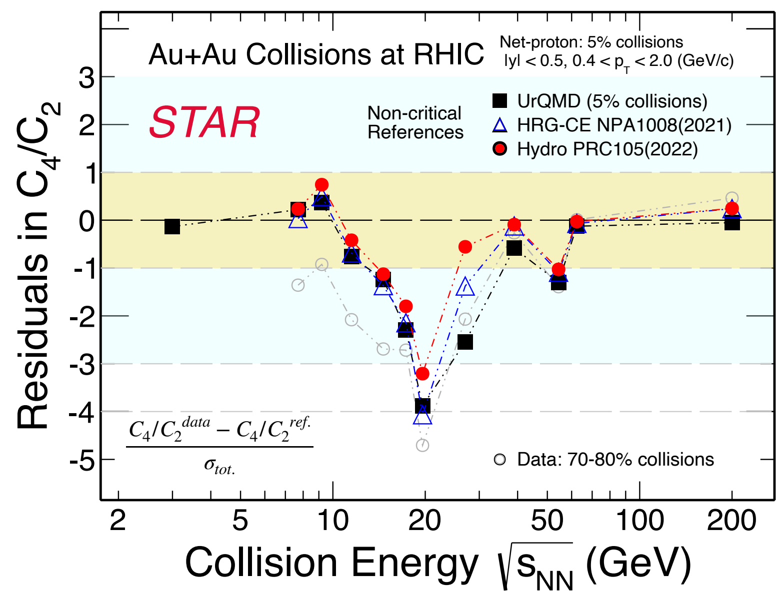
- **0-5% centrality** results show good agreement between Refmult3 and Refmult3X and centrality resolution effect is small.

Energy Dependence and Model Comparison

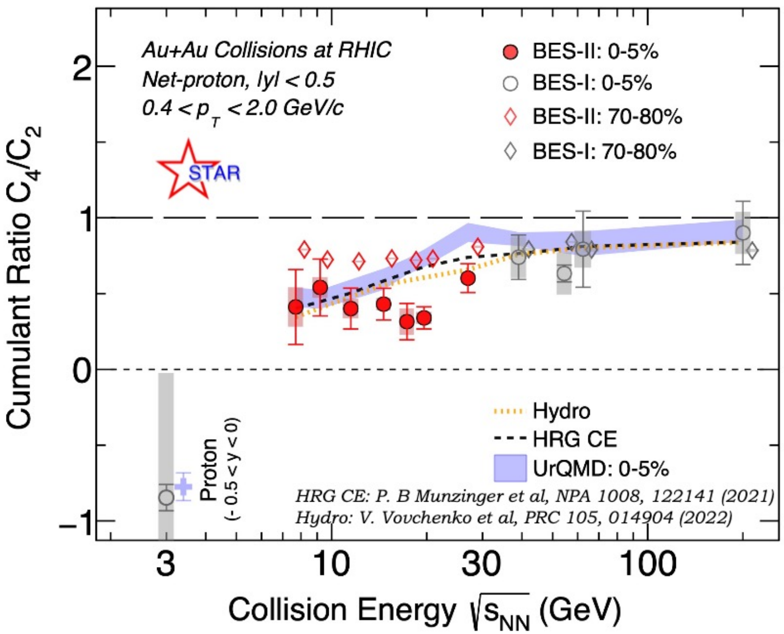




- Most central C_4/C_2 shows minimum around 20 GeV comparing to non-CP models and 70-80% collisions
  1) Maximum deviation: $3.2 - 4.7\sigma$ at 20 GeV ($1.3 - 2\sigma$ at BES-I)
  2) Overall deviation from $\sqrt{s_{NN}} = 7.7$ to 27 GeV: $1.9 - 5.4\sigma$ ($1.4 - 2.2\sigma$ at BES-I)

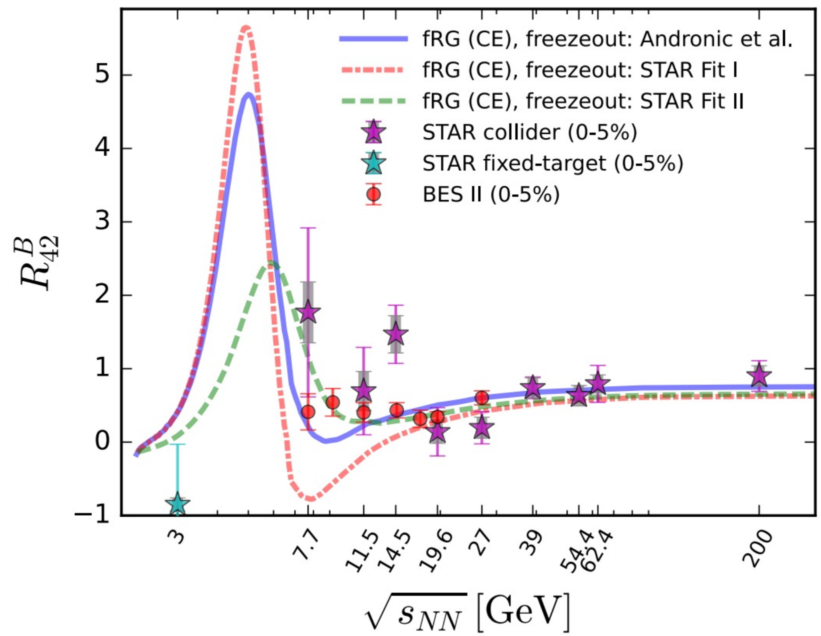
Continue the Critical Point Search

STAR Measurement：Au+Au 3-200 GeV



Wei-jie Fu, et al., arXiv : 2308.15508

FRG calculations :



STAR: PRL126, 92301(2021); PRC104, 024902 (2021)
PRL128, 202303(2022); PRC107, 024908 (2023)
HADES: PRC102, 024914(2020)

Two important things :

- Experimental Results between 3 – 4.5 GeV (STAR FXT)
- Precise dynamical modeling and non-CP baselines

Continue the Critical Point Search

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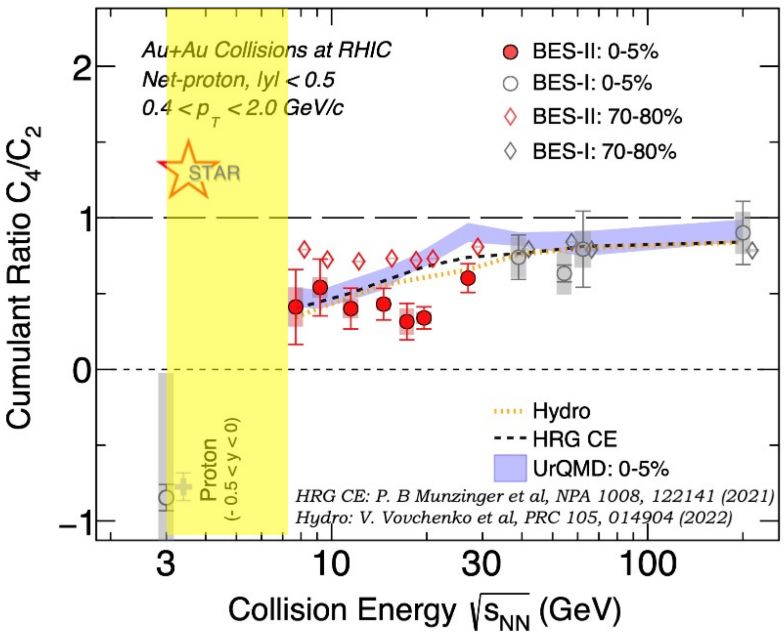
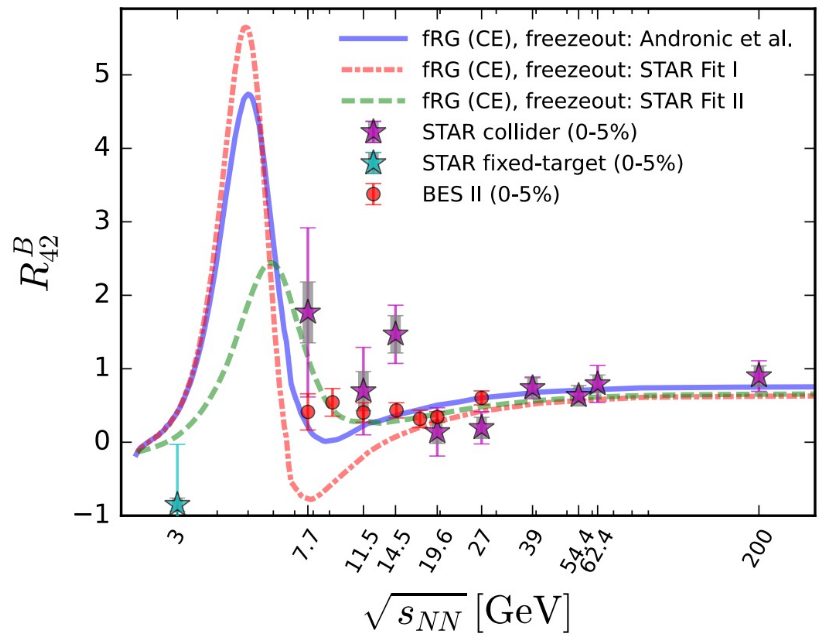


Wei-jie Fu, et al., arXiv : 2308.15508
FRG calculations : See Wei-jie Fu's talk



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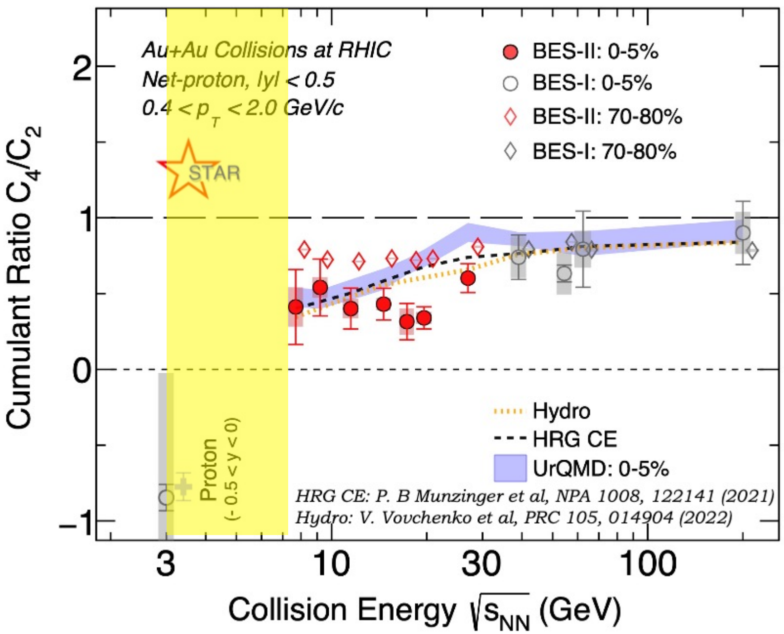

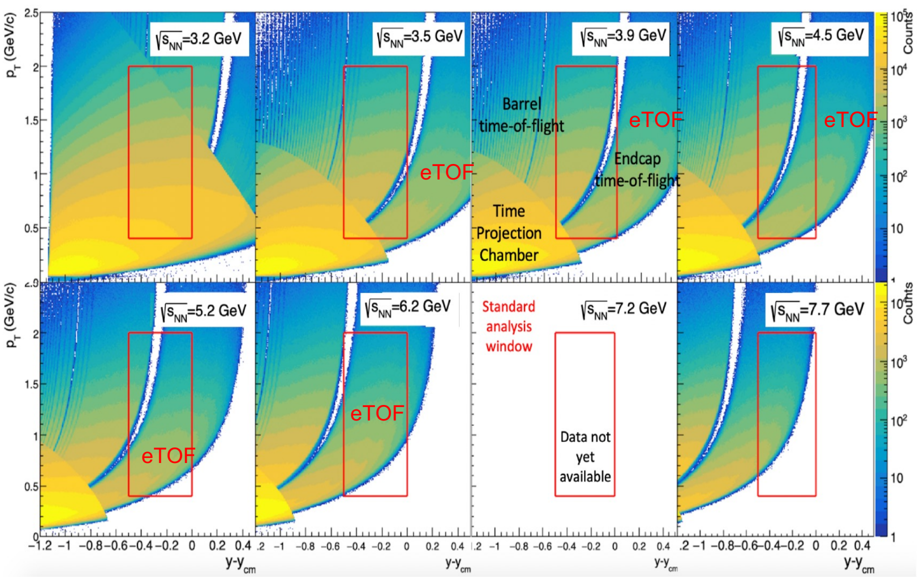

eTOF is crucial for mid-rapidity coverage at 3.5– 4.5 GeV

STAR: PRL126, 92301(2021); PRC104, 024902 (2021)
PRL128, 202303(2022); PRC107, 024908 (2023)
HADES: PRC102, 024914(2020)

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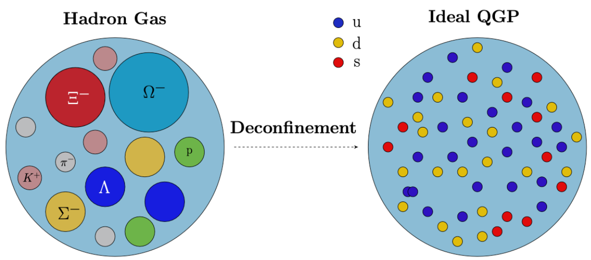
- Experimental Results between 3 – 4.5 GeV (STAR FXT)
- Precise dynamical modeling and non-CP baselines

Baryon-Strangeness Correlations : Theory



$$C_{BS} = -3\chi^{11}_{BS}/\chi^2_S = -3\frac{<BS> - <B><S>}{<S>^2}$$

➢ **Ideal QGP**: $B = \frac{1}{3}(u + d + s)$

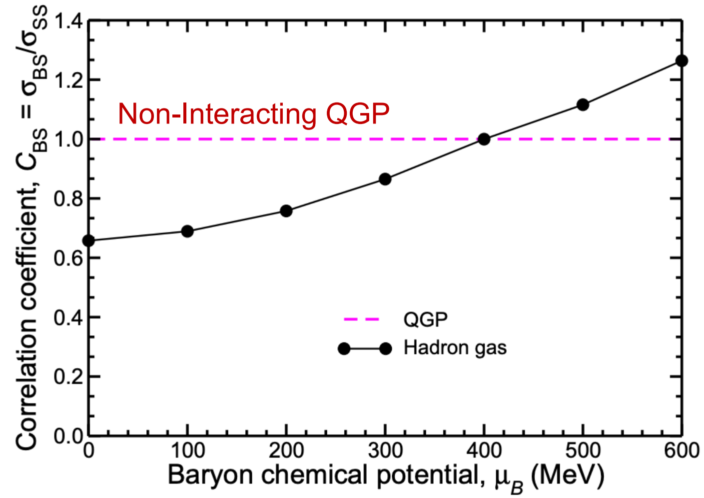
if quarks are uncorrelated

$\chi_{BS} = -\frac{1}{3}\chi_s^{\,2} \quad \rightarrow \quad C_{BS} = 1$

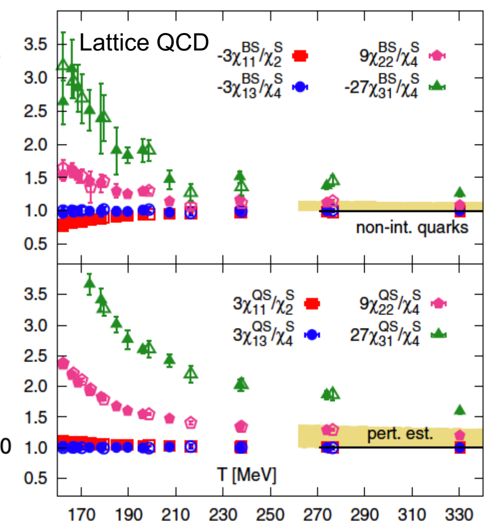
➢ **Hadronic Matter :**

Only include Lambda : $C_{BS} = 3$

Adding more strange meson make C_{BS} smaller



V. Koch, et al., PRL95, 182301 (2005).

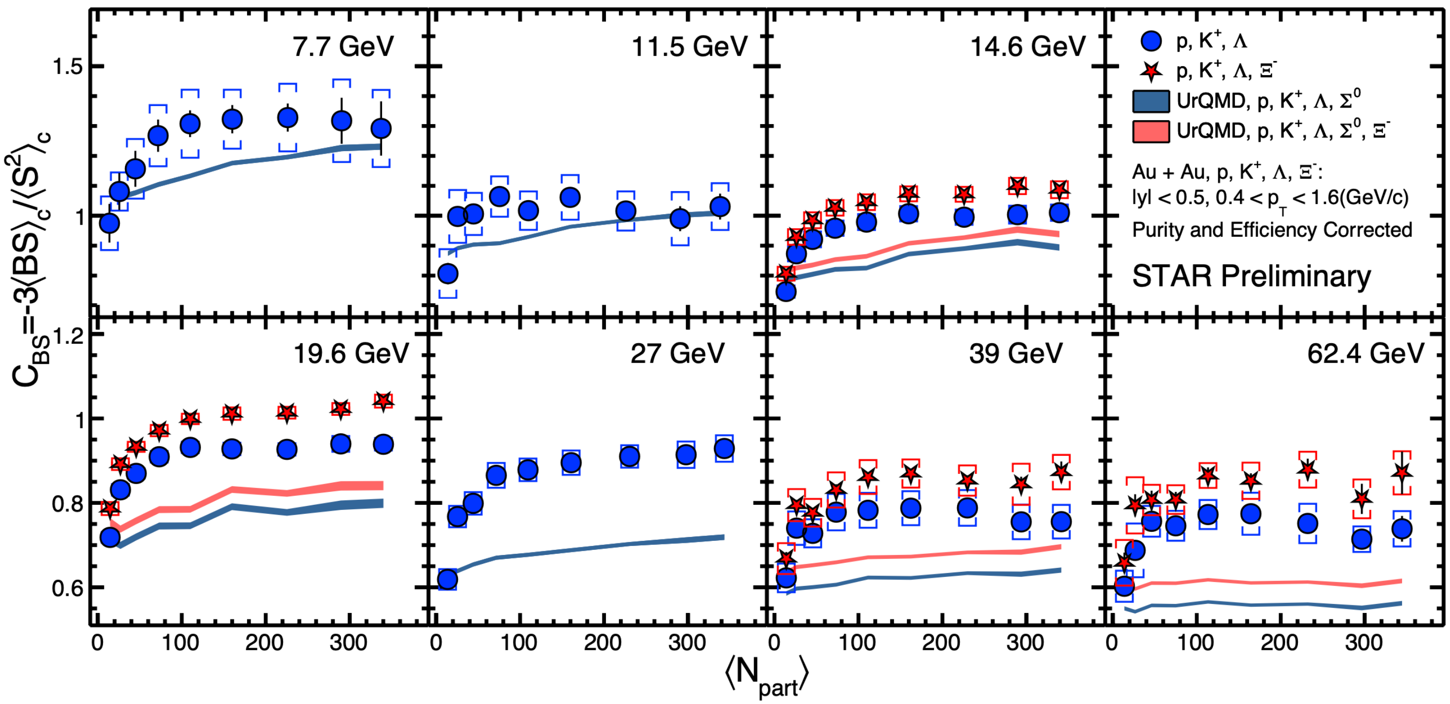


A. Bazavov, et al. (HotQCD) PRL 111, 082301 (2013).
H.-T. Ding, et al, EPJA 57,202 (2021)

➢ Sensitive to the degree of freedom of strongly interacting matter

➢ Used to search for the onset of deconfinement

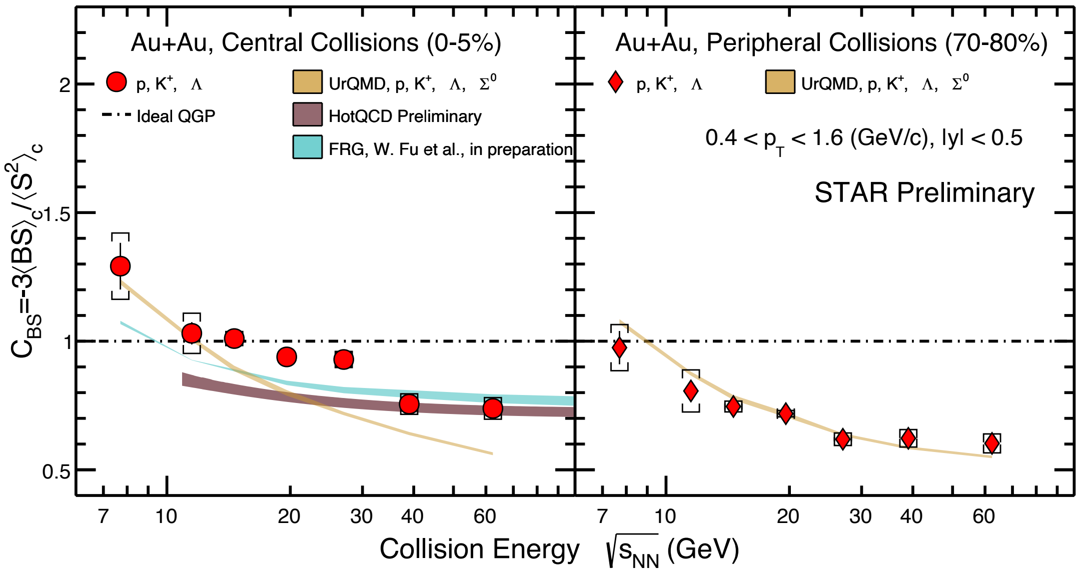
Centrality Dependence of C_{BS}

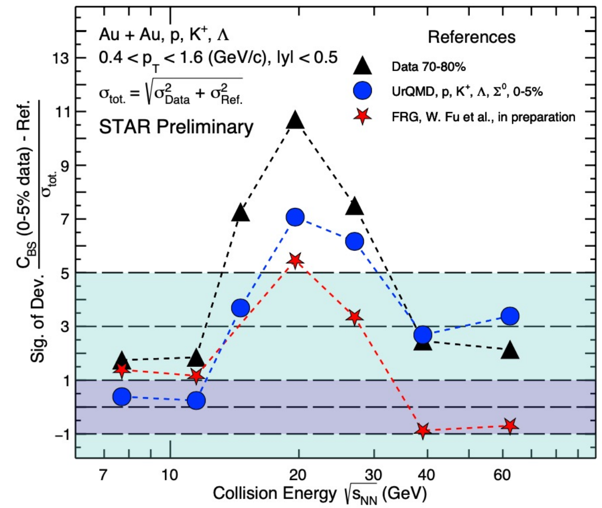


- Data of 14.6 and 19.6 GeV are from BES-II, other energies are from BES-I
- UrQMD can describe the centrality dependence of 7.7 GeV, 11.5 GeV, qualitatively and quantitatively, while it underestimates the higher energy.

STAR, CPOD2024

Energy Dependence of C_{BS} and Model Comparison



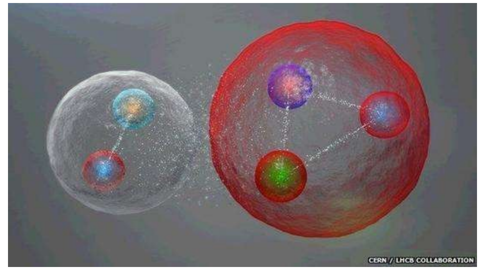


STAR, CPOD2024

- Peripheral collisions (70-80%) can be well described by UrQMD;
- For central collisions:
  1) At high energy is consistent with FRG and LQCD, 7.7 and 11.5 GeV are reproduced by UrQMD
  2) Largest deviation is found at 19.6 GeV, which is more than 5σ
- Analysis of BES-II data (both collider and FXT) are ongoing.

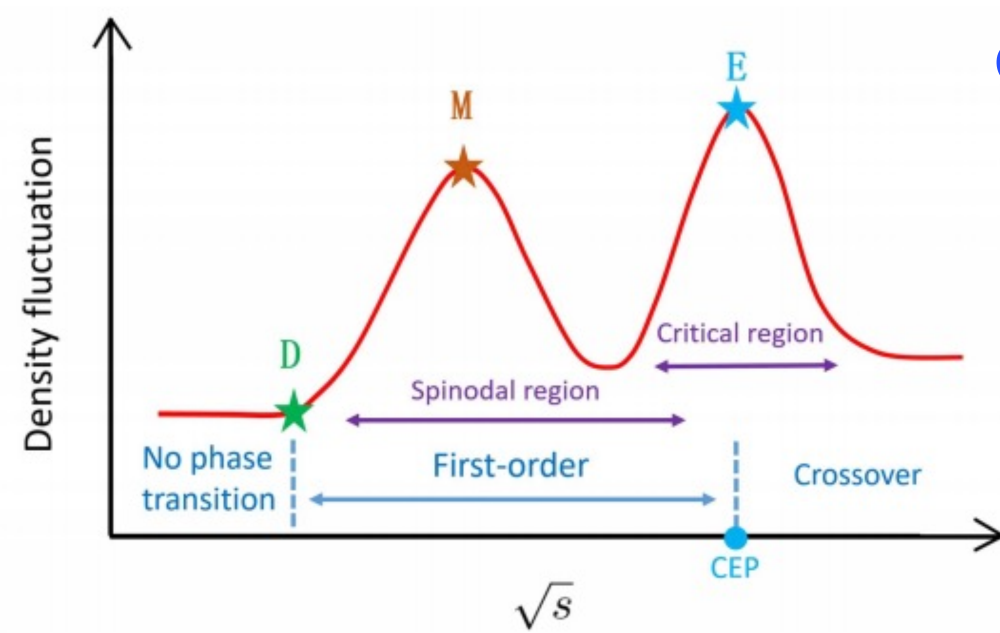
New Observable for CP: Light Nuclei Production

Near CP or 1st order phase transition, baryon



Light nuclei production

(Baryon Clustering)



Coalescence + nucleon density flu.

$$N_d = \frac{3}{2^{1/2}}\left(\frac{2\pi}{m_0 T_{\rm eff}}\right)^{3/2} N_p\langle n\rangle(1+\alpha\Delta n),$$

$$N_{^3H} = \frac{3^{3/2}}{4}\left(\frac{2\pi}{m_0 T_{\rm eff}}\right)^{3} N_p\langle n\rangle^2[1+(1+2\alpha)\Delta n],$$

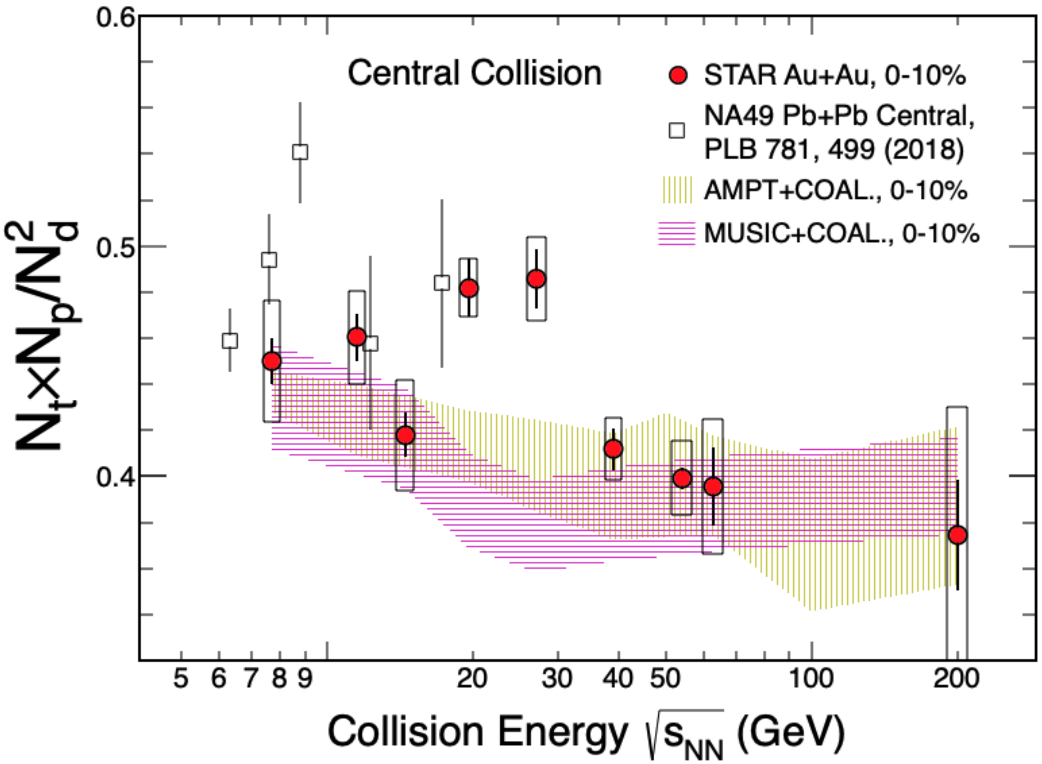
$$N_t \cdot N_p/N_d^2 \approx g(1+\Delta n)$$

Neutron density fluctuations:

$$\Delta n = \langle(\delta n)^2\rangle/\langle n\rangle^2$$

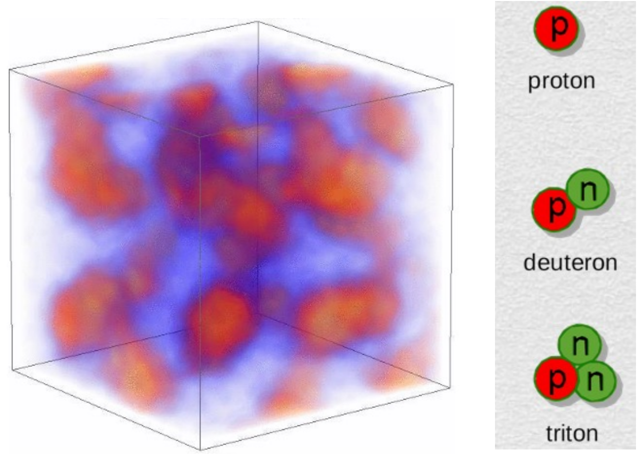
K. J. Sun, L. W. Chen, C. M. Ko, Z. Xu, Phys. Lett. B774, 103 (2017).
K. J. Sun, L. W. Chen, C. M. Ko, J. Pu, Z. Xu, Phys. Lett. B781, 499 (2018).
Edward Shuryak and Juan M. Torres-Rincon, arXiv:1805.04444

STAR金金碰撞能量扫描中轻核的产额比测量



STAR: PRL130, 202301 (2023)

中子密度涨落：$\Delta n = \langle (\delta n)^2 \rangle / \langle n \rangle^2$



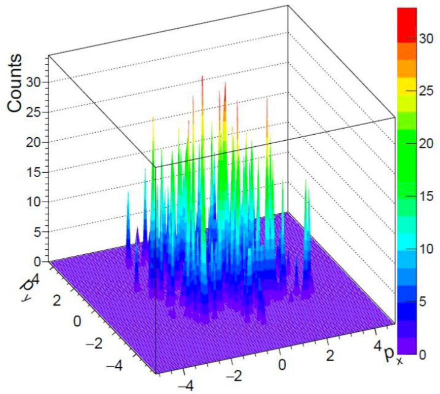
$$N_t \cdot N_p / N_d^2 \approx g(1 + \Delta n)$$

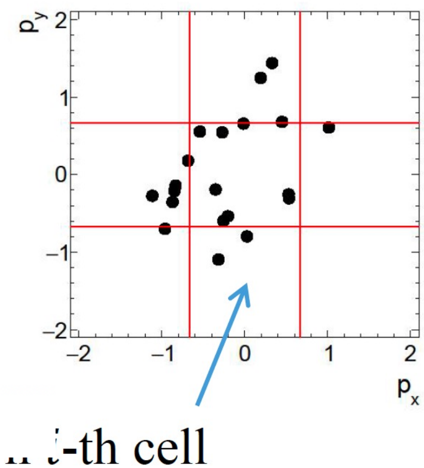
g=0.29

- Non-monotonic behavior observed in 0-10% central Au+Au collisions around 19.6 and 27 GeV with 4.1σ significance (combined) deviated from coalescence baseline.

- 首次对RHIC金金碰撞能量扫描中氚核产额进行测量
- 轻核产额比随碰撞能量显示出非单调能量依赖，对QCD临界点的寻找提供了重要实验依据

STAR金金碰撞能量扫描中带电粒子间歇的测量





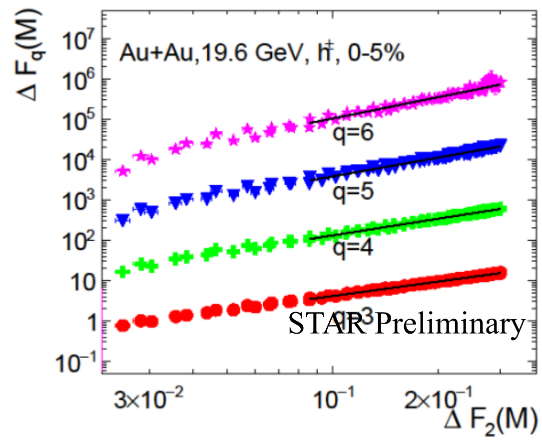
$$F_q(M) = \frac{<\frac{1}{M^D}\sum_{i=1}^{M^D} n_i(n_i-1)\dots(n_i-q+1)>}{<\frac{1}{M^D}\sum_{i=1}^{M^D} n_i>^q}$$

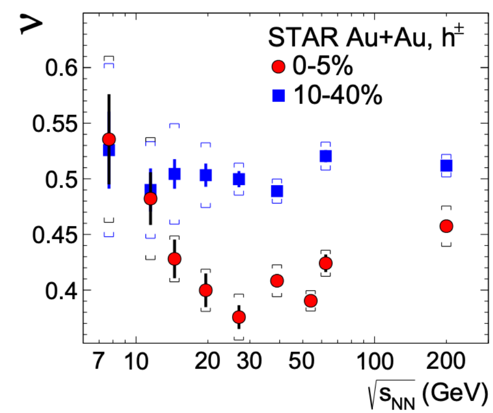
$$\Delta F_q(M) = F_q^{data}(M) - F_q^{mix}(M)$$

$$\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q}$$

$$\beta_q \propto (q-1)^{\nu}$$

Local density fluctuations near the QCD critical point can be probed via intermittency analysis in transverse momentum through the measurement of scaled factorial moments





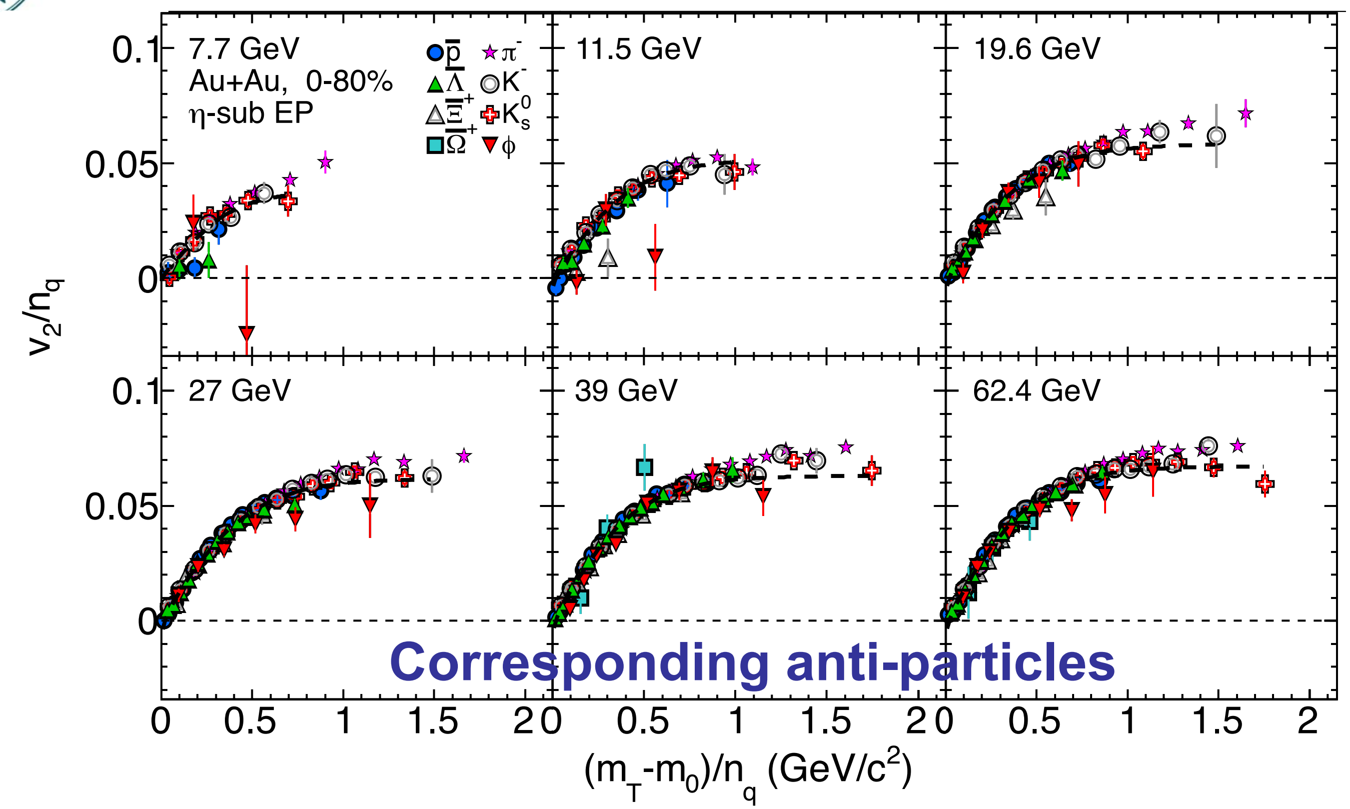
主要完成人：吴锦、林裕富、李治明、罗晓峰

Jin Wu (for STAR), ISMD 2021

STAR, PLB 845, 138165 (2023)

- STAR 实验中对 Au + Au 碰撞的间歇的首次观测，对寻找QCD临界点提供参考
- 中心碰撞下v的能量依赖显示出非单调行为，并且在$\sqrt{s_{NN}}$=20-27 GeV范围内显示出最小值

NCQ Scaling Test BES I



Dong, S.S. Shi, J. Zhao Phys. 110 301 (2013);

- Universal trend for most of particles and the corresponding anti-particles
- ϕ meson v_2 deviates from other particles ~ 2σ at the highest p_T data in 7.7 and 11.5 GeV collisions

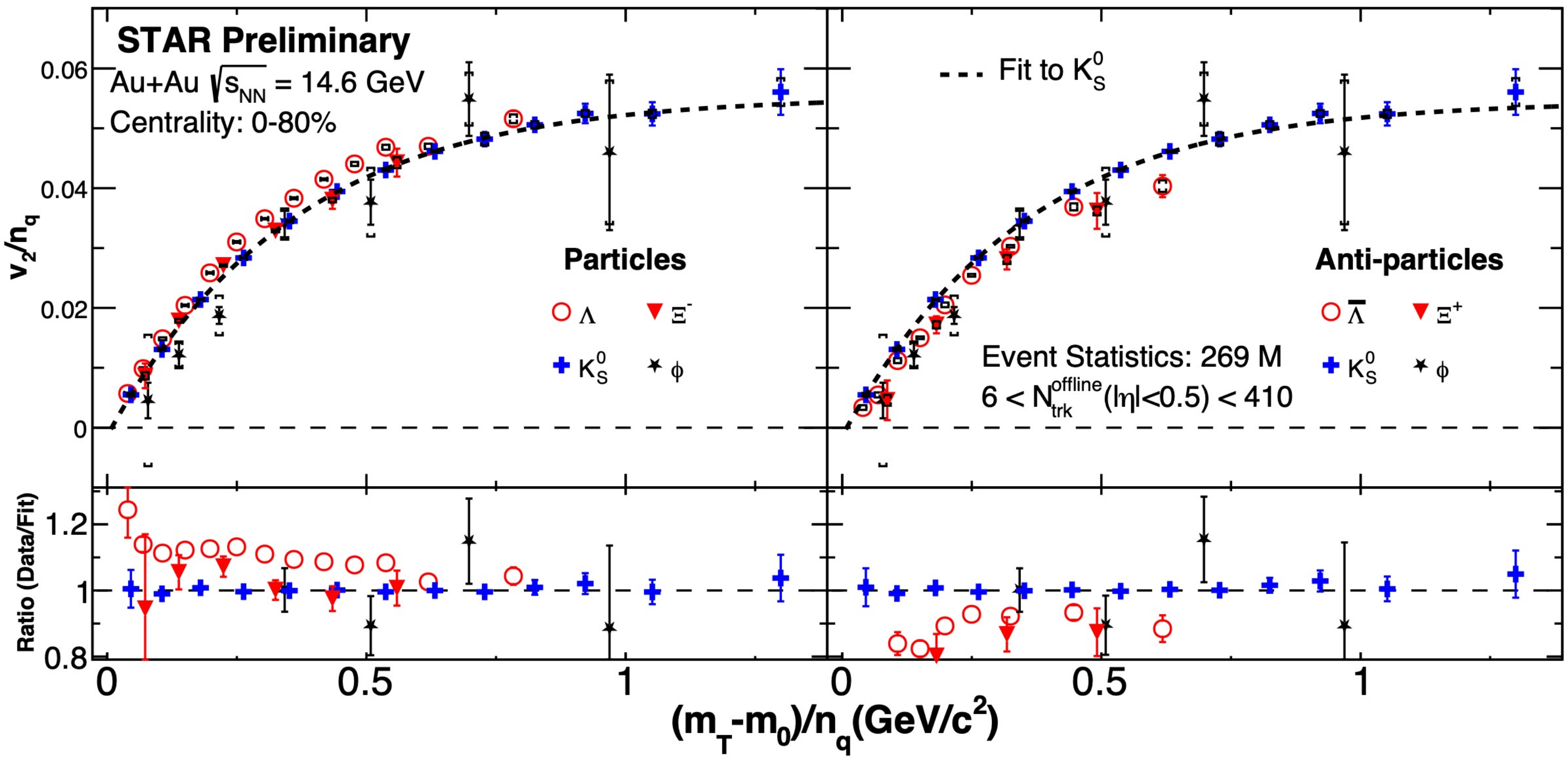
Hadronic interactions are more important at lower energies ?

More data for 7.7 and 11.5 GeV are needed for clear conclusion

Small or zero v_2 for ϕ meson -> without formation of partonic matter

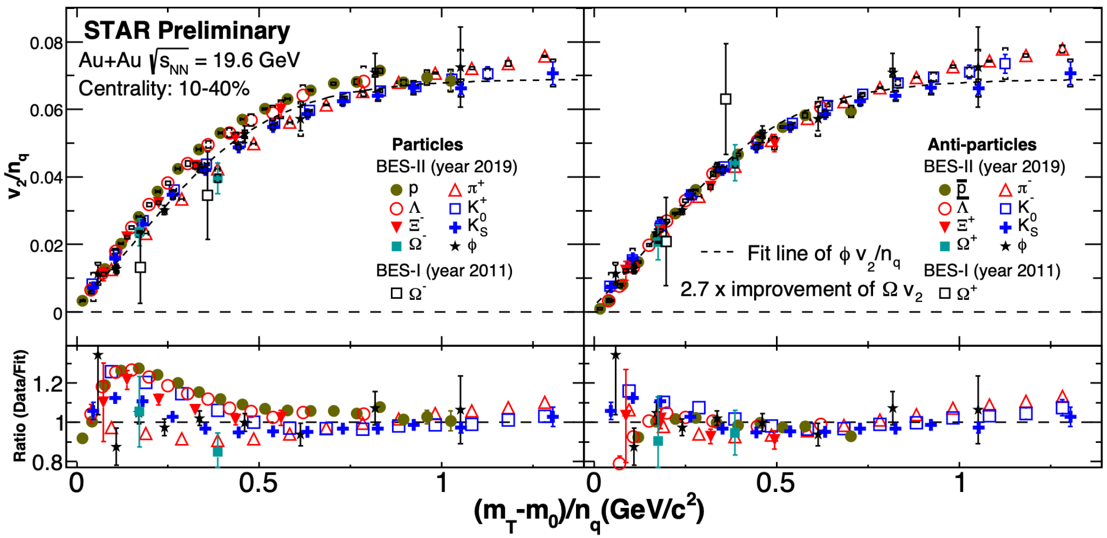
Ref: B. Mohanty and N. Xu: J. Phys. G 36, 064022(2009)

BESII v_2: 14.6 GeV

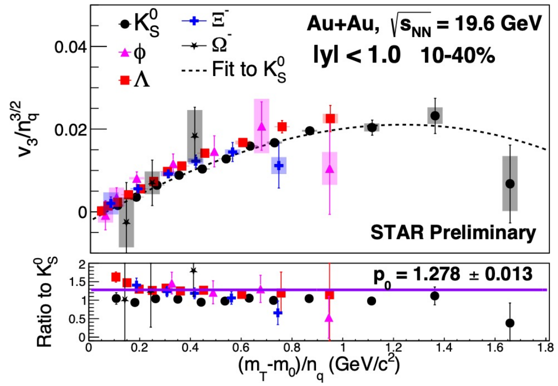


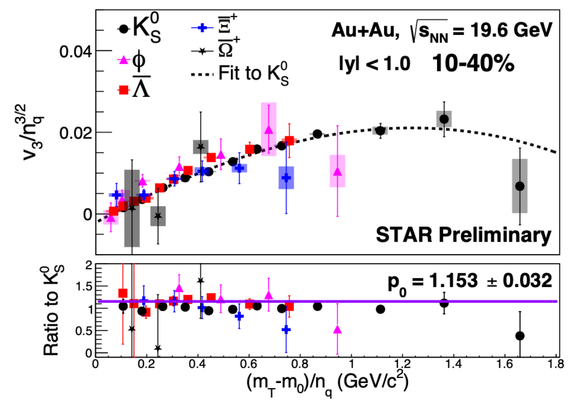
➢ The NCQ scaling holds within at 20% level

BESII v_2: 19.6 GeV



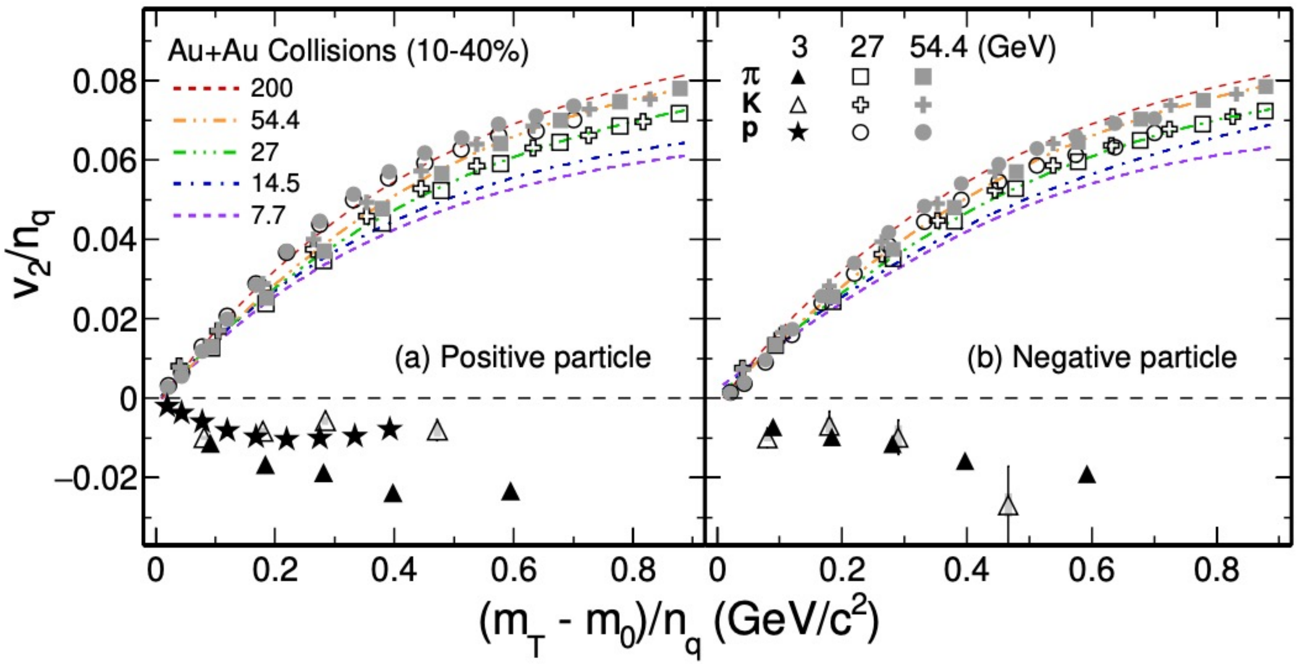
STAR 刘利珂: SQM2022





- The NCQ scaling holds within 20% for particles and within 10% for anti-particles
- The NCQ scaling of anti-particles better than particles: produced vs. transported quarks

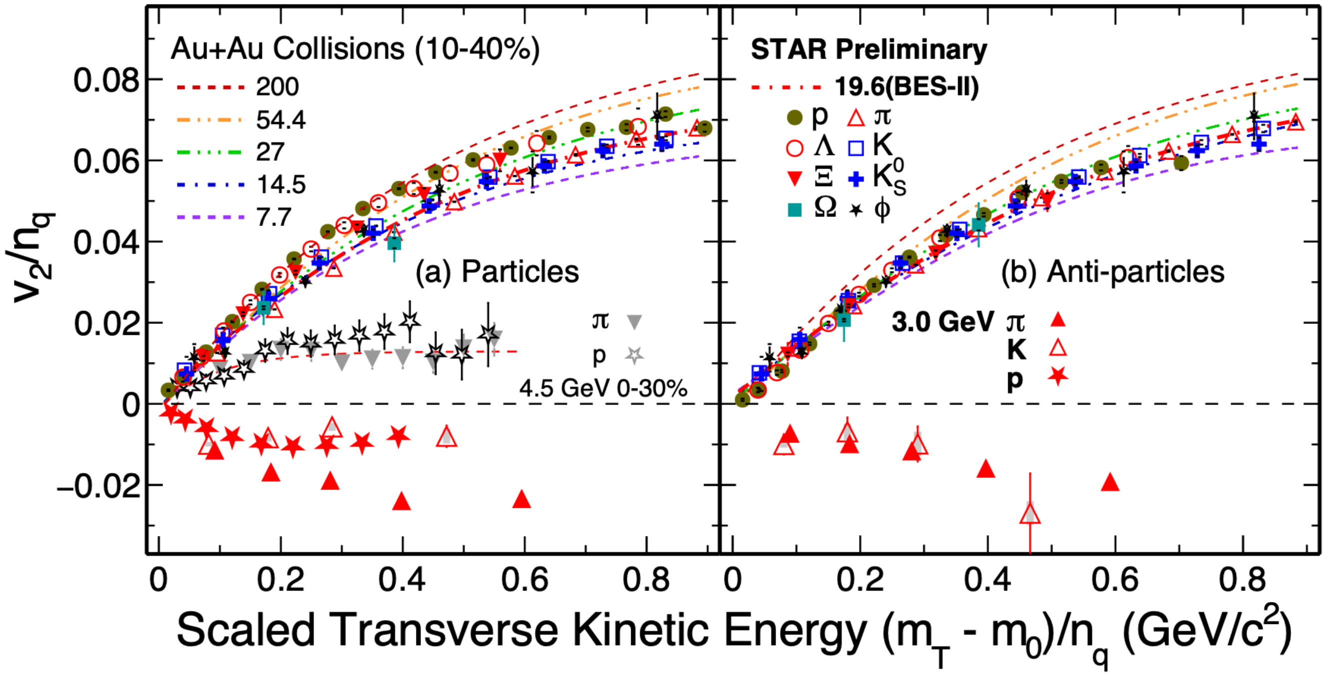
NCQ Scaling at 3 GeV



- At 3 GeV, the measured v_2 for all particles are negative and NCQ scaling is absent, especially for positive charged particles

STAR: Phys. Rev. C 88 (2013) 14902; Phys. Lett. B 827 (2022) 137003
X. Dong et al. Phys. Lett. B 597 (2004) 328-332

NCQ Scaling at 3 GeV

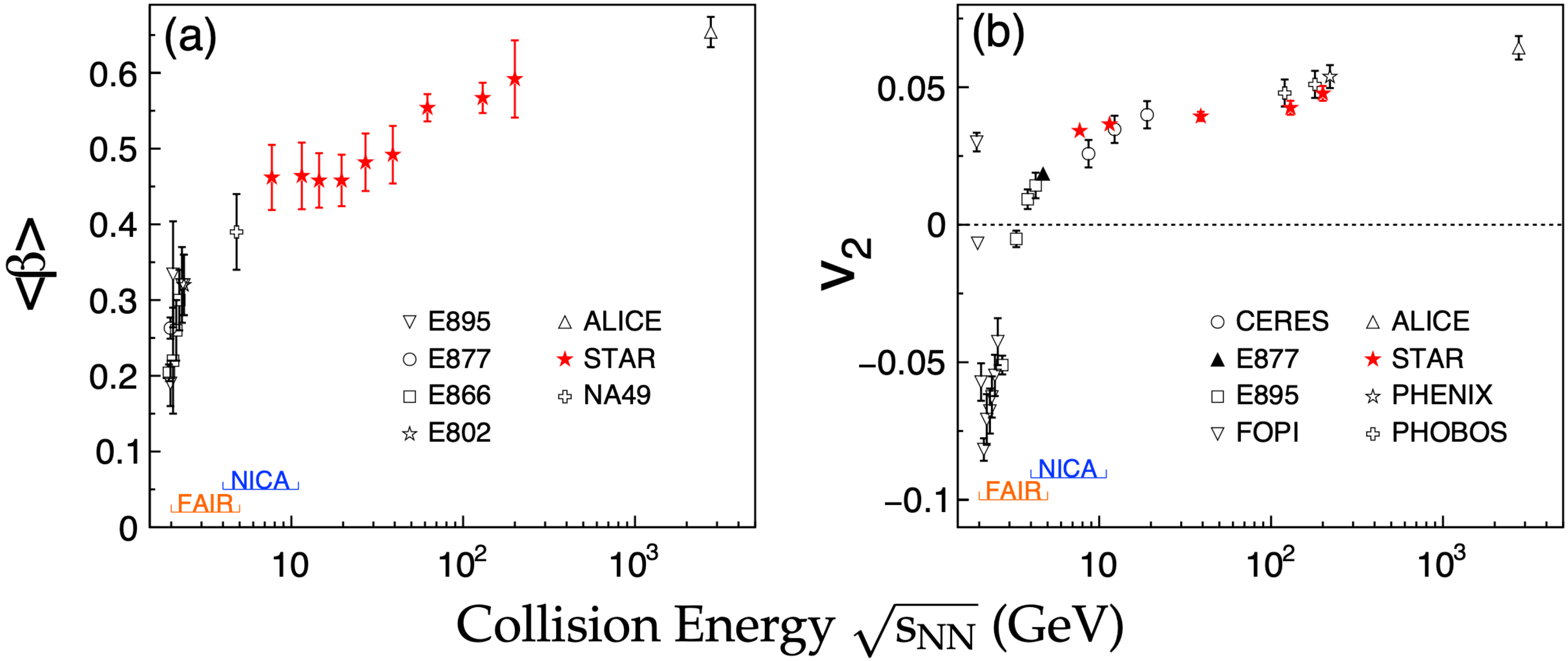


STAR: Phys. Lett. B 827 (2022) 137003 兰少位，施梳苏等

- The number of constituent quark (NCQ) scaling for v_2 holds down to 4.5 GeV, consistent with the nature of partonic collectivity
- At 3 GeV, the measured v_2 for all particles are negative and NCQ scaling is absent, especially for positive charged particles

STAR: Phys. Rev. C 88 (2013) 14902; Phys. Lett. B 827 (2022) 137003
X. Dong et al. Phys. Lett. B 597 (2004) 328-332

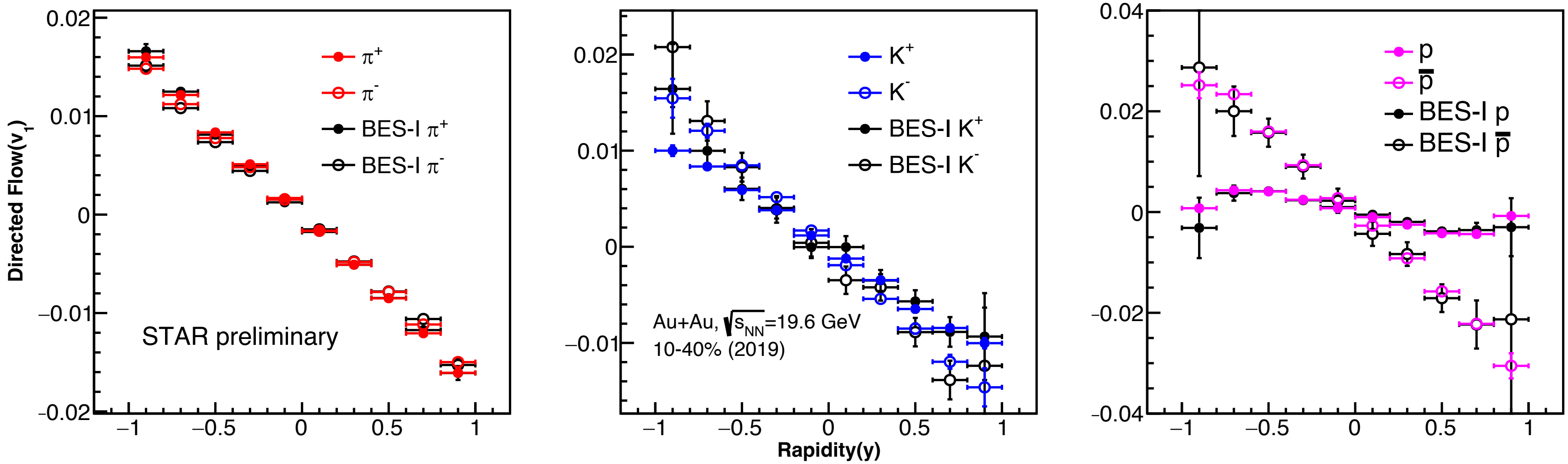
v_0/v_2: Softest Point

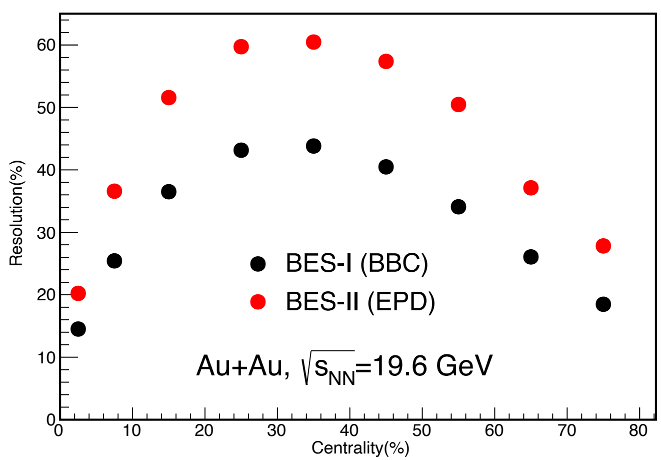


- A non-monotonic variation could be observed around the so-called "softest point of EOS"

P. F. Kolb, J. Sollfrank and U. Heinz, Phys. Rev. C 62, 054909 (2000).
H. Sorge, Phys. Rev. Lett. 82, 2048 (1999).

BESII v_1: 19.6 GeV



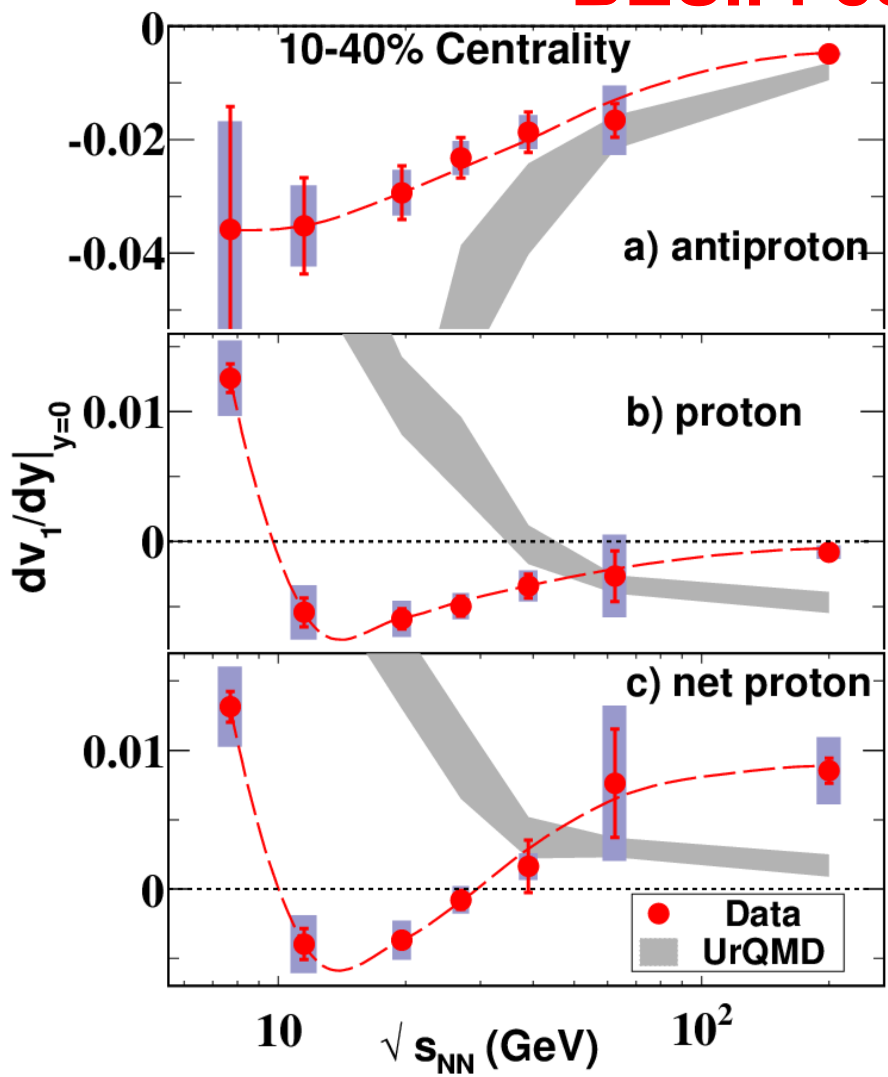


STAR 刘佐文: SQM2022, ISMD2022

- Resolution improved about 50% comparing to BES-I
- The statistical uncertainties reduced by a factor 8 comparing to BES-I results.

Directed Flow v_1: Softest Point

BESII : centrality dependence



dv_1/dy：中心快度区定向流对快度的斜率

- 流体力学计算认为极小值与一阶相变密切相关
- 净质子的斜率二次变号
  EOS softest point?
- UrQMD 与数据不符

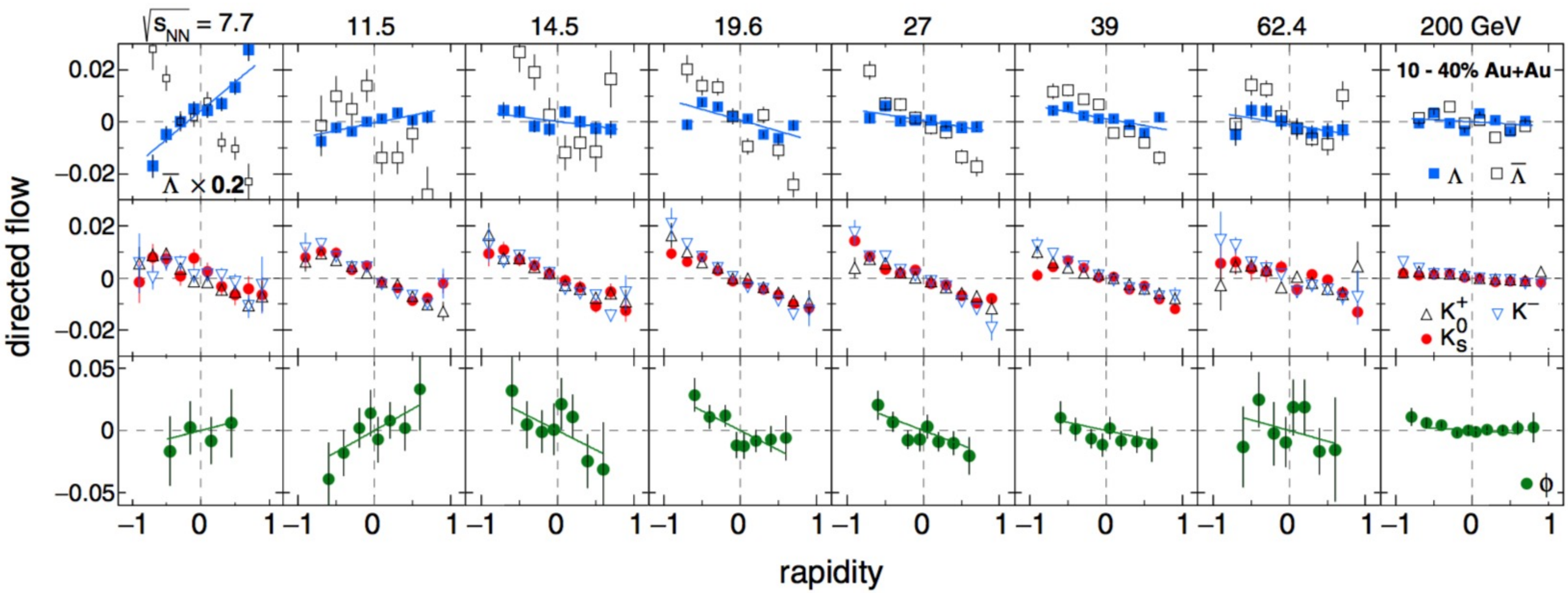
净质子的斜率为

$$[v_1(y)]_p = r(y)[v_1(y)]_{\bar{p}} + [1 - r(y)][v_1(y)]_{\text{net-}p}$$

r: 反质子与质子比.

STAR: Phys. Rev. Lett. 112, 162301(2014)
H. Stoecker, Nucl. Phys. A 750, 121(2005)

Directed Flow v_1: ϕ Mesons

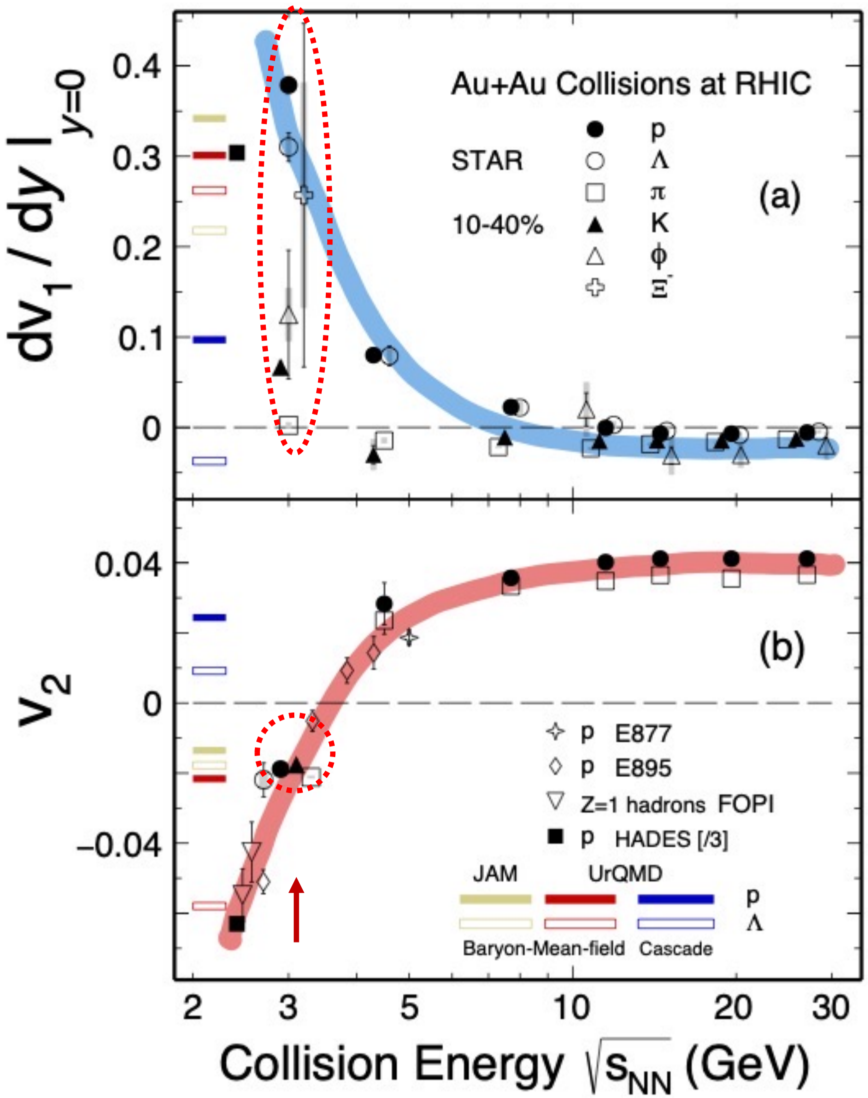


➢ Mesons and all produced baryons show negative slope except ϕ mesons when collisions energy < 14.5 GeV

Change of medium property? High precision data needed: BESII

STAR: Phys. Rev. Lett. **120**, 062301(2018)

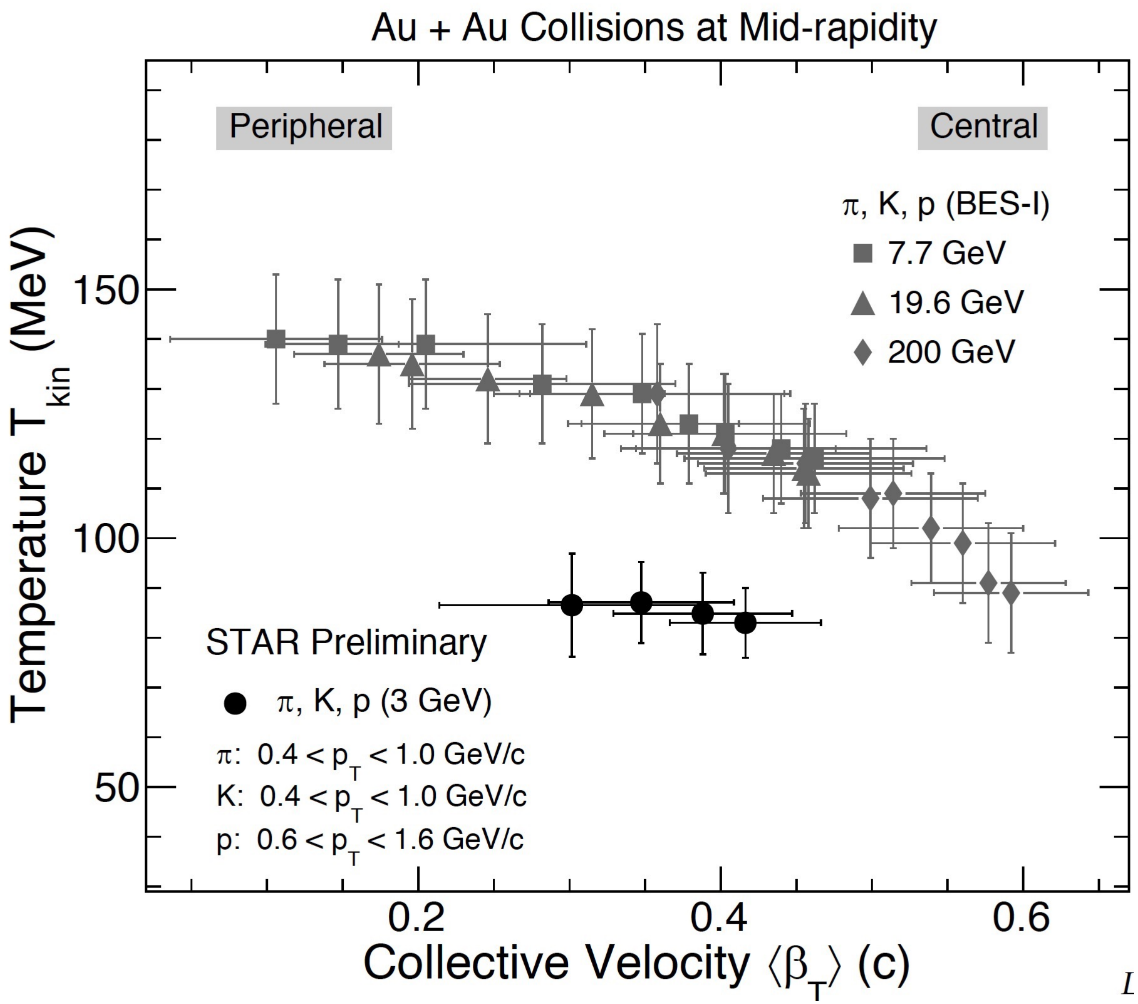
v_1 Slope and v_2 vs. Energy



- The v_1 slopes ($dv_1/dy|_{y=0}$) of baryons at 3 GeV are positive and larger than those of mesons
- For the first time, kaon and ϕ v_1 slopes are found to be positive at 3 GeV
- Opposite collective behavior to high energy results
- The results from UrQMD with baryonic mean-field potential qualitatively describe data at 3 GeV

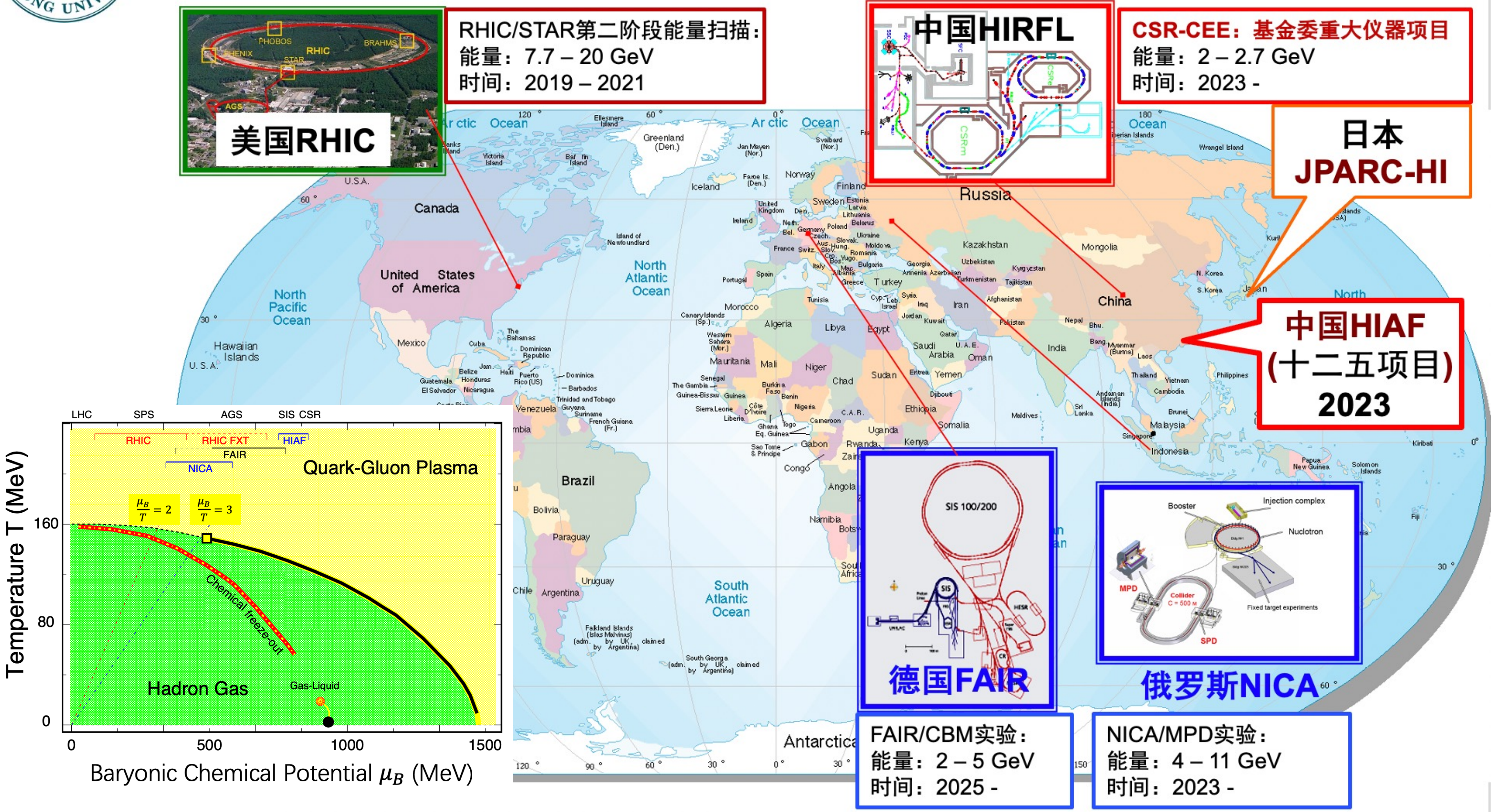
EoS dominated by the baryonic interactions at 3 GeV

3 GeV 动力学冻结温度



暗示3GeV所产生的热密核物质与高能量相比具有不同的状态方程

未来高重子密度区重离子碰撞实验

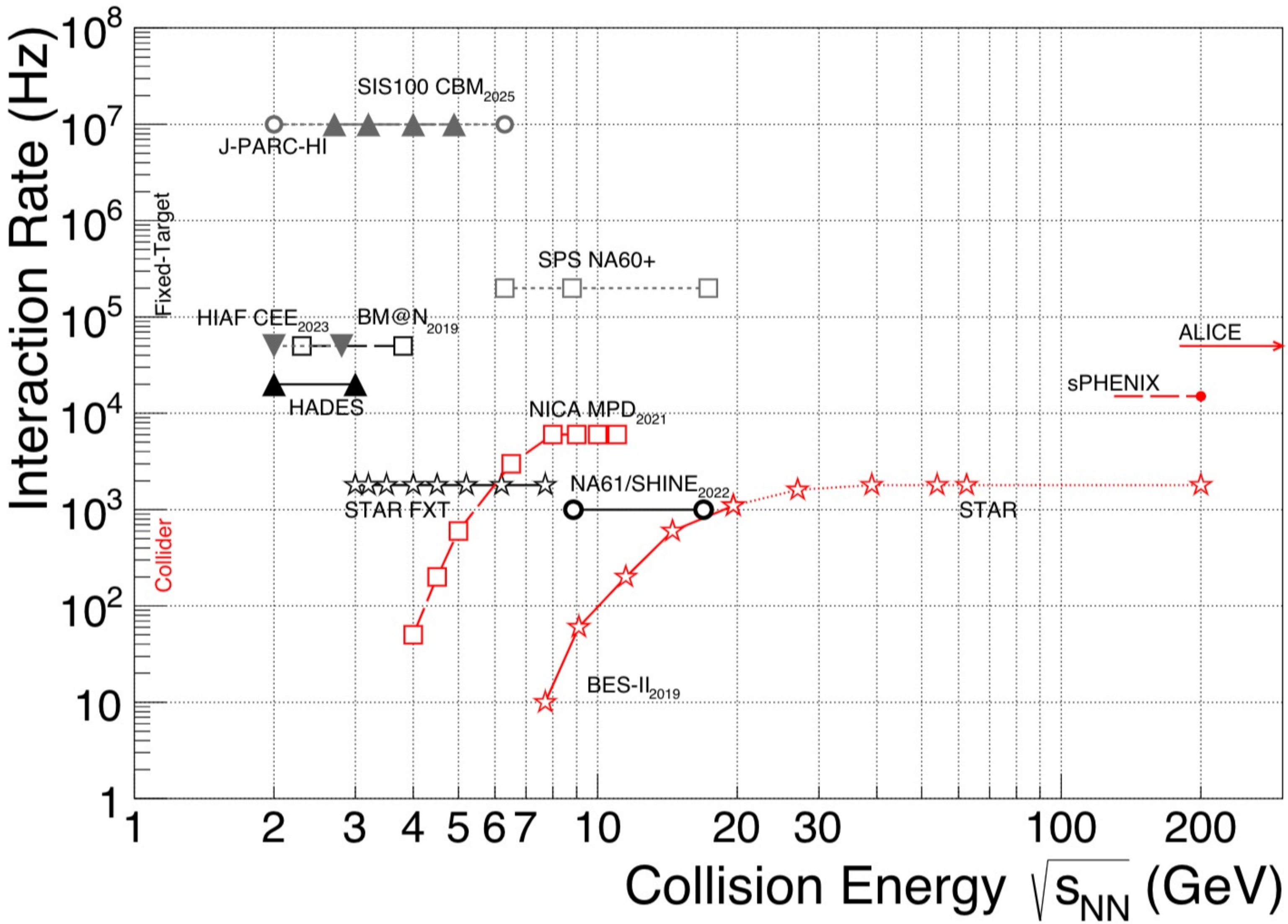


Explore the QCD phase structure at high baryon density with high precision:

(1) RHIC BES-II : Collider ($\sqrt{s_{NN}}$ =7.7 - 19.6 GeV) and FXT ($\sqrt{s_{NN}}$ = 3 - 7.7 GeV) mode.

(2) Future Facilities ($\sqrt{s_{NN}}$ =2 - 11 GeV) : FAIR/CBM, NICA/MPD, HIAF/CEE, JPARC-HI.

未来高重子密度区重离子碰撞实验



Stay tune for exciting physics at high baryon density !!

Facility for Antiproton and Ion Research: FAIR

FAIR计划2028年出束流？，耗资～€15亿

初级束流

10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$

10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u

3×10^{13}/s 30 GeV protons

次级束流

range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 higher in intensity than presently

antiprotons 3 - 30 GeV

冷却储存环

radioactive beams

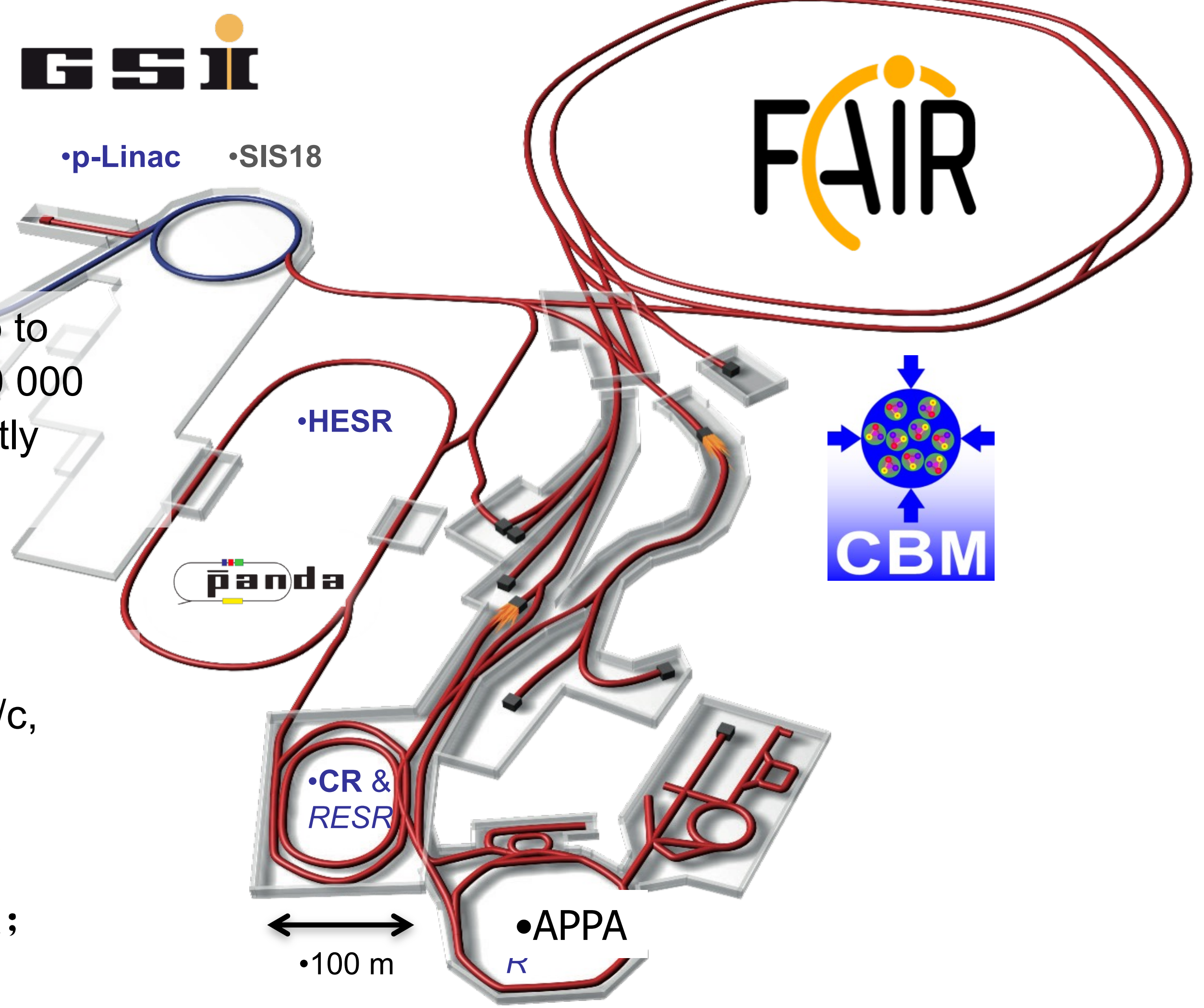
10^{11} antiprotons 1.5 - 15 GeV/c, stored and cooled

(1) 最新高科技加速器群

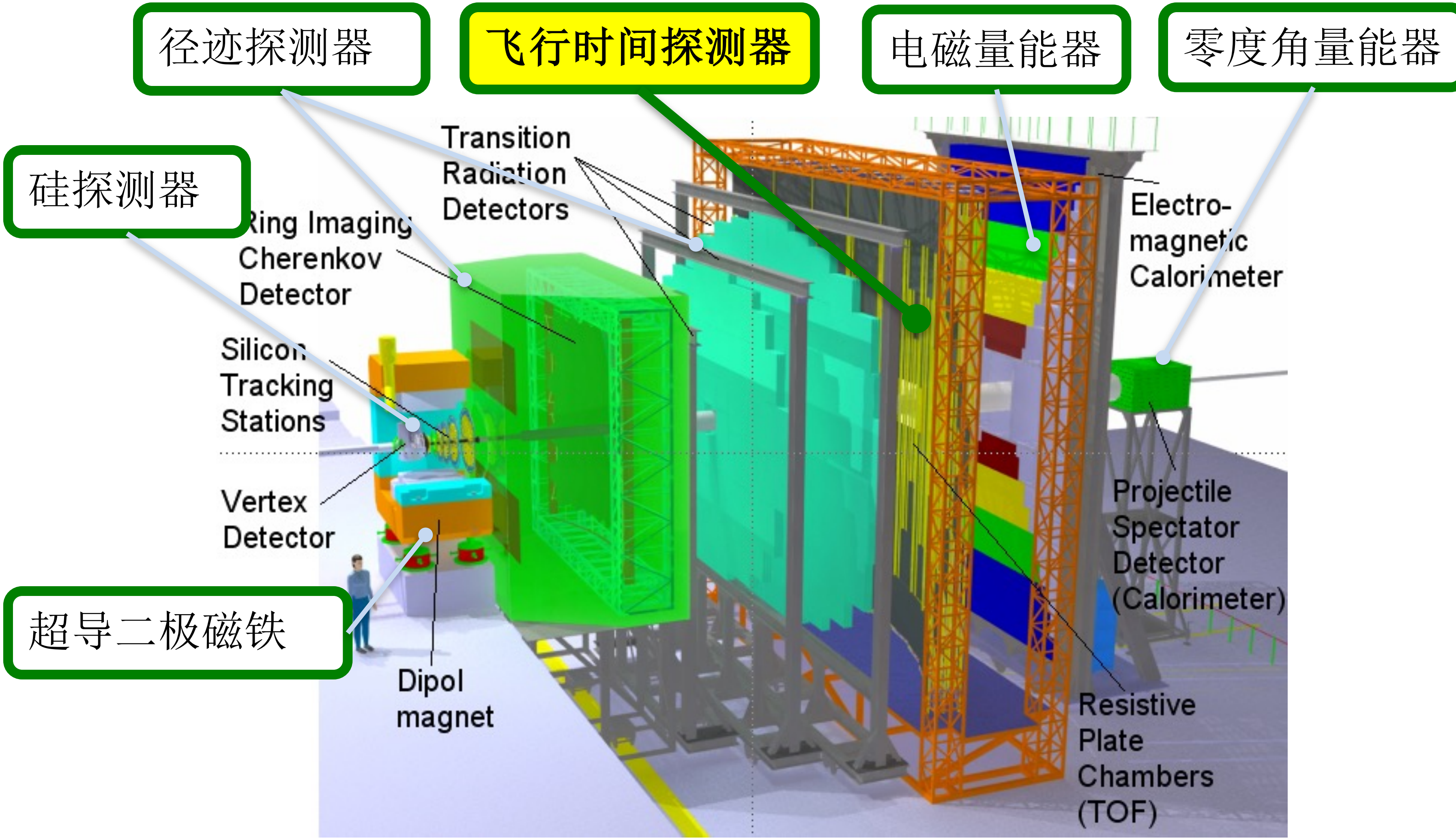
(2) 强子物理；天体物理；

放射性束流物理；

高重子密度物理(CBM)



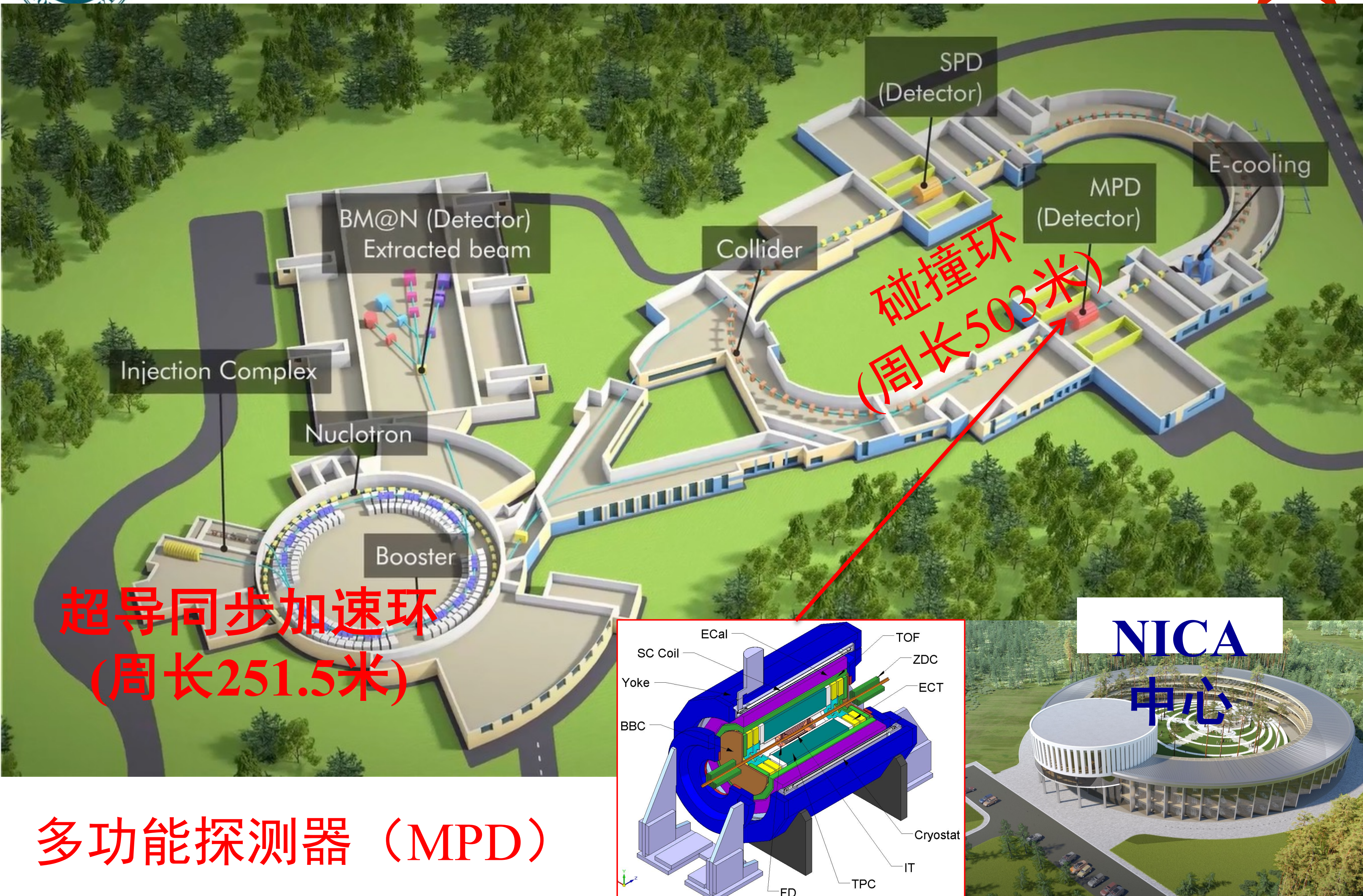
The Compressed Baryonic Matter Experiment: CBM



1） FAIR将是未来20年亮度最高的加速器群，$\sqrt{s_{NN}}\leq 12$ GeV，2018出束

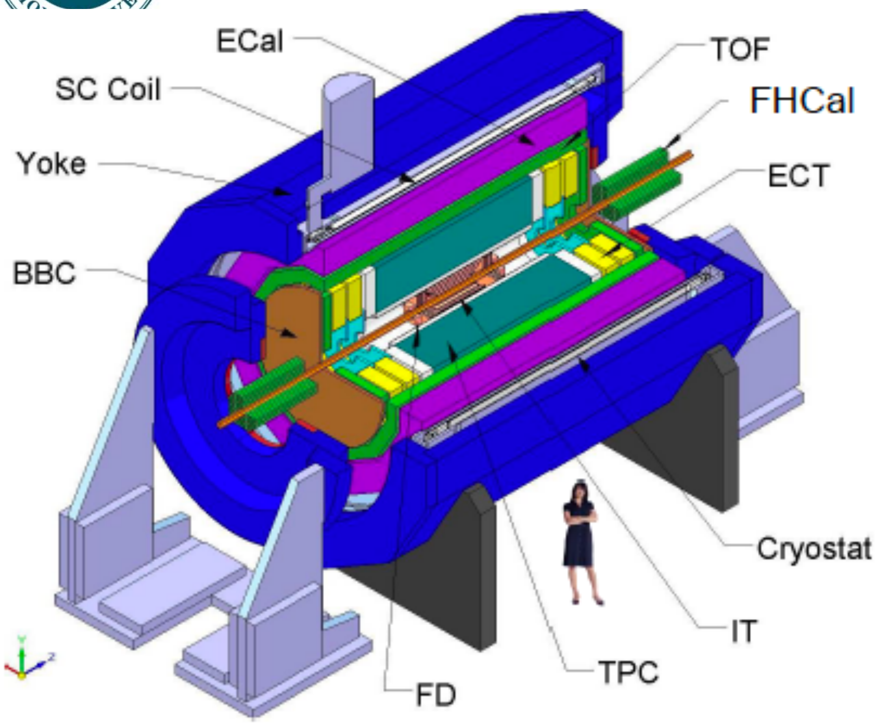
2） CBM将采用中国组研制的**高计数率**和**高时间精度**飞行时间探测器（TOF）

重离子超导同步加速器（NICA）



多功能探测器（MPD）

NICA/MPD实验国际合作组

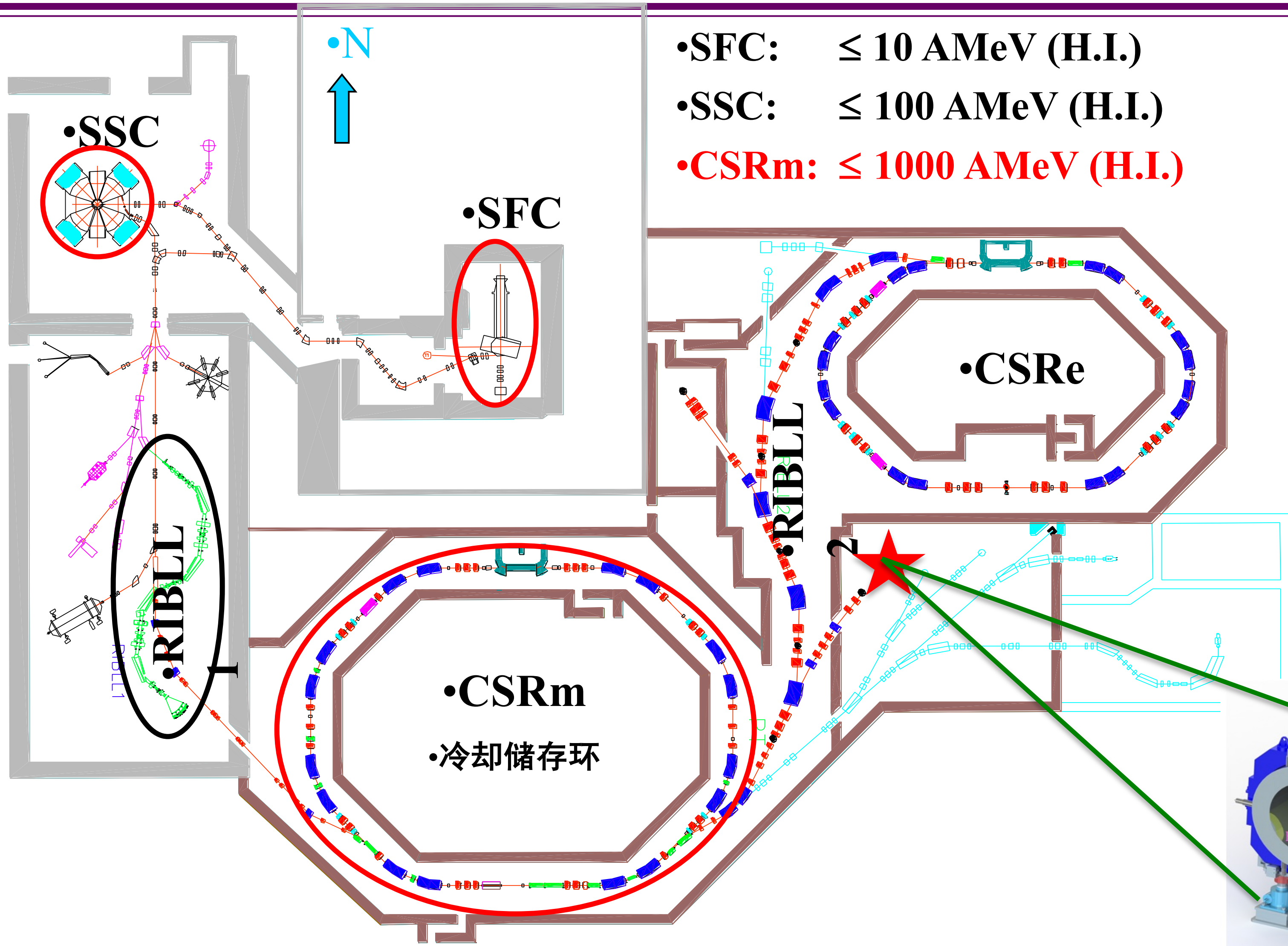


*IHEP, Beijing, **China**;*
*University of South China, **China**;*
*Palacky University, Olomouc, **Czech Republic**;*
*NPI CAS, Rez, **Czech Republic**;*
*Tbilisi State University, Tbilisi, **Georgia**;*
*Tubingen University, Tubingen, **Germany**;*
*Tel Aviv University, Tel Aviv, **Israel**;*
Joint Institute for Nuclear Research;
*IPT, Almaty, **Kazakhstan**;*
*UNAM, Mexico City, **Mexico**;*
*Institute of Applied Physics, Chisinev, **Moldova**;*
*WUT, Warsaw, **Poland**;*
*NCN, Otwock – Swierk, **Poland**;*
*UW, Wroclaw, **Poland**;*
*Jan Kochanowski University, Kielce, **Poland**;*
*INR RAS, Moscow, **Russia**;*
*MEPhI, Moscow, **Russia**;*
*PNPI, Gatchina, **Russia**;*
*INP MSU, Moscow, **Russia**;*
*SPSU - Dept. of NP, **Russia;***
*St. Petersburg, **Russia**;*
*SPSU – Dept. of HEP, St. Petersburg, **Russia**;*
*KI NRS, Moscow, **Russia**;*

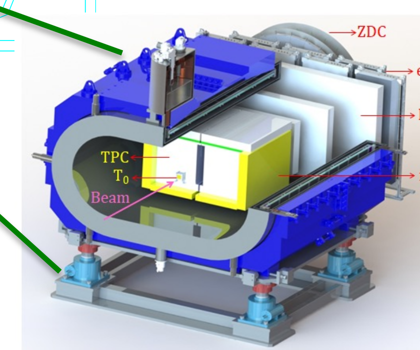
*Baku State University, NNRC, **Azerbaijan**;*
*University of Plovdiv, **Bulgaria;***
*University Tecnica Federico Santa Maria, Valparaiso, **Chili**;*
*Tsinghua University, Beijing, **China**;*
*USTC, Hefei, **China**;*
*Huizhou University, Huizhou, **China**;*
*Institute of Nuclear and Applied Physics, CAS, Shanghai, **China**;*
*Central China Normal University, **China**;*
*Shandong University, Shandong, **China**;*

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.)

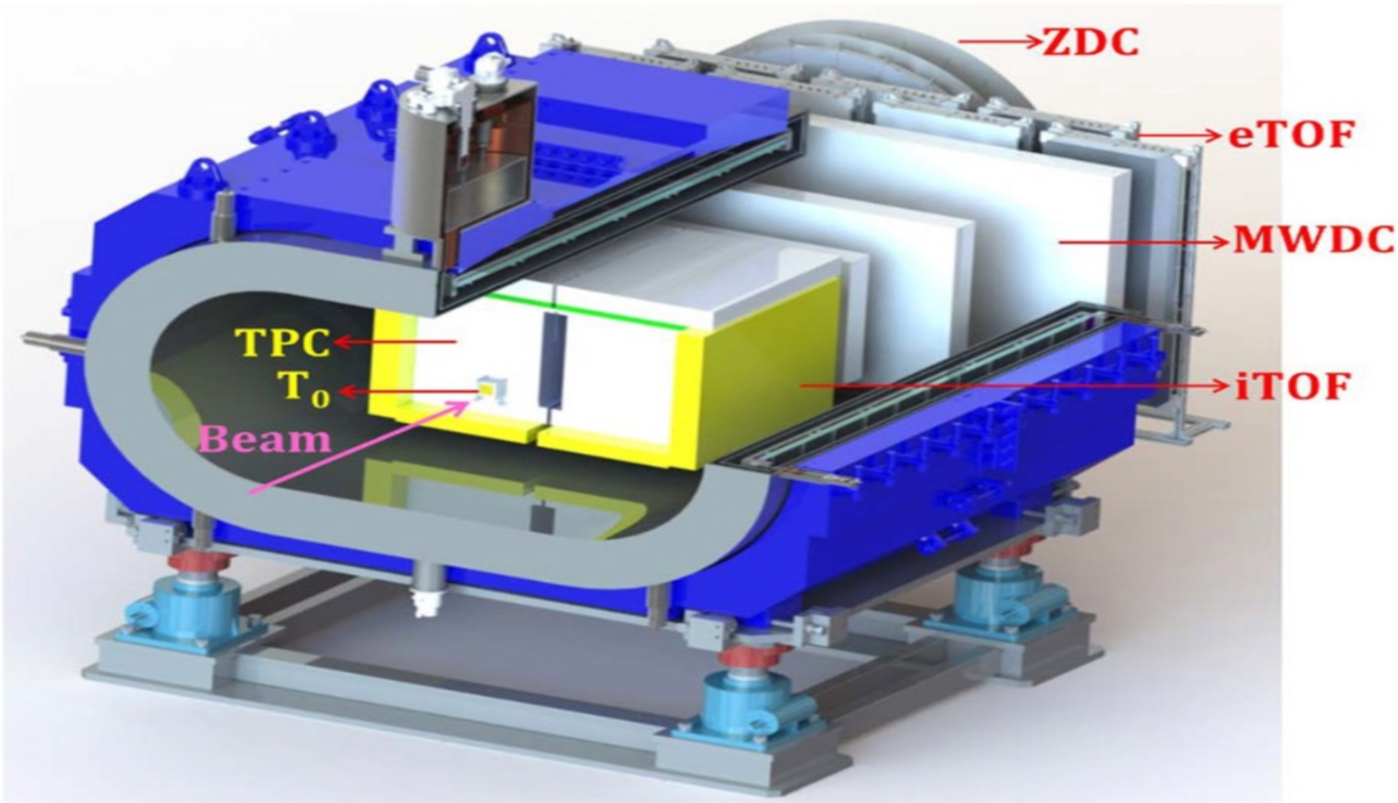


•外靶实验
•装置(CEE)



•兰州重离子加速器上CEE的研制

•低温高密核物质测量谱仪（CEE）



- 完成物理目标对仪器的要求
- 1) 精确的束流定位　　2)高精度的位置测量
- 3)良好的粒子分辨　　4) 新型数据获取系统
- 5) 大接收度超导二极磁铁

Summary IV

- 200 GeV碰撞质心能量净质子数的六阶涨落实验结果暗示低重子密度区强子物质相到夸克胶子等离子体相为平滑穿越。
- 中心碰撞中间歇标度指数和轻核产额与随碰撞能量的关系显现非单调的依赖性。
- 高阶矩和组分夸克的标度性研究显示 3 GeV可能没有夸克-胶子等离子体产生
- 需要 3 – 7 GeV 四阶涨落的实验测量去理解和判断相变临界点是否存在

Summary and Outlook

（I）2000 - 2012: RHIC, LHC

1) 强耦合夸克胶子等离子体产生，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。

2) 在$\mu_B=0$附近的相变是平滑过渡。

（II）2010 - 2014: RHIC BES-I (20≤μ_B≤400 MeV，200≥$\sqrt{s_{NN}}$≥7.7 GeV)

1) $\sqrt{s_{NN}}$≤15 GeV，μ_B≥300 MeV, 夸克胶子等离子体(QGP)信号逐渐消失，强子相互作用主导。

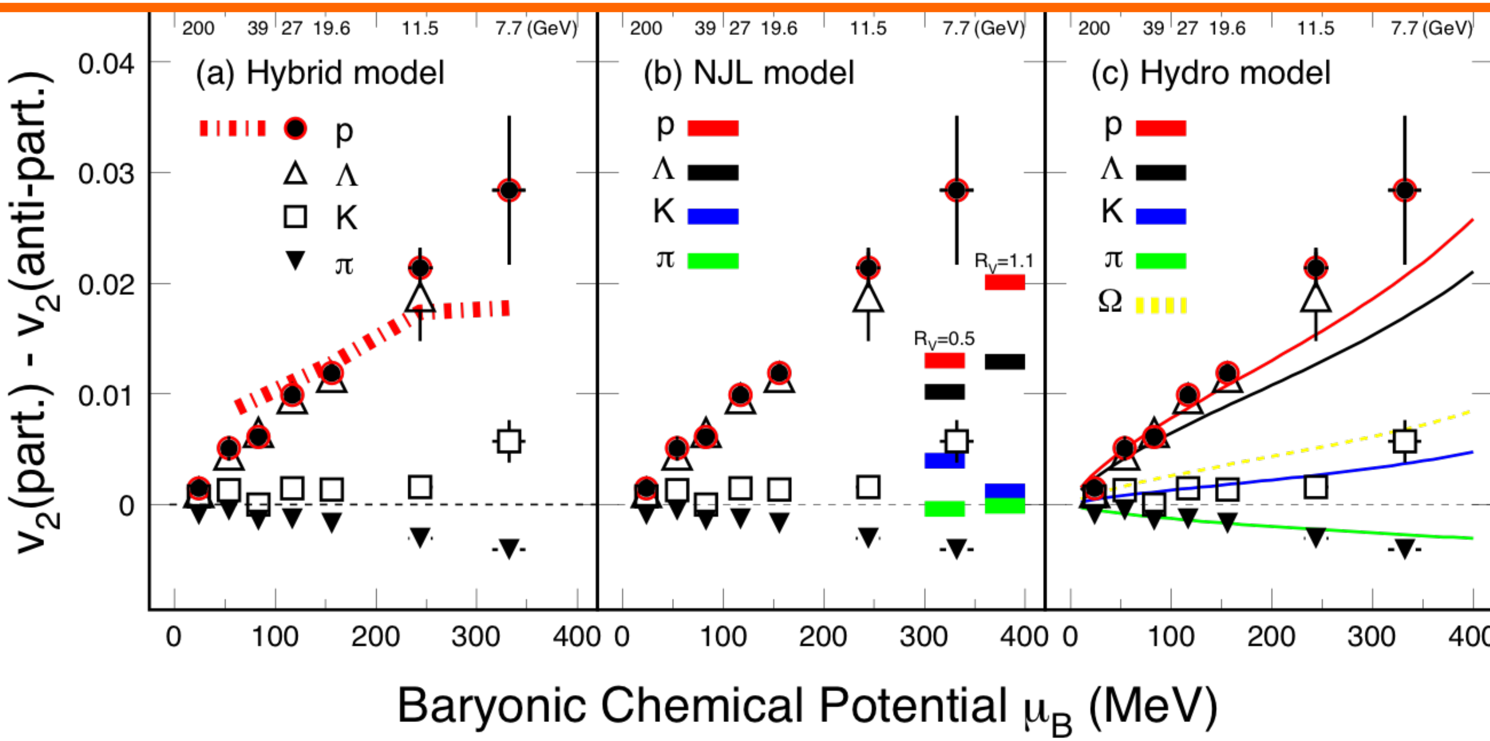
2) 集体流和涨落实验结果有相变迹象。但是需要更高精度的数据来进一步证明。

（III）2018 – QCD相变临界点及相边界的寻找

1）高阶矩和组分夸克的标度性研究显示 3 GeV可能没有夸克-胶子等离子体产生，需要 3 – 7 GeV 四阶涨落的实验测量去理解和判断相变临界点是否存在

2）FAIR/CBM、NICA/MPD、HIAF/CEE（$\sqrt{s_{NN}}$≤12 GeV, μ_B≥300 MeV）最新高科技加速器、探测器，亮度高

Particle vs. Anti-particle v_2

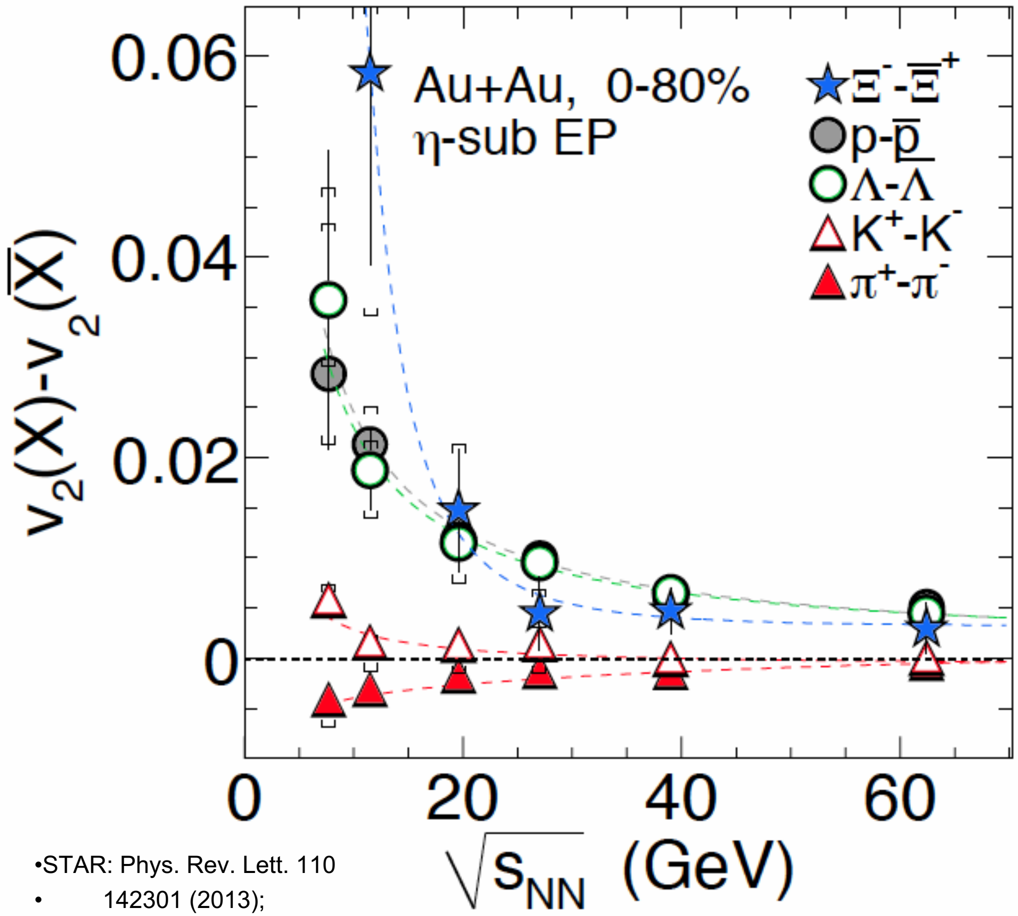


BESII : multi-strange hadrons

- **The difference between particles and anti-particles increases with decreasing beam energy – NCQ scaling breaks**
- **Model comparison**
  - Hydro + Transport (UrQMD): consistent with baryon data
  - Nambu-Jona-Lasino (NJL) model (partonic + hadronic potential): hadron splitting consistent
  - Analytical hydrodynamic solution: $\Delta v_2^{\bar{p}} > \Delta v_2^{\Lambda} > \Delta v_2^{\Xi} > \Delta v_2^{\Omega}$

J. Steinheimer et al., PRC86, 44903(2012); J. Xu et al., PRL112, 012301(2014), H. Liu et al., PLB798, 135002(2019).; Y. Hatta et al., PRD92, 114010(2015)

Particles vs. Anti-particles



- STAR: Phys. Rev. Lett. 110
- 142301 (2013);
- arXiv:1301.2348

- **Beam energy ≥ 39 GeV**

Δv_2 for baryon and anti-baryon within 10%

Almost no difference for mesons

- **Beam energy < 39 GeV**

The difference of baryon and anti-baryon v_2

→ *Increasing with decrease of beam energy*

$v_2(K^+)>v_2(K^-)$ at 7.7-19.6 GeV

$v_2(\pi^-)>v_2(\pi^+)$ at 7.7-19.6 GeV

- **Possible explanation**

Baryon transport to mid-rapidity?

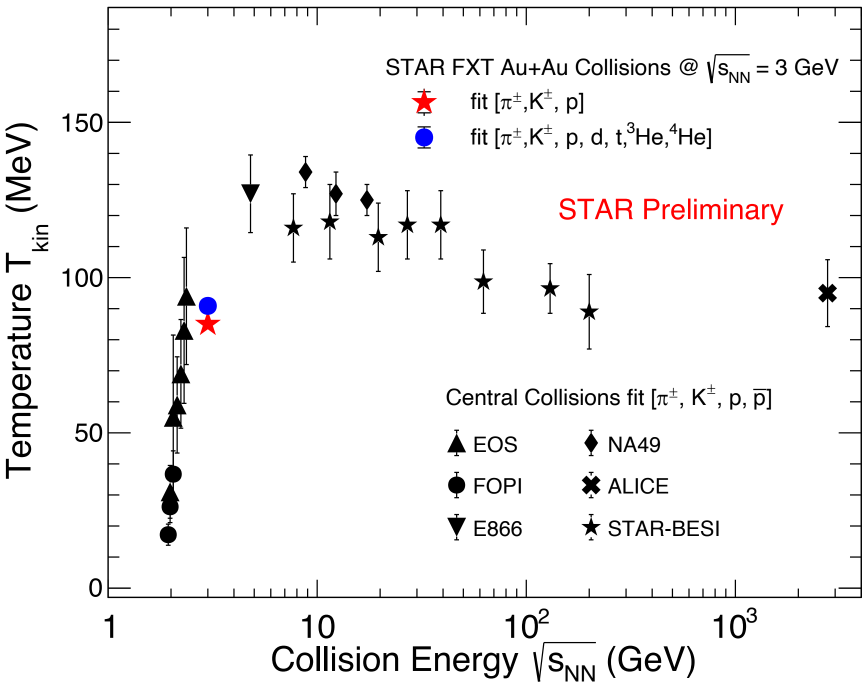
ref: J. Dunlop et al., PRC 84, 044914 (2011)

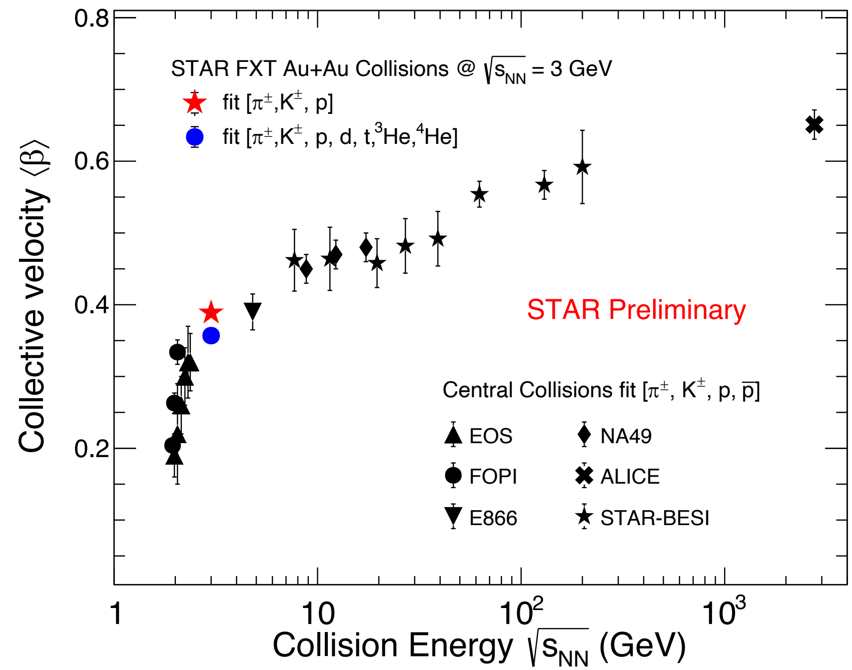
Hadronic potential?

ref: J. Xu et al., PRC 85, 041901 **(2012)**

The difference between particles and anti-particles is observed

Energy dependence of T_{kin} and ⟨ β ⟩





- T_{kin} and ⟨ β ⟩ at central collisions follow the energy dependence trend obtained by the world experiment

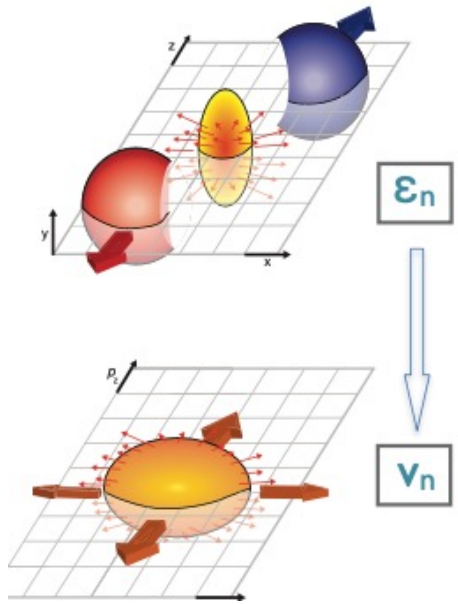
Phys. Rev. C 96, 044904(2017)
Phys. Rev. C 88, 044910 (2013)
Phys. Rev. C 79, 034909(2009)
Eur. Phys. J. C 2, 661 (1998)
Nucl. Phys. A612, 493 (1997)
Phys. Rev. Lett. 75, 2662 (1995)
arXiv:nucl-ex/9806002

Short introduction to statistical thermodynamics (A)

- The *maximum entropy principle* leads to the thermal most likely distribution for different particle species.
- !
- Entropy: the number of possible micro-states Ω being compatible with a macro-state for a given set of macroscopic variables (E, V, N):
- !
- !
- Compatibility to a given macroscopic state can be realized *exactly* or *only in the statistical mean*.

L. Boltzmann

initial anisotropy and final state flow



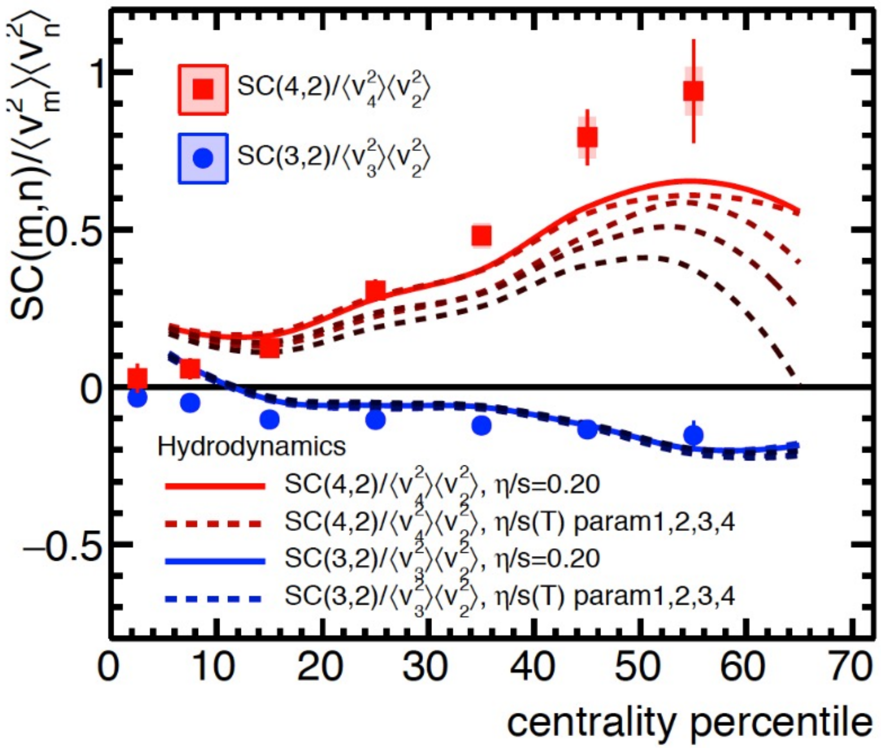
- ✓ $v_2 \propto \varepsilon_2$ → Linear response
- ✓ $v_3 \propto \varepsilon_3$ → Linear response
- ✖ ~~$v_4 \propto \varepsilon_4$~~ → Linear & Non-linear response
- ✖ ~~$v_5 \propto \varepsilon_5$~~ → Linear & Non-linear response
- ✖ ~~$v_6 \propto \varepsilon_6$~~ → Linear & Non-linear response

Normalized symmetric cumulant (NSC)

ALICE, PRL117, 182301 (2016)

$$SC(m,n) = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

$$NSC(m,n) = \frac{SC(m,n)}{\langle v_m^2 \rangle \langle v_n^2 \rangle}$$

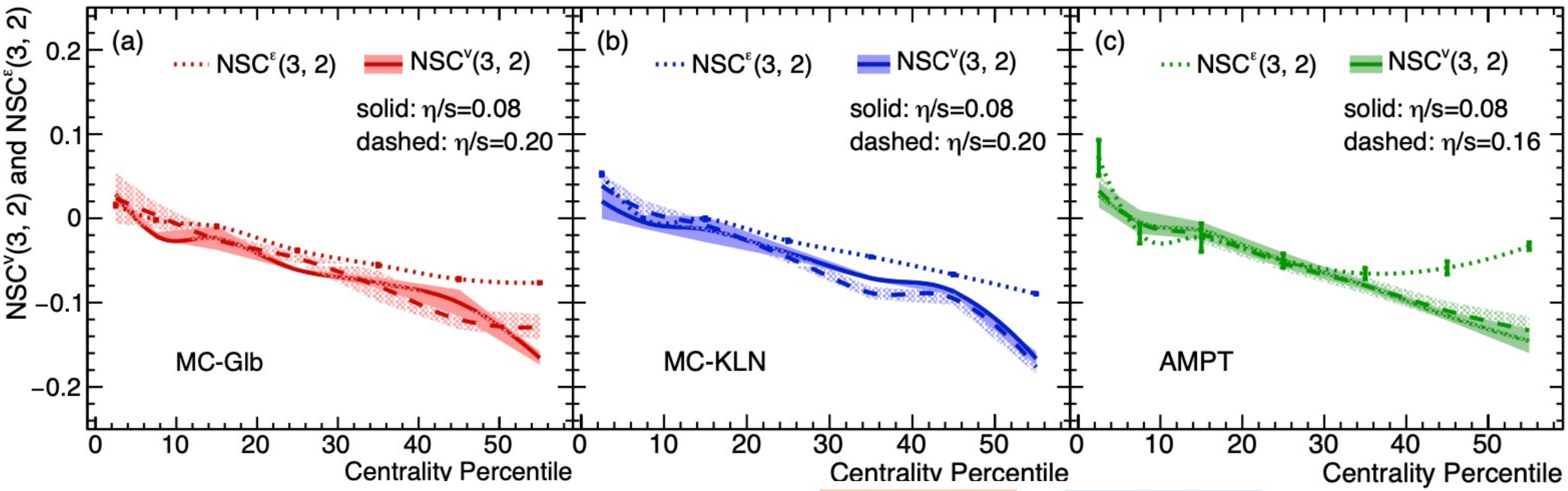


NSC should be independent of magnitudes of v_n and v_m

- NSC(4,2) provides stronger constraints on the η/s in hydro than individual v_n measurements alone.
- NSC(3,2) is less sensitive (or even insensitive) the detailed setting of η/s(T)

NSC(3,2) and NSC$^{\varepsilon}$(3,2)

VISH2+1, X. Zhu et al., arXiv: 1608.05305



$$v_2 \propto \varepsilon_2$$
$$v_3 \propto \varepsilon_3$$

$$\Rightarrow \quad \frac{\langle v_3^2\, v_2^2\rangle}{\langle v_3^2\rangle\,\langle v_2^2\rangle} \approx \frac{\langle \varepsilon_3^2\, \varepsilon_2^2\rangle}{\langle \varepsilon_3^2\rangle\,\langle \varepsilon_2^2\rangle}$$

NSC^{v}(3,2) NSC$^{\varepsilon}$(3,2)

NSC(3,2) in hydrodynamic calculations

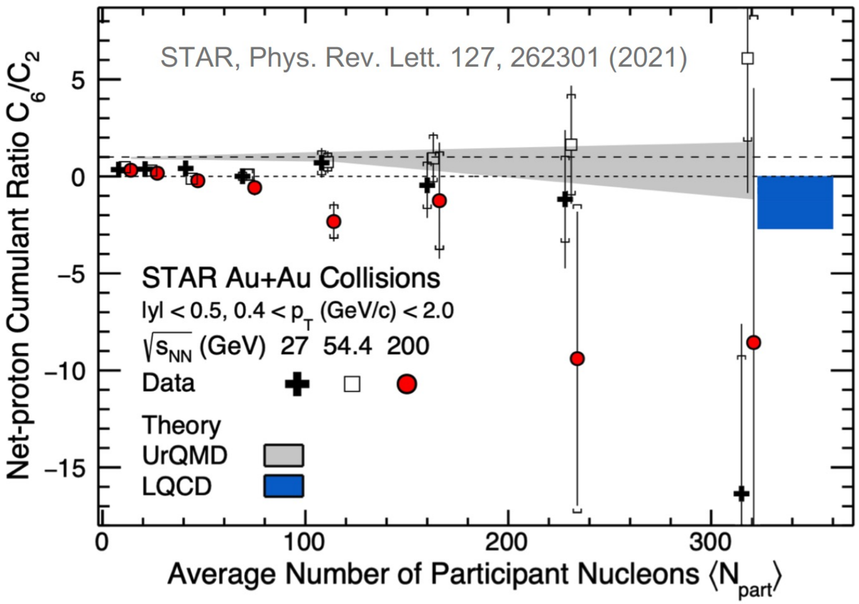
- mainly driven by initial NSC$^{\varepsilon}$(3,2) for central- and middle-central collisions
- ***New approach to tune initial state models***
- less sensitivity to η/s
- independent of kinematic cuts

SC and NSC with other harmonics

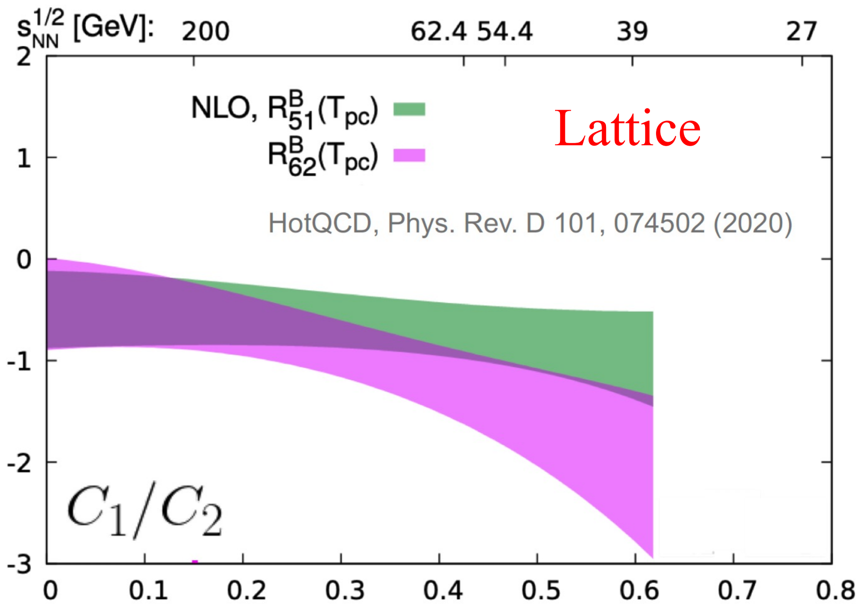
NSC(3,2) in hydrodynamic calculations

- mainly driven by initial $NSC^{\varepsilon}(3,2)$ for central- and middle-central collisions
- ***New approach to tune initial state models***
- less sensitivity to η/s
- independent of kinematic cuts

Higher-order baryon number fluctuations



STAR, Phys. Rev. Lett. 127, 262301 (2021)

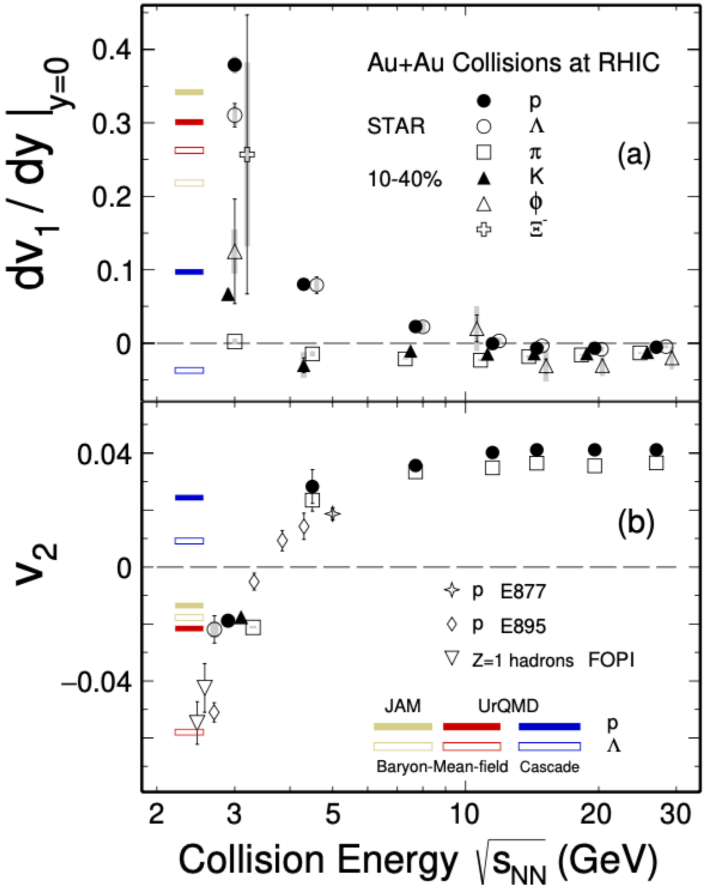


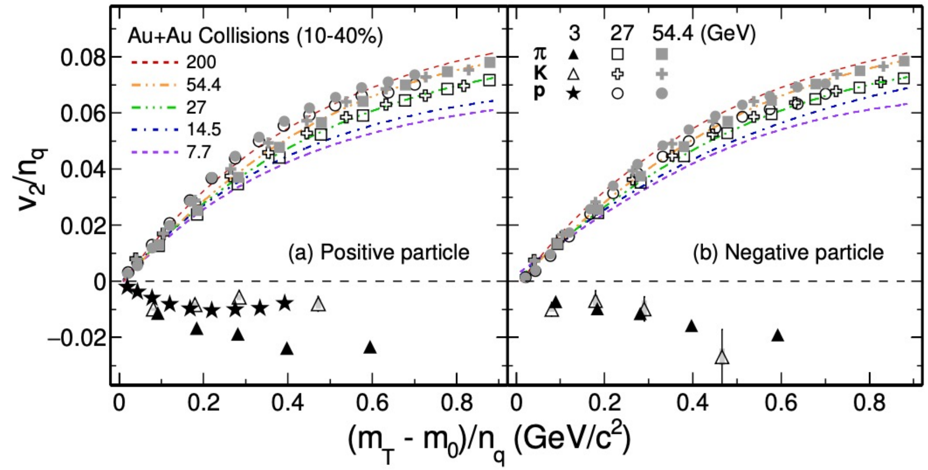
丁亨通(hotQCD)等, Phys. Rev. D 101, 074502 (2020);

- First principle Lattice QCD calculation predicts $C_6/C_2 < 0$.
- C_6/C_2 progressively negative from peripheral to central collisions

Indicate smooth crossover at 200 GeV.

3 GeV：部分子集体运动的消失





STAR： Phys.Lett. **B827**, 137003(2022)

- 组分夸克标度性在3 GeV的碰撞中破坏：部分子自由度->强子自由度
- 定向流斜率和v_2定性的与加入平均场的强子输运模型UrQMD符合：重子相互作用主导的状态方程

$$\begin{cases} \Delta B = \frac{1}{3}\Delta u + \frac{1}{3}\Delta d + \frac{1}{3}\Delta s \\ \Delta S = -\Delta s \end{cases}$$

$$\langle \Delta B\, \Delta S\rangle = -\frac{1}{3}\langle (\Delta u \Delta s + \Delta d \Delta s + (\Delta s)^2)\rangle$$

$$\langle \Delta B\rangle\langle \Delta S\rangle = -\frac{1}{3}\langle \Delta u\rangle\langle \Delta s\rangle - \frac{1}{3}\langle \Delta d\rangle\langle \Delta s\rangle - \frac{1}{3}\langle \Delta s\rangle^2$$

如果 u, d, s 变量独立

所以 $\langle \Delta u \Delta s\rangle = \langle \Delta u\rangle\langle \Delta s\rangle$

$\langle \Delta d \Delta s\rangle = \langle \Delta d\rangle\langle \Delta s\rangle$

$$\Rightarrow \langle \Delta B \Delta S\rangle - \langle \Delta B\rangle\langle \Delta S\rangle = -\frac{1}{3}\left(\langle (\Delta s)^2\rangle - \langle \Delta s\rangle^2\right)$$

$$= -\frac{1}{3}\langle (\Delta s)^2\rangle_c$$

所以 $$C_{BS} = -3 \times \frac{\langle \Delta B \Delta S\rangle - \langle \Delta B\rangle\langle \Delta S\rangle}{\langle (\Delta S)^2\rangle_c} = 1$$

只有 Lambda. $\Delta B = \Delta\Lambda$ $\quad \Delta S = \bar{\Lambda} - \Lambda = -\Delta\Lambda$

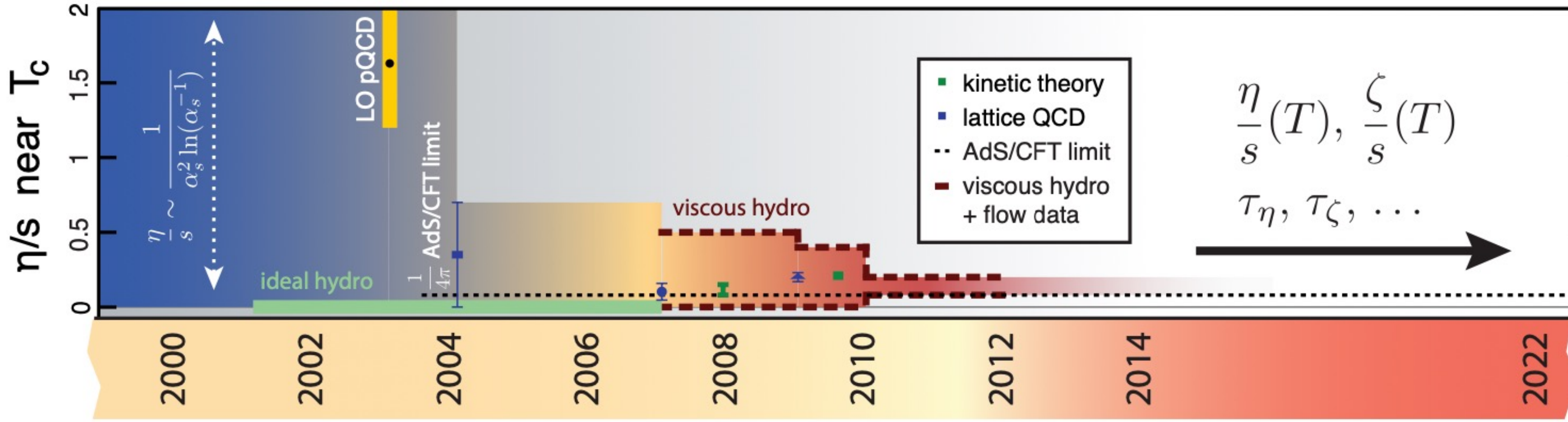
$$\therefore \langle \Delta B \Delta S\rangle - \langle \Delta B\rangle\langle \Delta S\rangle = -[\langle (\Delta\Lambda)^2\rangle - \langle \Delta\Lambda\rangle^2]$$

$$\langle (\Delta S)^2\rangle_c = \langle (\Delta\Lambda)^2\rangle - \langle \Delta\Lambda\rangle^2$$

所以 $C_{BS} = -3 \times (-1) = 3$

The knowledge about the shear viscosity over time

Broad theoretical efforts and experimental advances lead to increasingly precise determination of η/s



Björn Schenke QM2015 student day

LO pQCD: P. Arnold, G. D. Moore, L. G. Yaffe, JHEP 0305 (2003) 051
AdS/CFT: P. Kovtun, D. T. Son, A. O. Starinets, Phys.Rev.Lett. 94 (2005) 111601
Lattice QCD: A. Nakamura, S. Sakai, Phys.Rev.Lett. 94 (2005) 072305
H. B. Meyer, Phys.Rev. D76 (2007) 101701; Nucl.Phys. A830 (2009) 641C-648C
Ideal hydro: P. F. Kolb, J. Sollfrank, U. W. Heinz, Phys.Rev. C62 (2000) 054909
P. F. Kolb, P. Huovinen, U. W. Heinz, H. Heiselberg, Phys.Lett. B500 (2001) 232-240
pQCD/kin. theory: Z. Xu, C. Greiner, H. Stöcker, Phys.Rev.Lett. 101 (2008) 082302
J.-W. Chen, H. Dong, K. Ohnishi, Q. Wang, Phys.Lett. B685 (2010) 277-282
Viscous hydro: P. Romatschke, U. Romatschke, Phys.Rev.Lett. 99 (2007) 172301
M. Luzum, P. Romatschke, Phys.Rev. C78 (2008) 034915
H. Song, U. W. Heinz, J.Phys. G36 (2009) 064033
H. Song, S. A. Bass, U. Heinz, T. Hirano, C. Shen, Phys.Rev.Lett. 106 (2011) 192301

Major Upgrades for BES-II

All 3 detectors fully installed prior to start of Run-19

Very successful and important for BES-II

iTPC:
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 to 60 MeV/c
- Ready in 2019

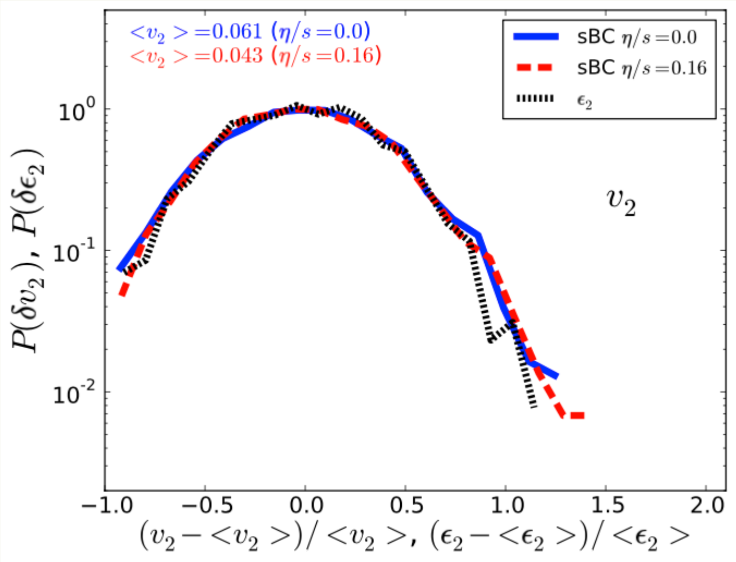
eTOF:
- Forward rapidity coverage
- PID at $\eta = 0.9$ to 1.5
- **Borrowed from CBM-FAIR**
- Ready in 2019

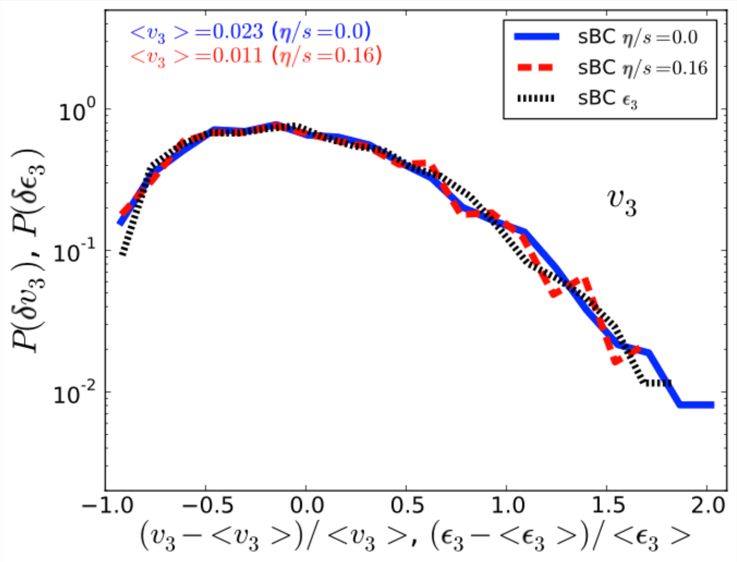
EPD:
- Improves trigger
- Better centrality & event plane measurements
- Ready in 2018

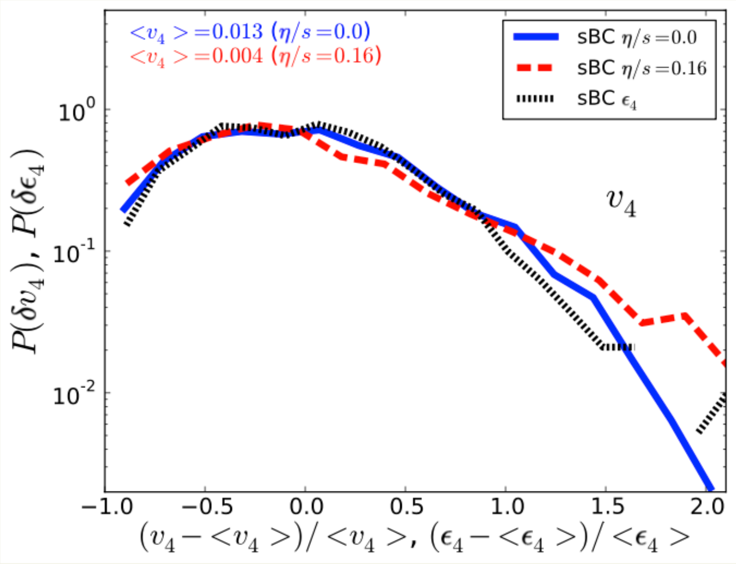
1) **Enlarge rapidity acceptance**
2) **Improve particle identification**
3) **Enhance centrality/event plane resolution**

iTPC: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
eTOF: STAR and CBM eTOF group, arXiv: 1609.05102
EPD: J. Adams, et al. Nucl. Instr. Meth. A 968, 163970 (2020)

Distributions of v_n event-by-event



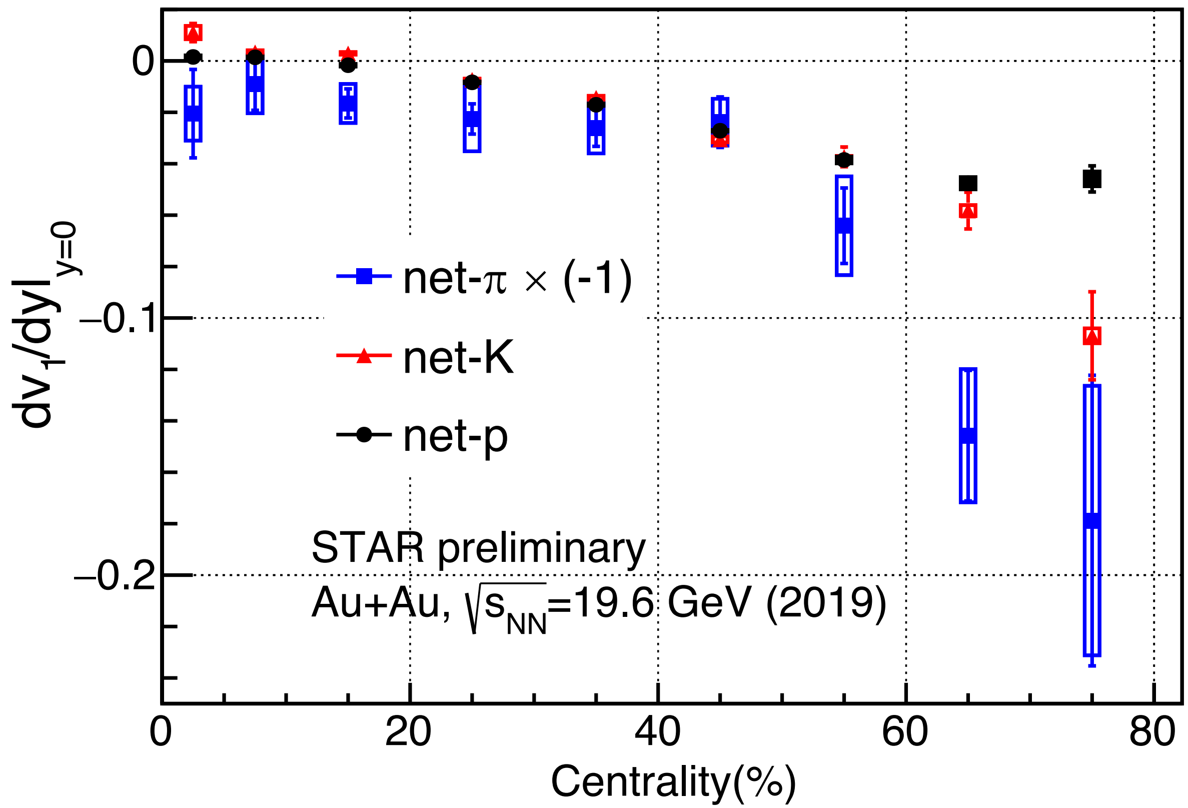




Niemi *et al.* Phys.Rev.C87, 054901 (2013)

- $\delta v_n \approx \delta\epsilon_n$ **independent of η/s**
- **measurement of initial state?**

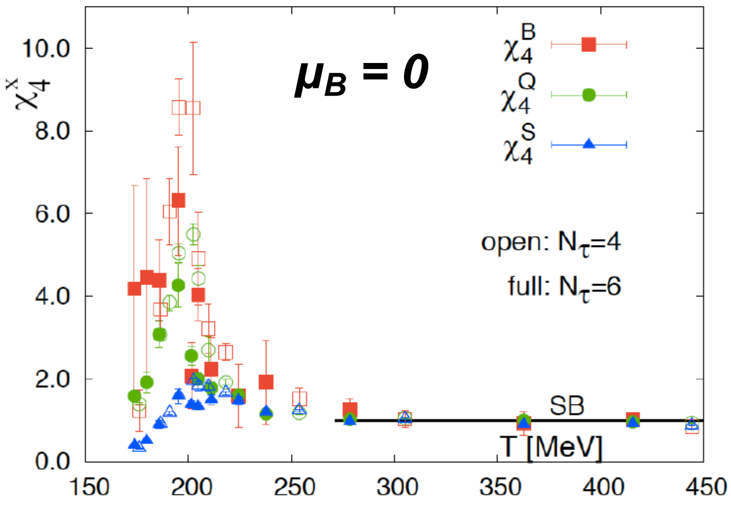
dv_1/dy vs. Centrality

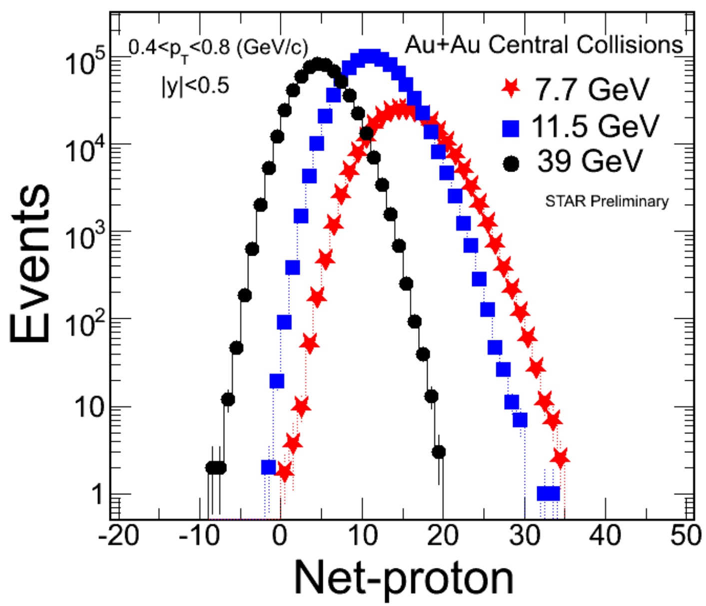


- v_1 slope of net-particle is larger in more peripheral collisions
  More transported quarks in the peripheral collisions
- v_1 slope of net-proton and net-kaon are similar in central and mid-central collisions
- 14.6 GeV: wait for final official centrality definition

Net-pion dv1/dy is positive at all centralities. To facilitate plotting in the figure opposite, net-pion dv1/dy is shown with reversed sign.

Higher Moments and Criticality





1) Higher moments of conserved quantum numbers: ***Q, S, B***, in high-energy nuclear collisions

2) Sensitive to critical point (ξ correlation length):

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \ \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \ \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

3) Direct comparison with calculations at any order:

$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

4) **Extract susceptibilities and freeze-out temperature**. An independent/important test of thermal equilibrium in heavy ion collisions.

References:

- STAR: *PRL***105**, 22303(10); *ibid*, **112**, 032302(14)
- S. Ejiri, F. Karsch, K. Redlich, *PLB633*, 275(06) // M. Stephanov: *PRL*102, 032301(09) // R.V. Gavai and S. Gupta, *PLB696*, 459(11) // F. Karsch et al, *PLB695*, 136(11),
- A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // V. Skokov et al., PRC88, 034901(13)
- PBM, A. Rustamov, J. Stachel, arXiv:1612.00702

Event Plane Method

A. M. Poskanzer, S. A. Voloshin, Phys. Rev. C58, 1671 (1998)

- Estimation of the true reaction plane using elliptic flow itself.
  - flow vector

$$Q_n \cos(n\Psi_n) = X_n = \sum_i w_i \cos(n\phi_i)$$

$$Q_n \sin(n\Psi_n) = Y_n = \sum_i w_i \sin(n\phi_i)$$

$$\Psi_n = \left(\tan^{-1}\frac{\sum_i w_i \cos(n\phi_i)}{\sum_i w_i \sin(n\phi_i)}\right)/n$$

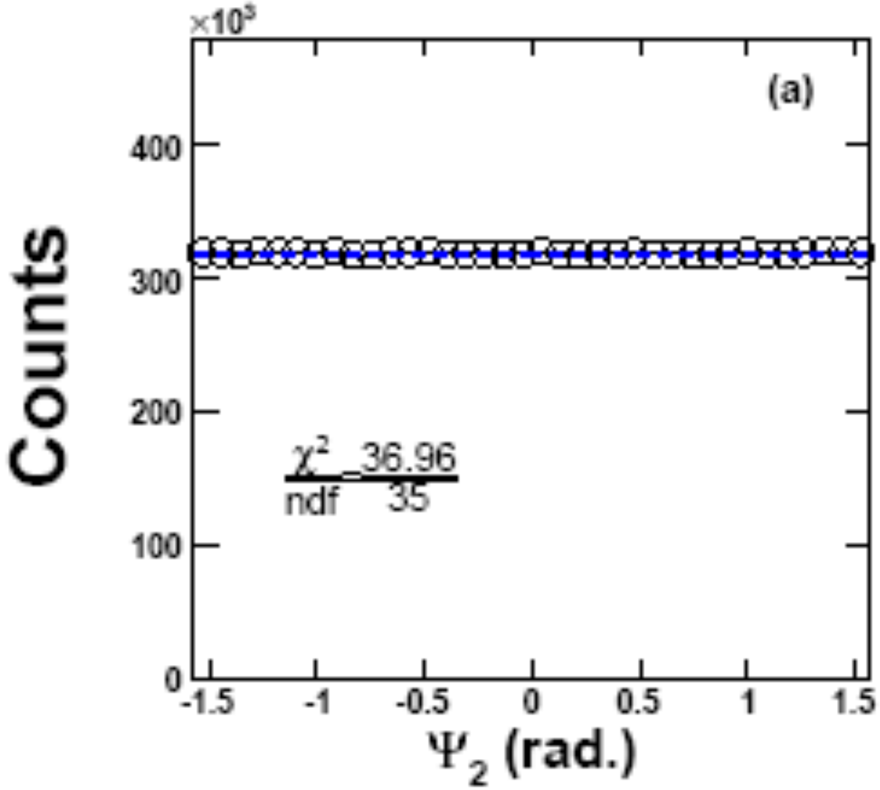
  where sum over all particles.
  - event plane angle

$$v_n^{obs} = \langle\cos[n(\phi - \Psi_n)]\rangle$$

$$v_n = v_n^{obs}/\langle\cos[n(\Psi_n - \Psi_r)]\rangle$$

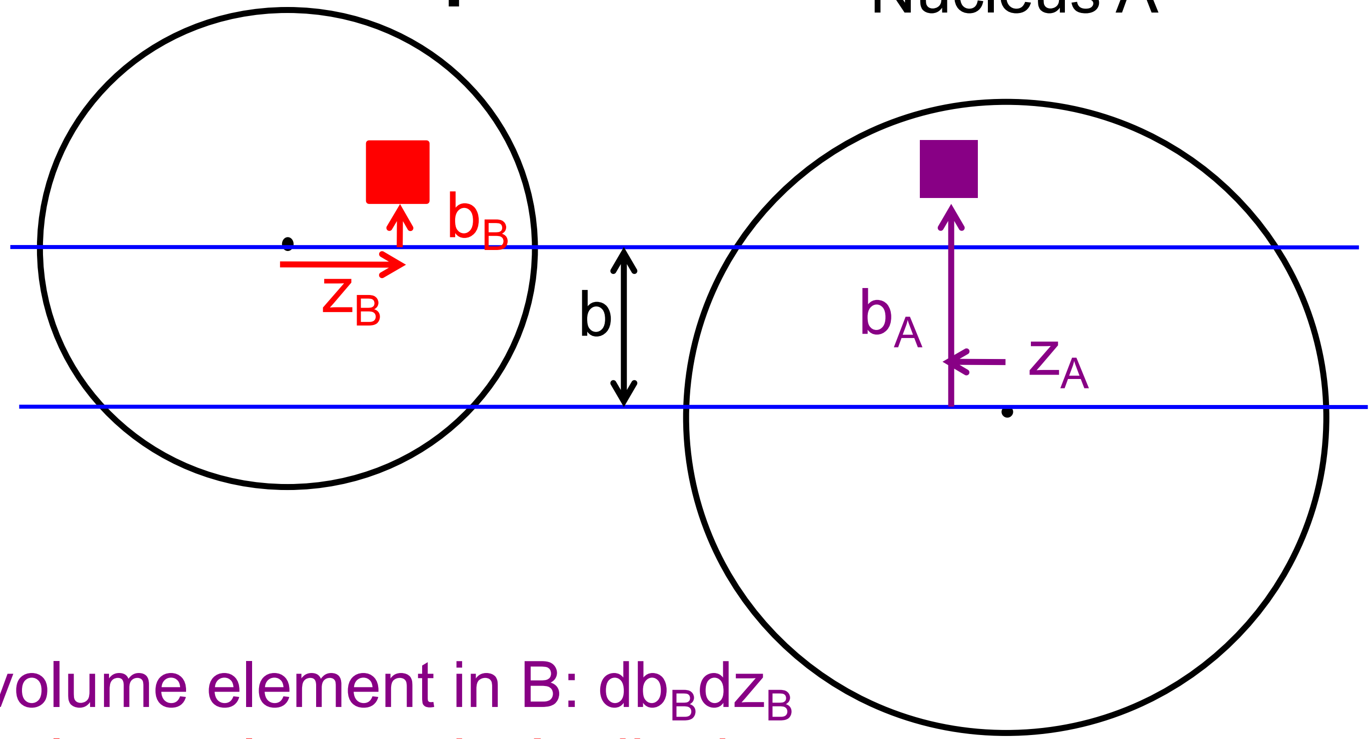
- v_2 calculation

- Non-flow: not correlated to EP.
  - resonance, jets.



Flat distribution.

Glauber model: calculate probabilities



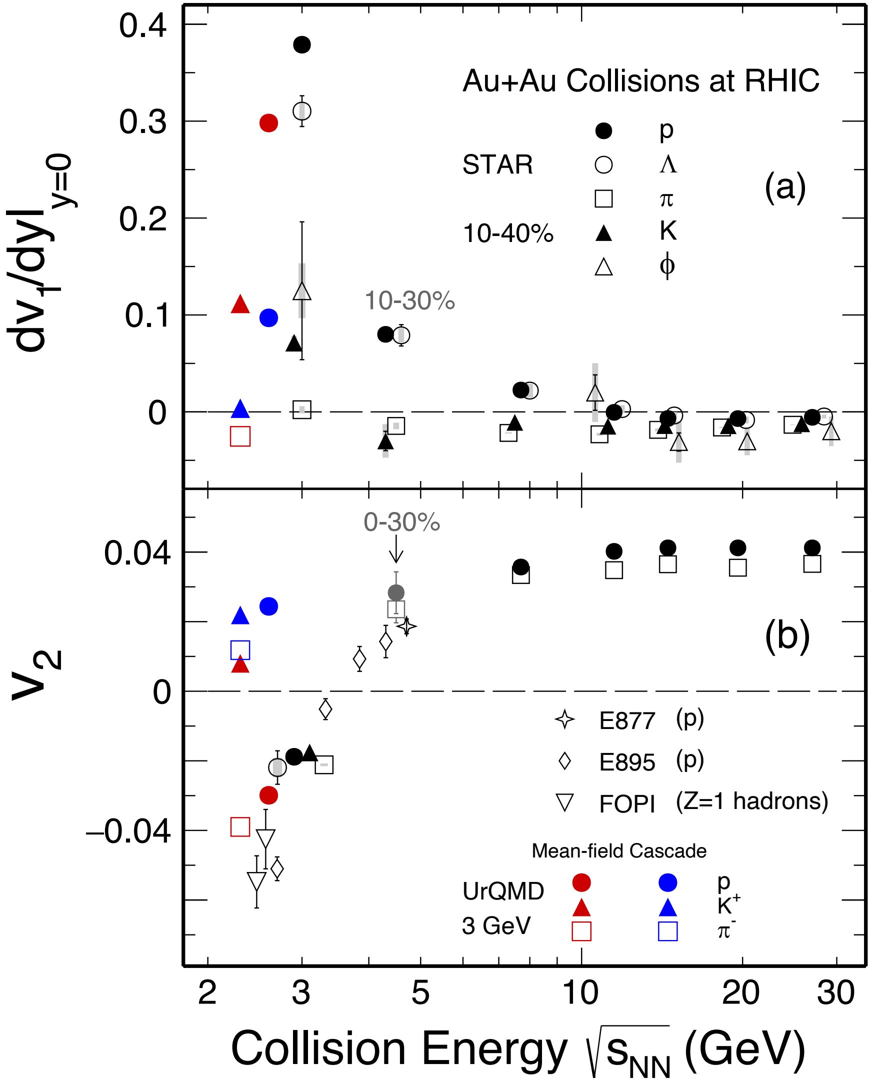
volume element in B: $db_B dz_B$

volume element in A: $db_A dz_A$

Probability of finding a nucleon in volume element B =

$\rho_B(b_B, z_B)\, db_B dz_B$ (ρ_B is nuclear density * nucleons in B)

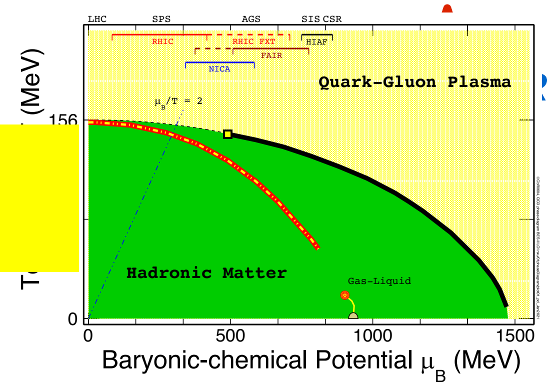
dv_1/dy and v_2 at 3 GeV

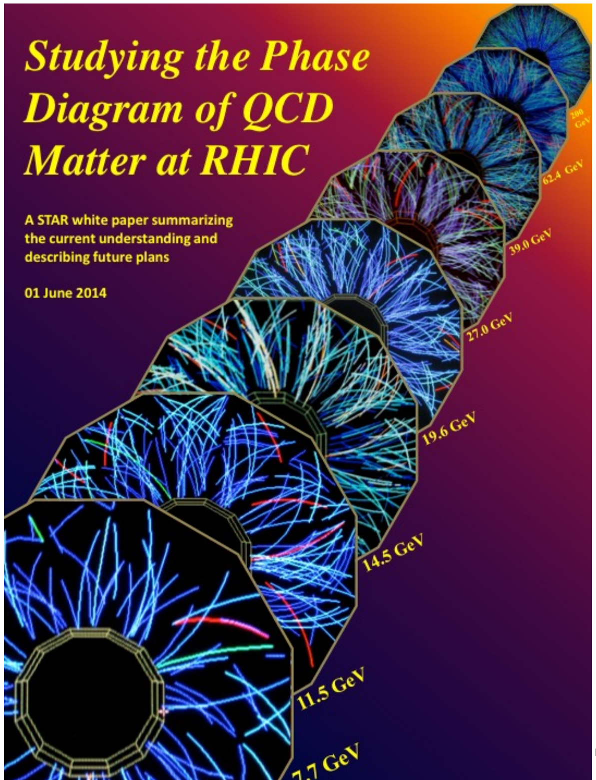


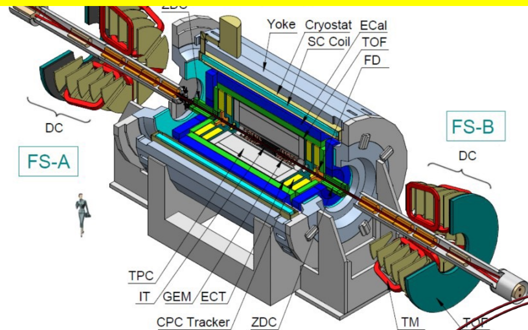
- The v1 slopes ($dv_1/dy|y=0$) of baryons at 3 GeV are positive and larger than those of mesons
- For the first time, kaon and ϕ v_1 slopes are found to be positive at 3 GeV, consistent with a change of EoS
- Negative elliptic flow at mid-rapidity for all hadrons at 3 GeV
- The results from UrQMD with baryonic mean-field potential qualitatively describe data at 3 GeV
- EoS dominated by the baryonic interactions at 3 GeV

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

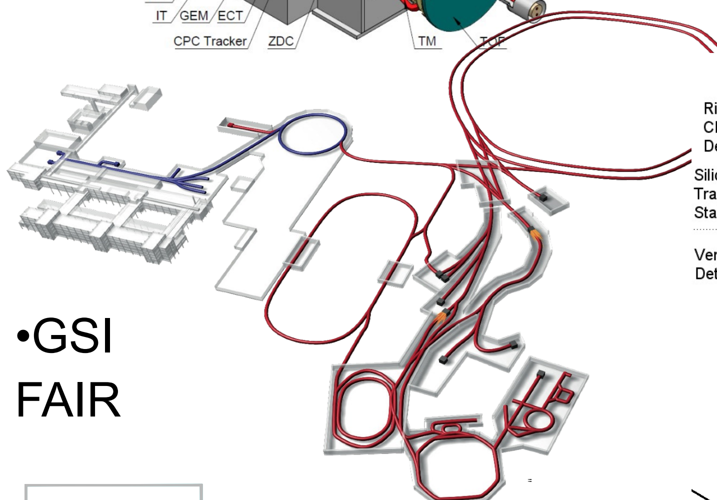




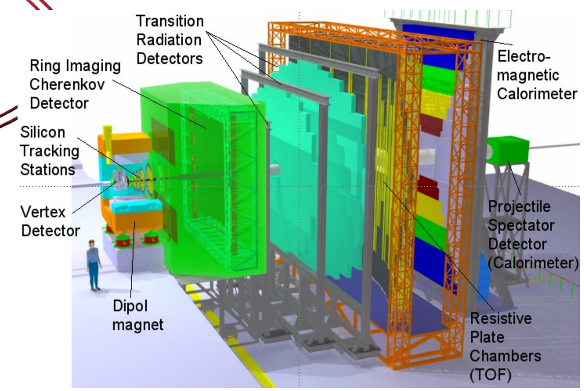


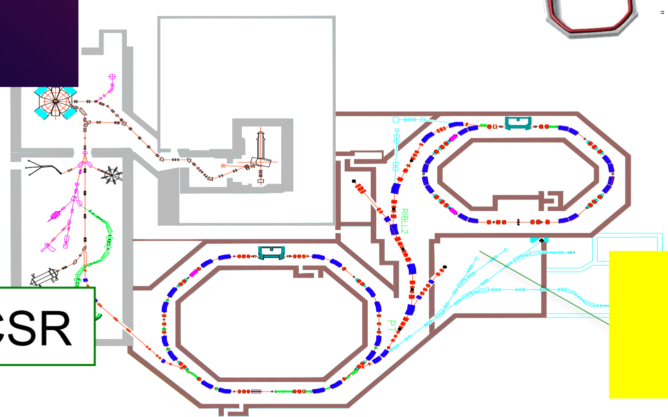
•NICA 科技部国际专项

CBM 973

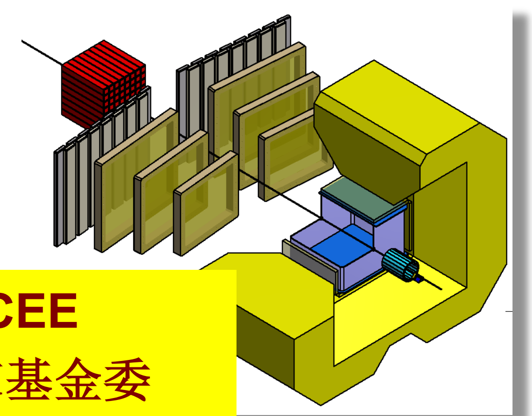


•GSI
FAIR





•HIRFL-CSR

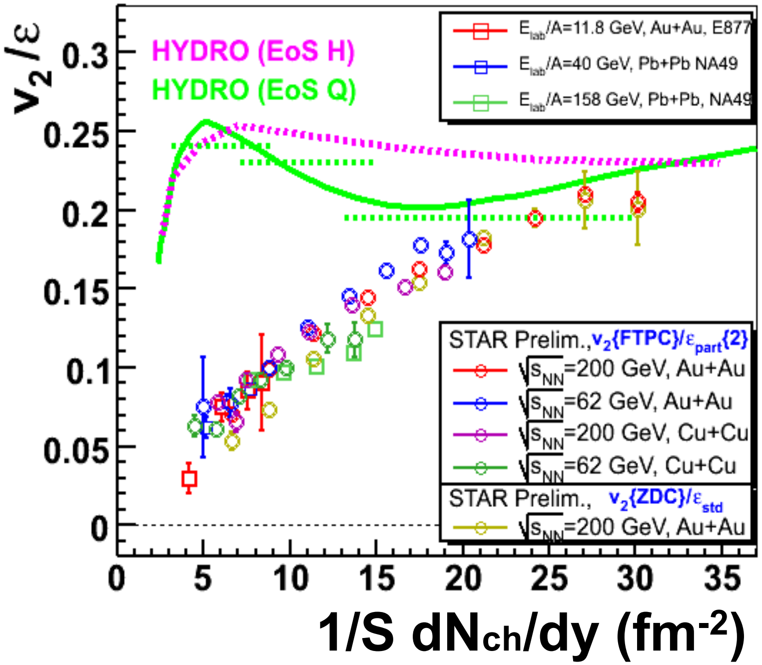


•CEE
•国家基金委

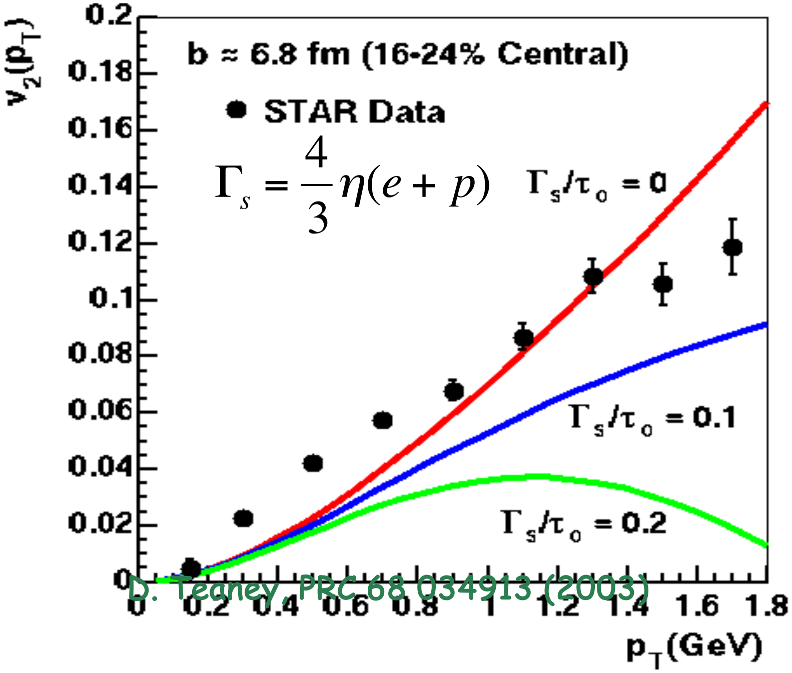
Thanks !

How Perfect ?

S. A. Voloshin (STAR) : J. Phys. G**34**, S883 (2007)



S. Voloshin, A. Poskanzer, PLB 474, 27, 2000.
Data: S. Voloshin, nucl-ex/ 0701038
Hydro: Kolb, Sollfrank, Heinz, PRC 62 (2000) 054909



v_2/ε approaches the limit of ideal hydrodynamics
Viscosity reduces v_2
Viscosity needs to be small in order to explain data

Almost nothing can be more liquid-like than it !

Properties of QCD Matter

Which properties of hot QCD matter can we hope to determine ?

$$T_{\mu\nu} \Leftrightarrow \varepsilon, p, s$$

Equation of state: spectra, coll. flow, fluctuations

$$c_S^2 = \partial p / \partial \varepsilon$$

Speed of sound: correlations

The Bulk

$$\eta = \frac{1}{T} \int d^4x \left\langle T_{xy}(x) T_{xy}(0) \right\rangle$$

Shear viscosity: anisotropic collective flow

$$\hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle F^{a+i}(y^-) F_i^{a+}(0) \right\rangle$$

$$\hat{e} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle i\partial^- A^{a+}(y^-) A^{a+}(0) \right\rangle$$

$$\hat{e}_2 = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle F^{a+-}(y^-) F^{a+-}(0) \right\rangle$$

Momentum/energy diffusion:
parton energy loss, jet fragmentation

$$m_D = -\lim_{|x| \to \infty} \frac{1}{|x|} \ln \left\langle E^a(x) E^a(0) \right\rangle$$

Color screening: Quarkonium states

Statistical Model

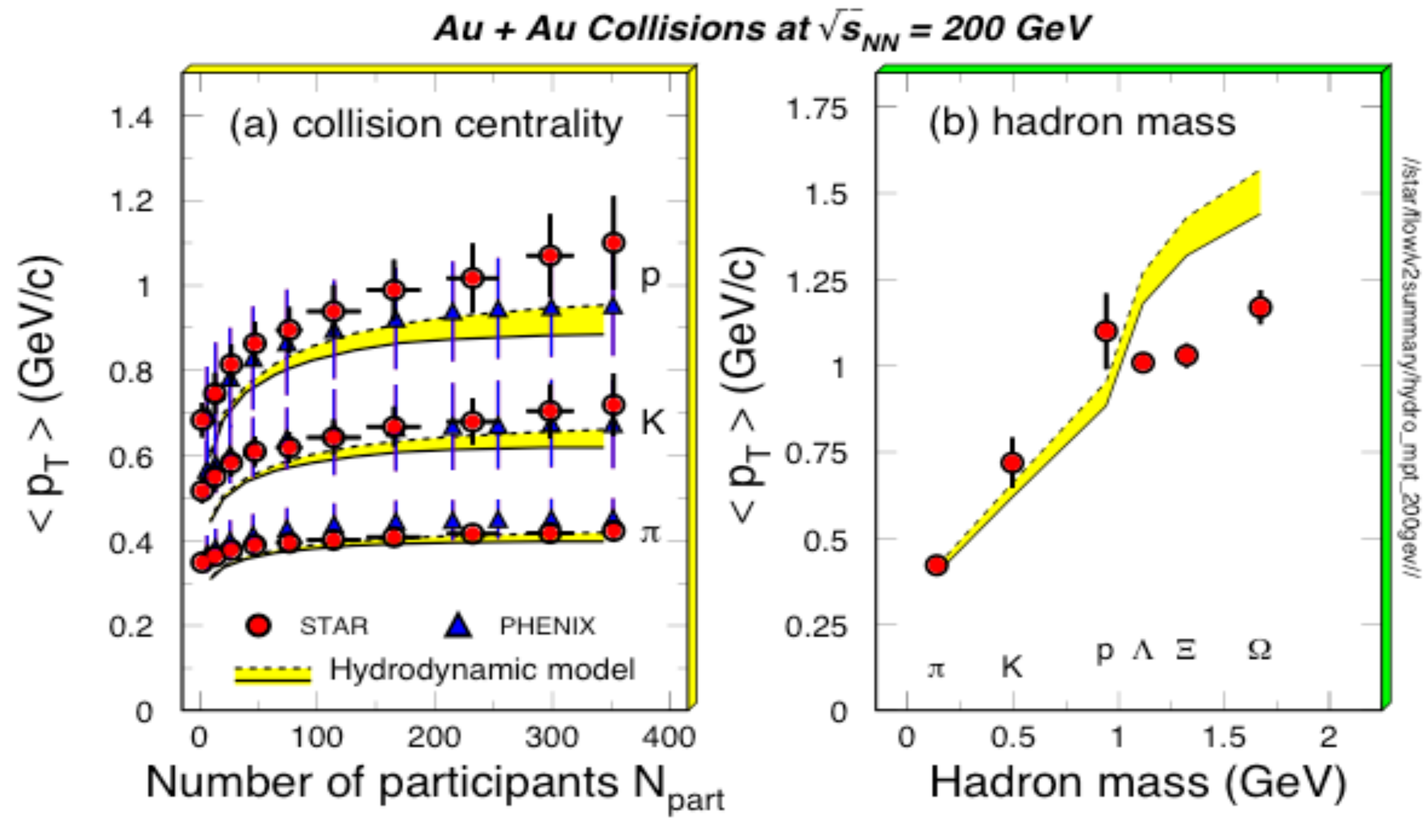
$$lnZ(T,V,\vec{\mu}) = \sum_i lnZ_i(T,V,\vec{\mu}) \qquad \vec{\mu} = (\mu_B, \mu_S, \mu_Q)$$

$$lnZ_i(T,V,\vec{\mu}) = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp ln\left[1 \pm \lambda_i e^{-\beta \varepsilon_i}\right]$$

Spin-isospin factor g_i , fugacity

$$\lambda_i(T,\vec{\mu}) = exp\left(\frac{B_i\mu_B + S_i\mu_S + Q_i\mu_Q}{T}\right)$$

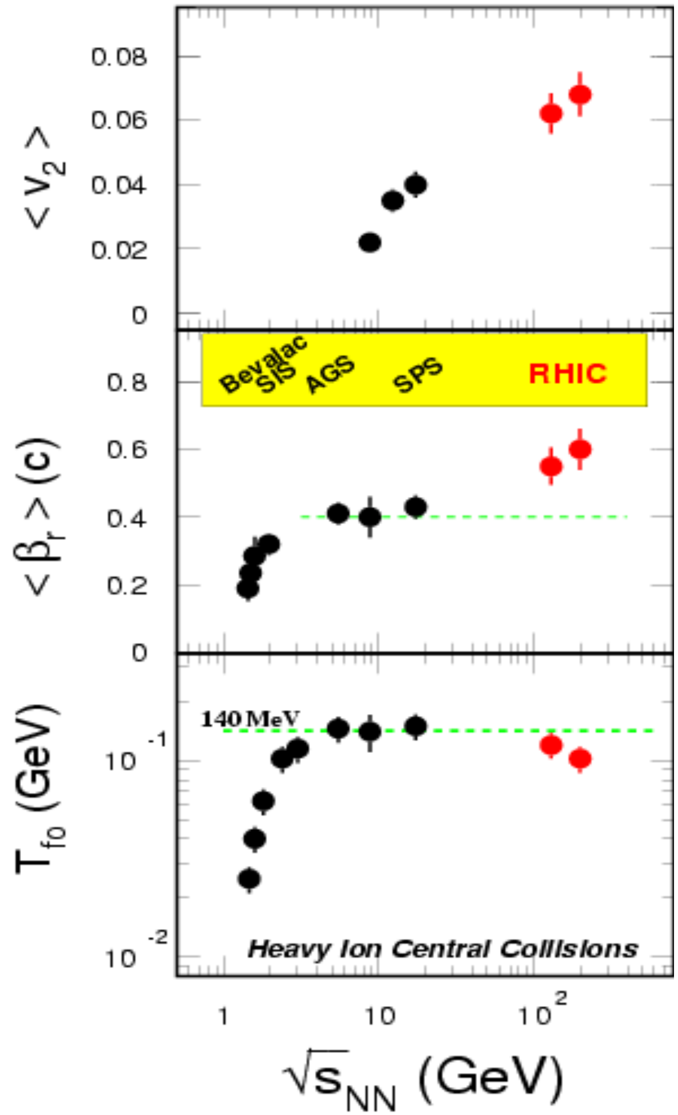
Compare with Model Results

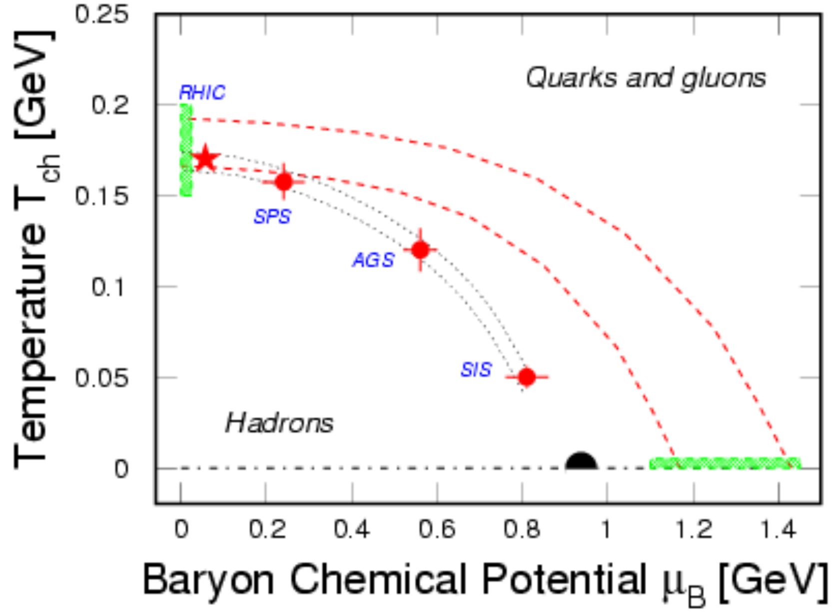


Model results fit to *π, K, p* spectra well, but over predicted $<p_T>$ for multi-strange hadrons - **Do they freeze-out earlier?**

Phys. Rev. ***C69*** *034909 (04); Phys. Rev. Lett.* ***92****, 112301(04);* ***92****, 182301(04); P. Kolb et al., Phys. Rev.* ***C67*** *044903(03)*

Freeze-out systematics

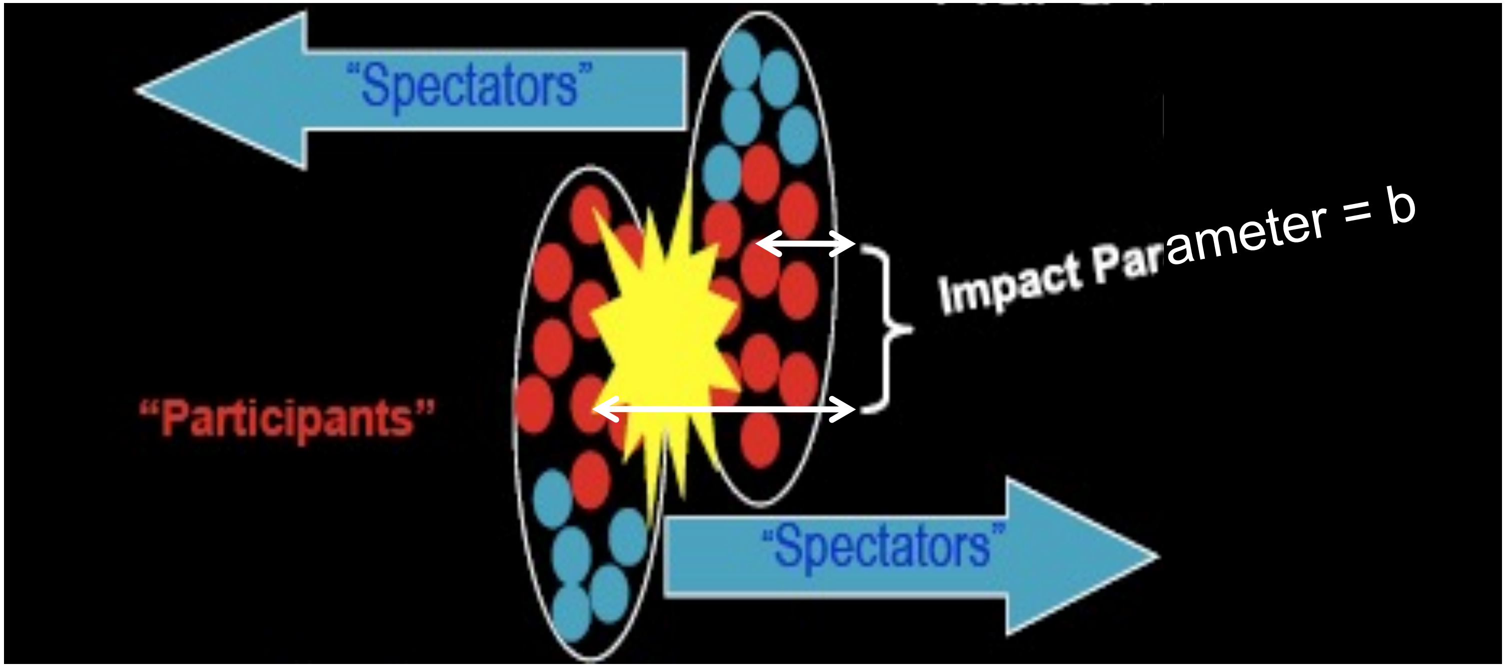




The additional increase in β_T is likely due to partonic pressure at RHIC.

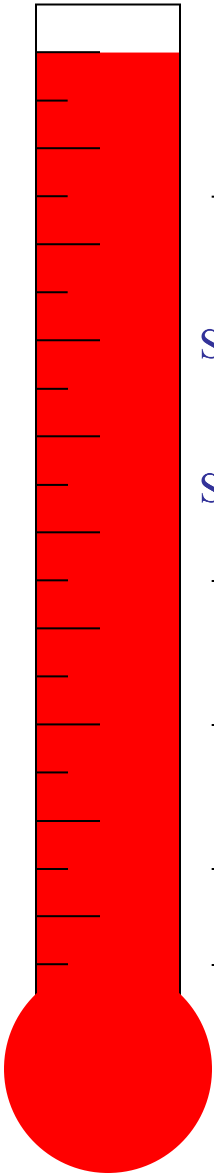
1) Smaller baryon chemical potential
μ_B = 25 MeV with T_{ch} = 160 MeV
2) Stronger transverse flow, β_T= 0.6(c)

Collision Geometry



Use Glauber model of nucleons in the nucleus
calculate # of participant nucleons N_{part}
# of binary NN collisions N_{coll}

Perspective on Temperature



~10¹² K

~10⁹ K

~10⁶ K

~6000 K

~300 K

~3 K

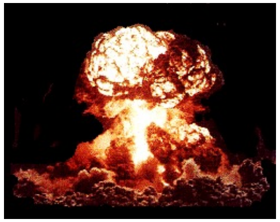
~10⁻⁶ K

~10⁻¹⁰ K

Nucleus-Nucleus collisions

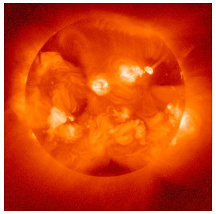
~ **120 MeV**

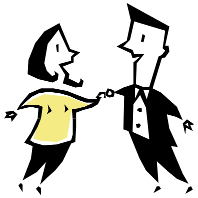
Neutron Star Thermonuclear Explosion



Solar Interior

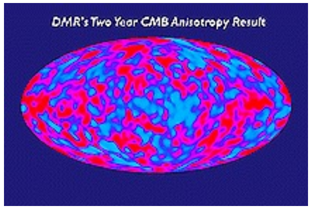
Solar Surface





Room Temperature

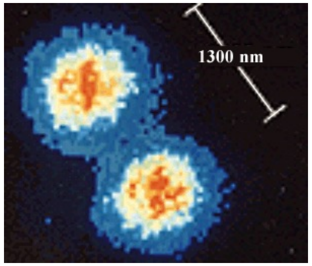
~ **1/40 eV**



Cosmic Microwave Background

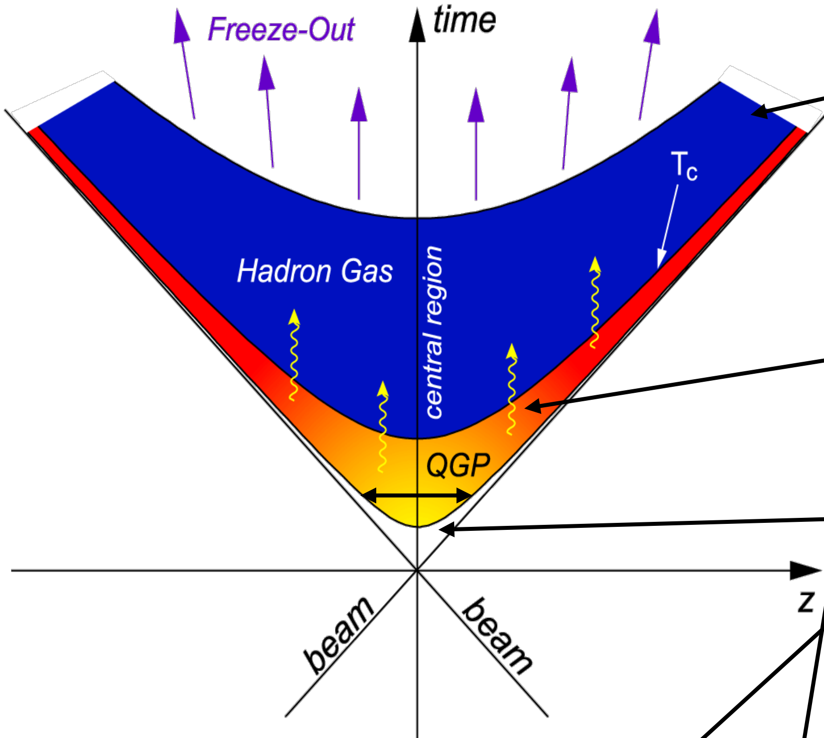
Rhodium metal spin cooling (2000)

(Low-T World Record!)



Trapped Ions

Evolution of High Energy Heavy Ion Collisions



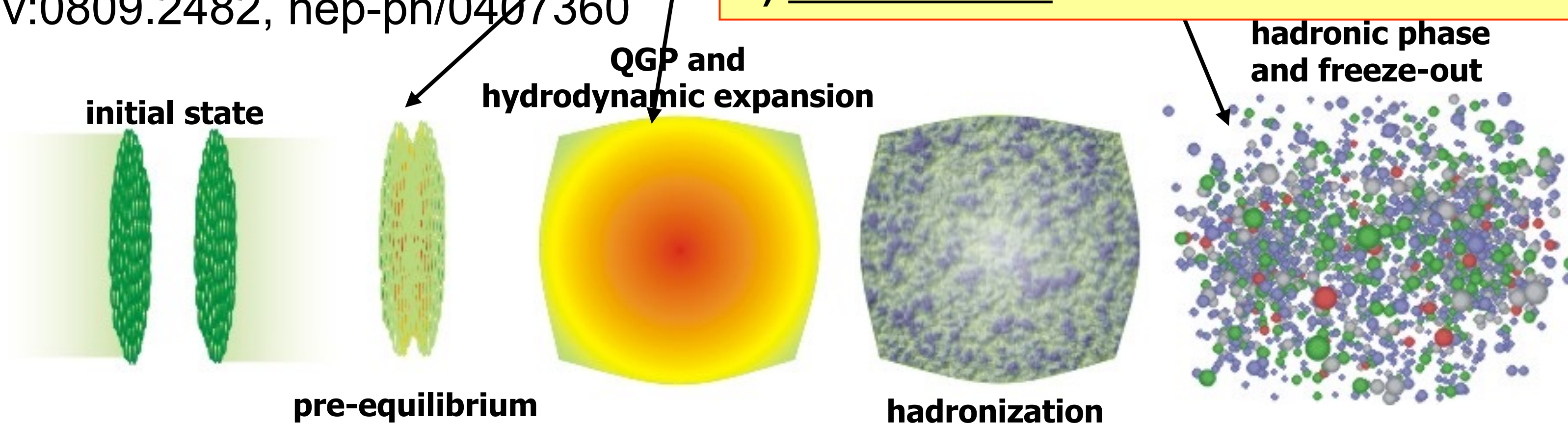
Freeze out Stage: ~10-15fm/c
Chemical freeze out: Inelastic scatt. cease.
Kinetic freeze out: Elastic scatt. cease.

QGP thermal and Expansion Stage: 1-10fm/c
Collective expansion, Parton energy loss et al.,
Hadronization: Recombination and coalescence.

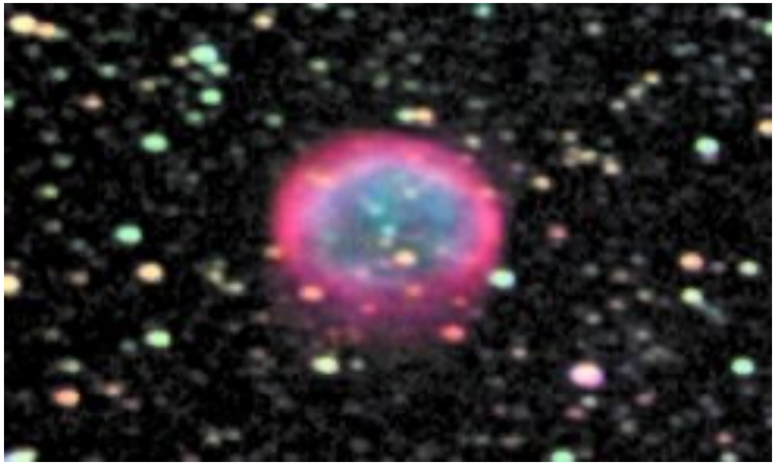
Pre-equilibrium parton hard scattering.

Experimental probes:
1) ***Penetrating probes:*** "jets" **Energy loss**
2) ***Bulk probes*** **:Elliptic flow, radial flow**
3) ***Fluctuation*****:**

arxiv:0809.2482, hep-ph/0407360



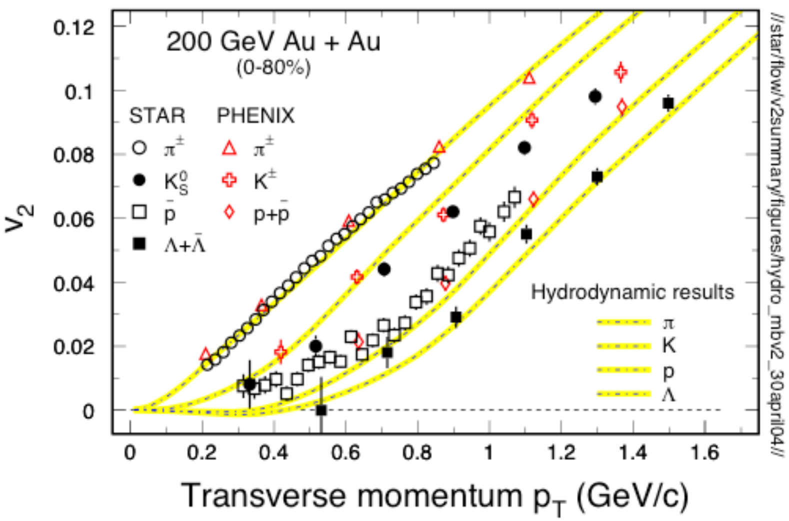
Description of Collisions

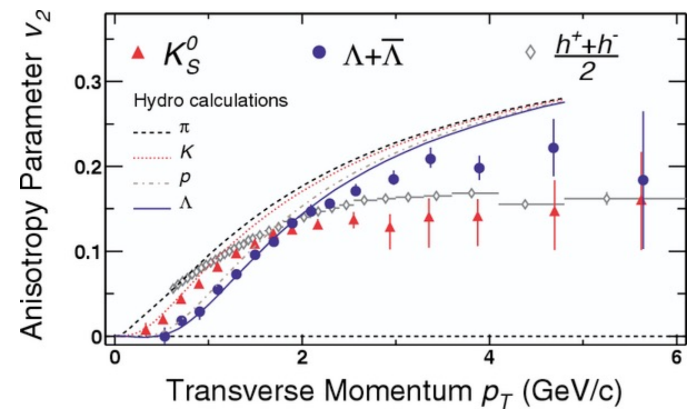


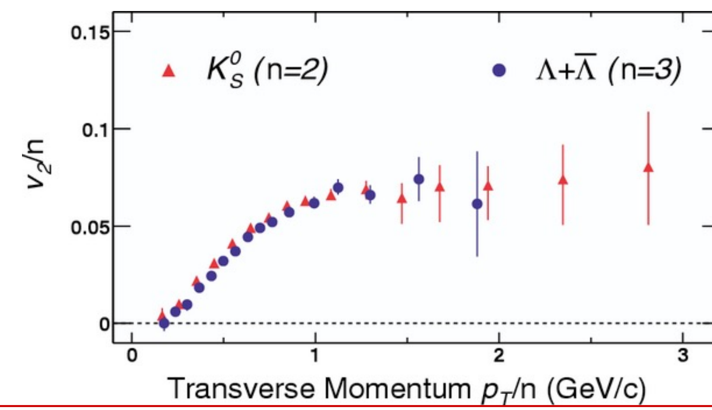
- Nuclei are liquid
- Hydrodynamics is suitable description

- Our system is between one that can be treated with particle physics methods (few particles) and solid state physics (10^{23} particles)
- Multi-disciplinary approach

v_2 in Au Au Collisions at 200 GeV







For hadron formation by coalescence of co-moving partons

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

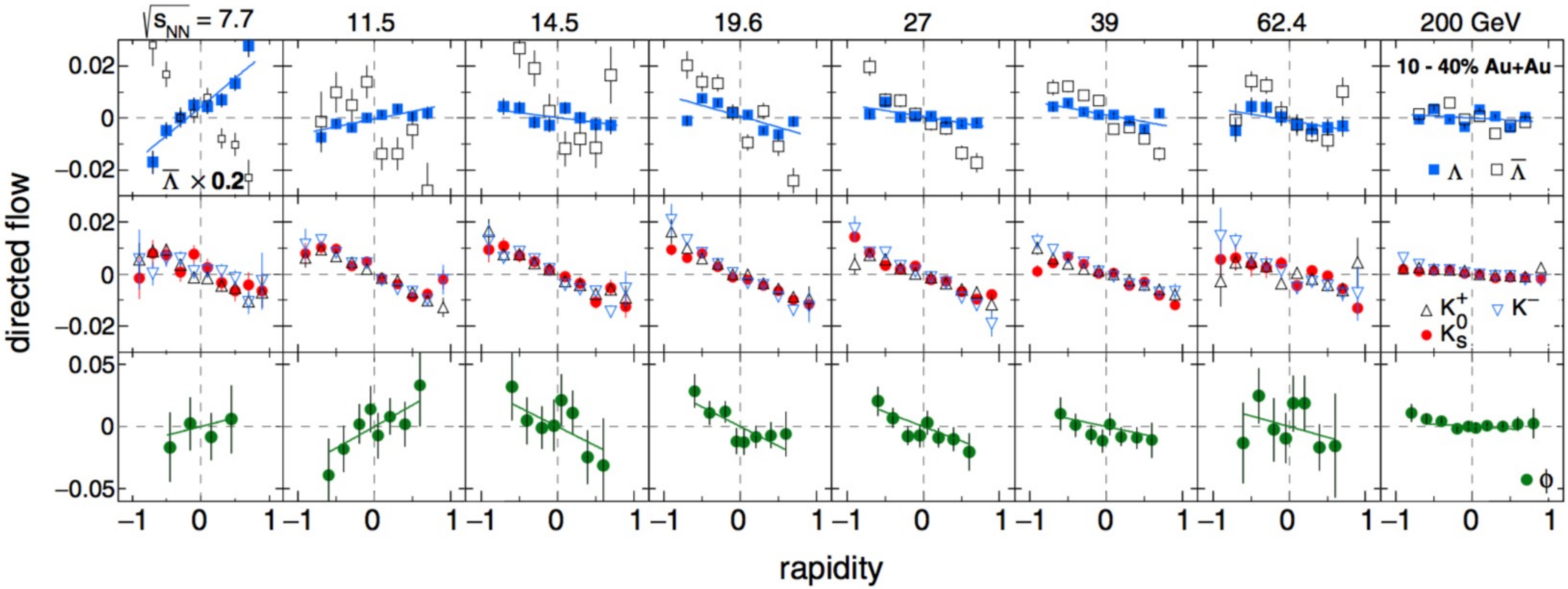
$$v_2^{baryon}(p_T) \approx 3 \cdot v_2^{quark}(p_T/3)$$

D. Molnar and S. A. Voloshin PRL 91,092301 2003

Hadrons at intermediate pT coalesce from comoving quarks

STAR （H. Long, JH Fu, H. Huang, N. Xu) PRL 92,052302 (2004) 1.6M + 1.5M events

•相结构：能量扫描直接流

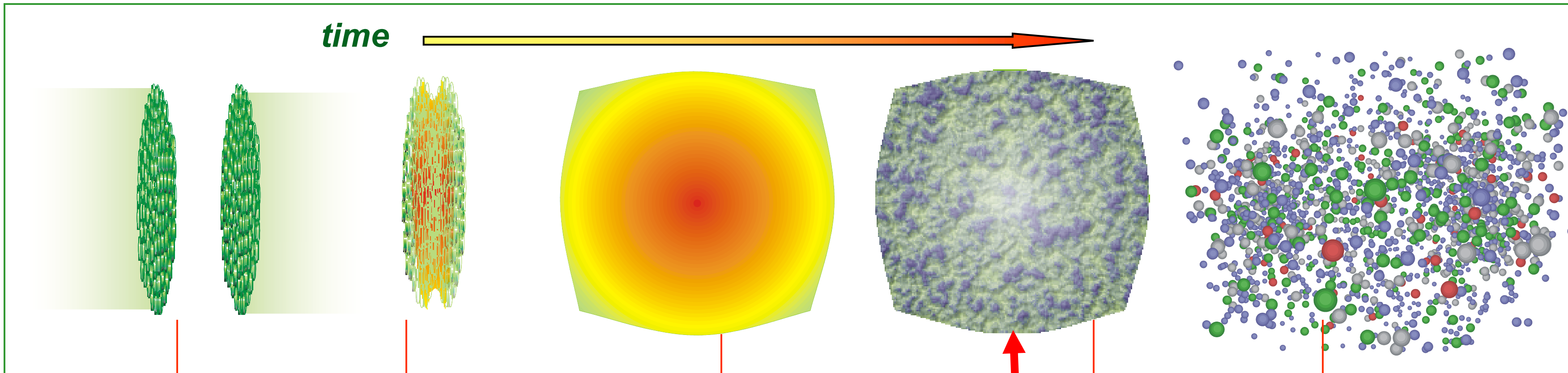


➢ 碰撞能量小于14.5 GeV：除ϕ介子之外的所有介子和产生的重子v_1相对于快度的斜率均小于零

• *碰撞所产生介质性质的差异？需要更高精度的数据。*

• **STAR:** Phys. Rev. Lett. **120**, 062301(2018)

High-energy Nuclear Collisions



Initial conditions and interactions

Hot and Dense

Cooling down freezing out

Chemical/kinetic freezing out

Experimental probes:

1) ***Penetrating probes:*** "jets" **Energy loss**
2) ***Bulk probes*** **:Elliptic flow, radial flow**
3) ***Fluctuation*:**

Lee-Yang Zero Method

- Flow vector projection into arbitrary lab angel θ.

$$\mathbf{Q}_\mathbf{n}^\theta = \sum_{j=1}^{N} w_j \cos(n(\phi_j - \theta))$$

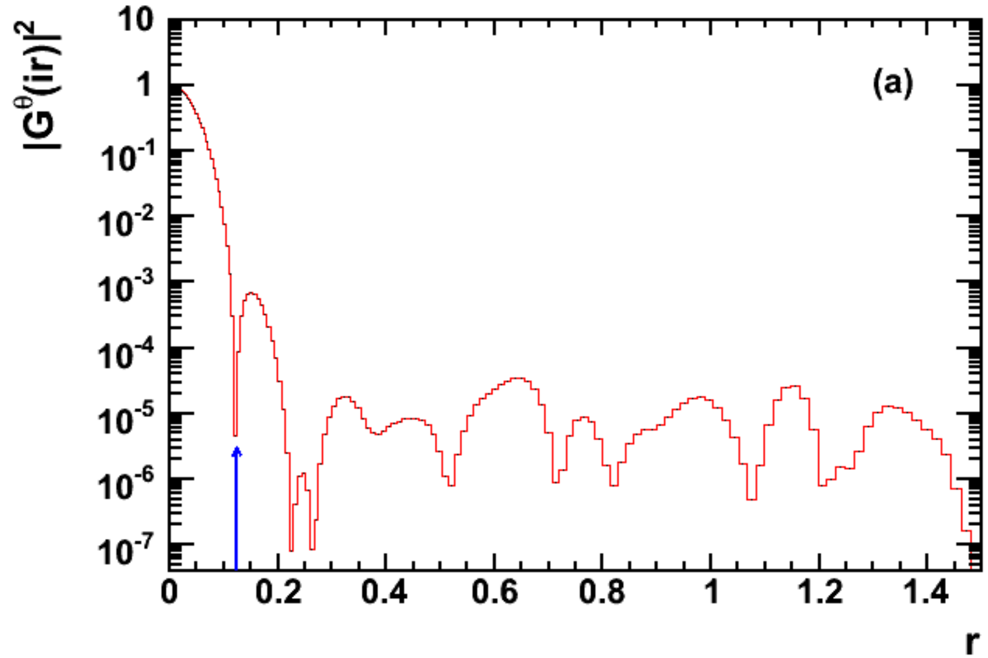
- Sum generating function for a given θ. First minimum determines r_0^θ.

$$\mathbf{G}_\mathbf{n}^\theta(\mathbf{r}) = \mid \langle e^{irQ_n^\theta} \rangle \mid$$

- Flow measured from r_0^θ using genuine correlations among all particles. Average over θ is to remove acceptance effect.

$$v_n(\eta, p_t) = \langle v_n^\theta(\eta, p_t) \rangle_\theta$$

- Suppress non-flow



$$V_n^\theta = j_{01}/r_0^\theta \qquad j_{01} = 2.405$$

$$v_n^\theta(\eta, p_t) = V_n^\theta \mathbf{Re}\left(\frac{\left\langle \cos[n(\psi - \theta)] e^{ir_0^\theta Q^\theta} \right\rangle}{\left\langle Q^\theta e^{ir_0^\theta Q^\theta} \right\rangle} \right)$$

All particles

R. S. Bhalerao, N. Borghini, J.-Y.Ollitrault, Nucl. Phy. A 727 (2003) 373-426

v_2 Methods

- Two-particle:
  - $v_2\{2\}$: each particle with every other particle
  - $v_2\{subEP\}$: each particle with the EP of the other subevent
  - $v_2\{EP\}$ "standard": each particle with the EP of all the others
  - $v_2\{SP\}$: same, weighted with the length of the Q vector

- Many-particle:
  - $v_2\{4\}$: 4-particle - 2 * (2-particle)^2
  - $v_2\{LYZ\}$: Lee-Yang Zeros multi-particle correlation

- Different sensitivities to nonflow and fluctuations

Review of azimuthal anisotropy: arXiv: 0809.2949

Hydro-motion in Nuclear Collisions

$$T^{\mu\nu} = \int dxdp \frac{p^{\mu}p^{\nu}}{p^{00}} f(xp)$$

$$T^{\mu\nu} = (\varepsilon + p)u^{\mu}u^{\nu} - pg^{\mu\nu},$$

$$u^{\mu} = \gamma(1, v)$$

$$\partial_{\mu} J_B^{\mu} = 0, \qquad J_B^{\mu} = n_B u^{\mu}$$

$$\partial_{\mu} s^{\mu} = 0, \qquad s^{\mu} = s u^{\mu}$$

f(x,p): phase space
- information on dynamics

$T^{\mu\nu}$: energy-momentum tensor

ideal hydrodynamics

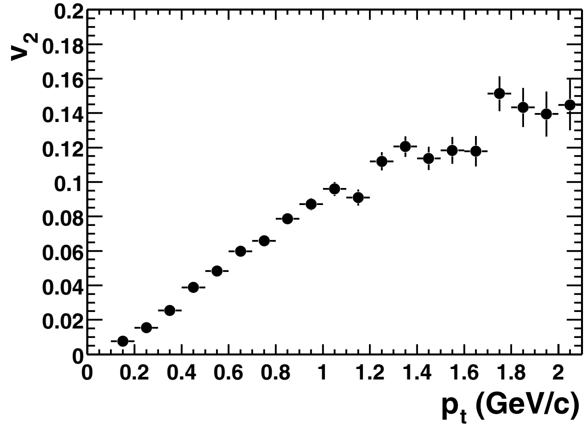
u^{μ}: 4-velocity, γ: Lorentz factor

K.J. Eskola, et al., nucl-th/9705015
L. Ch, ISBN-

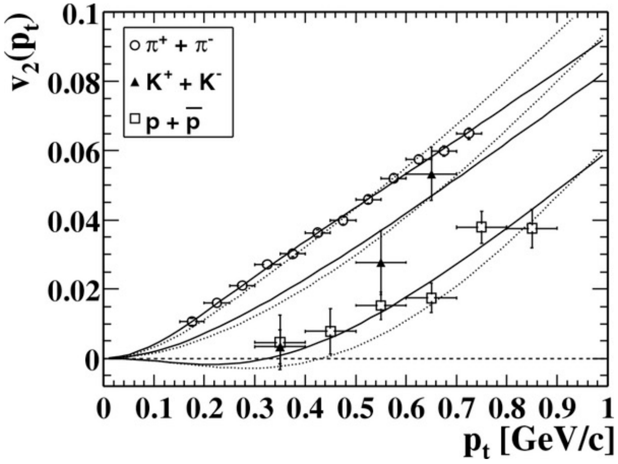
- Initial conditions (?)
- EOS (?)
- Freeze-out conditions (?)

$\Rightarrow$ Hydrodynamic solutions

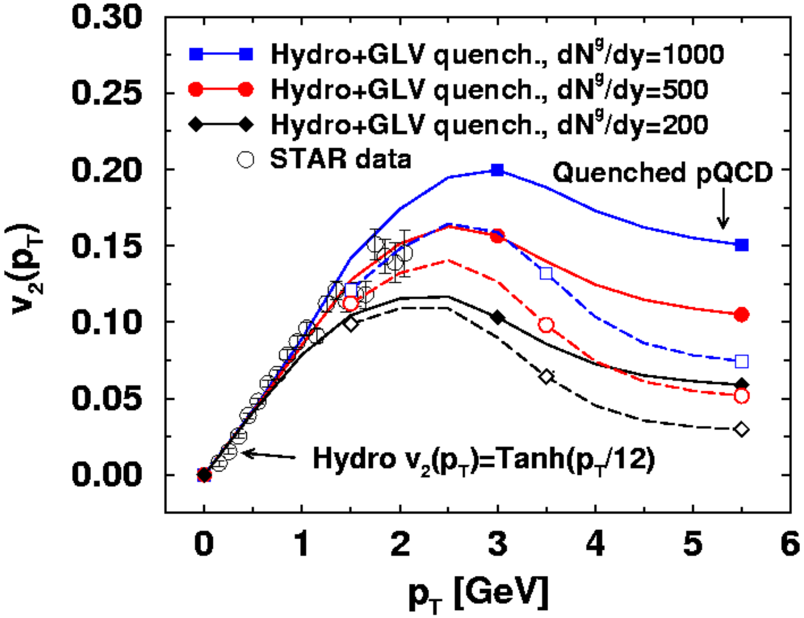
v_2 in Au Au Collisions at 130 GeV



STAR PRL 86,402(2001) 22k event



STAR: A. Tang PRL 87, 182301(2001) 120k events

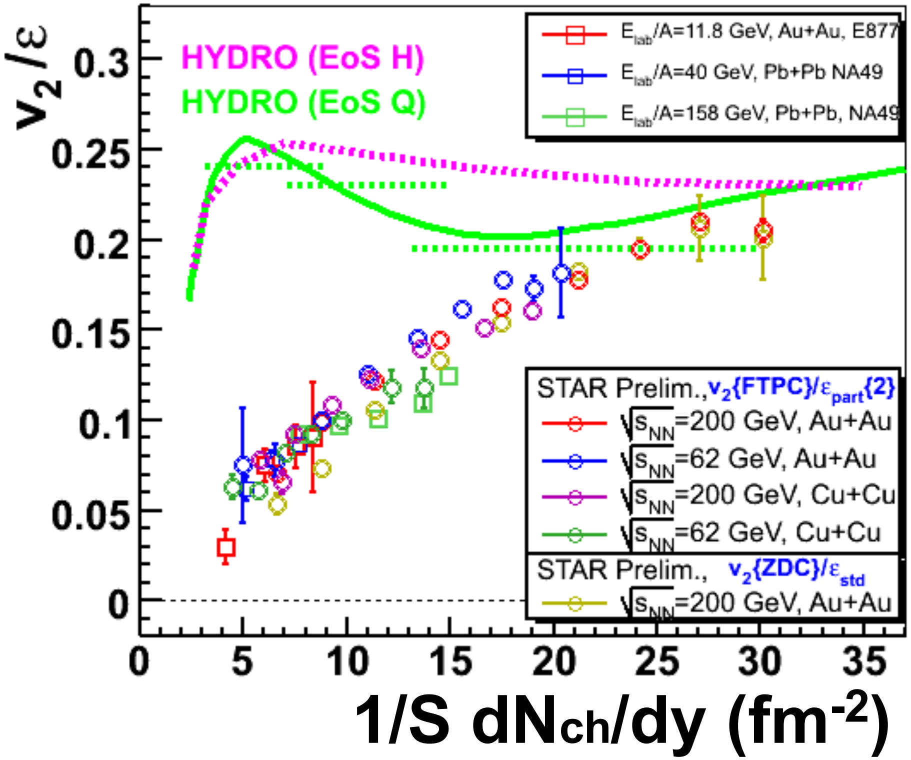


M. Gyulassy, I. Vitev and X.N. Wang, Phys. Rev. Lett. 86, 2537(2001).

$$v_2(p_t) \approx \frac{v_{2s}(p_t)dN_s + v_{2h}(p_t)dN_h}{dN_s + dN_h}$$

Towards Ideal Hydro Limit

S. A. Voloshin (STAR) : J. Phys. G**34**, S883 (2007)



H. Heiselberg, A.-M. Levy, PRC**59**, 2716 (1999)
S. A. Voloshin, A. M. Poskanzer, PLB**474**, 27 (2000)

Low density limit (LDL)

$$\frac{v_2}{\varepsilon} \propto \frac{1}{S}\frac{dN}{dy} \quad (\lambda \geq R)$$

Hydro limit

$$\frac{v_2}{\varepsilon} \propto \text{const.} \quad (\lambda \rightarrow 0)$$

- v_2/ε increase from AGS to RHIC.
- Has v_2/ε reached ideal hydro limit ?

- Need initial conditions for Hydro: ε, *u*μ at τ = τ0 Need equation of state $p = p(\varepsilon)$, which gives $c^2_s = dp/d\varepsilon$
- Need functions for transport coefficients η, ζ.
- Need algorithm to solve (nonlinear!) hydro equations
- Need method to convert hydro information to particles ("freeze-out")

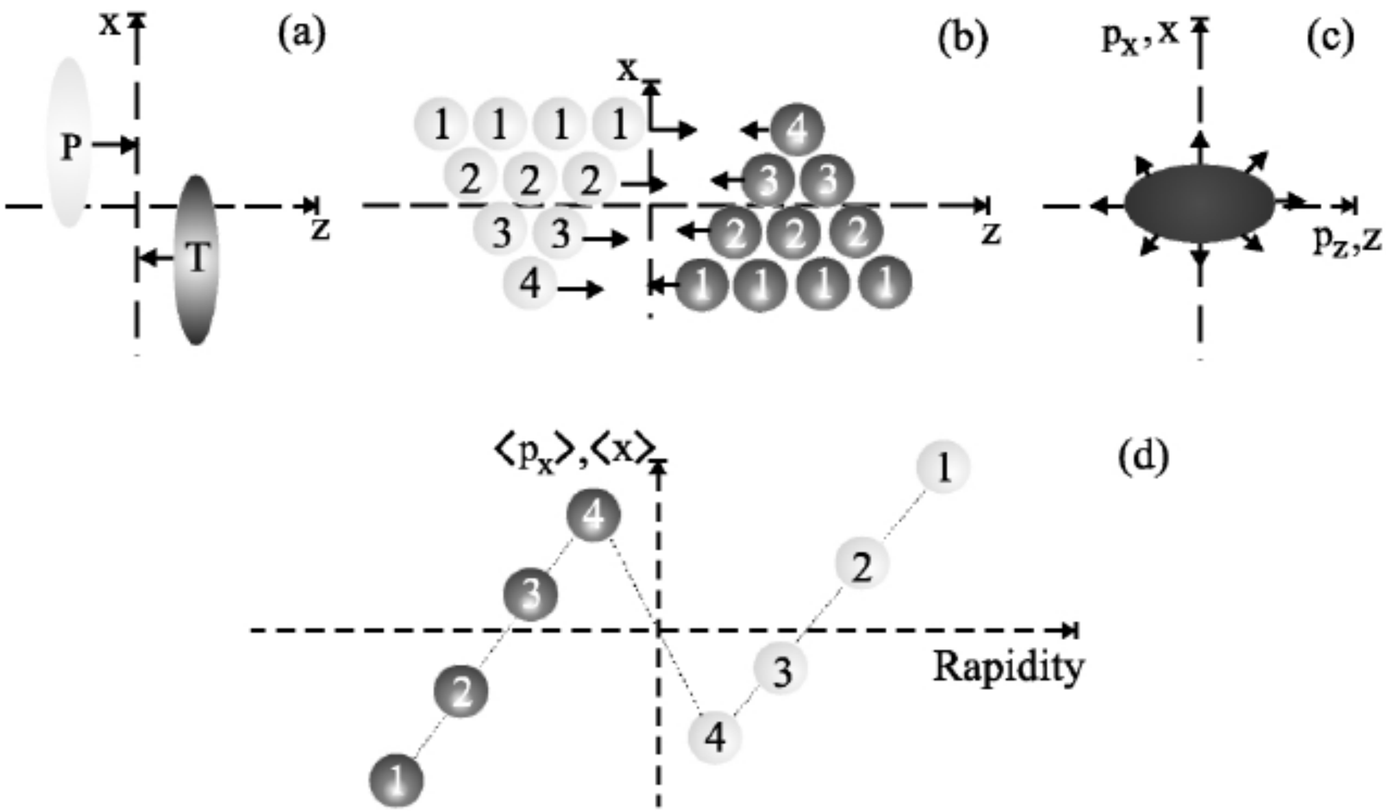
Initial Conditions

IC's for hydro not known. Here are some popular *choices*:

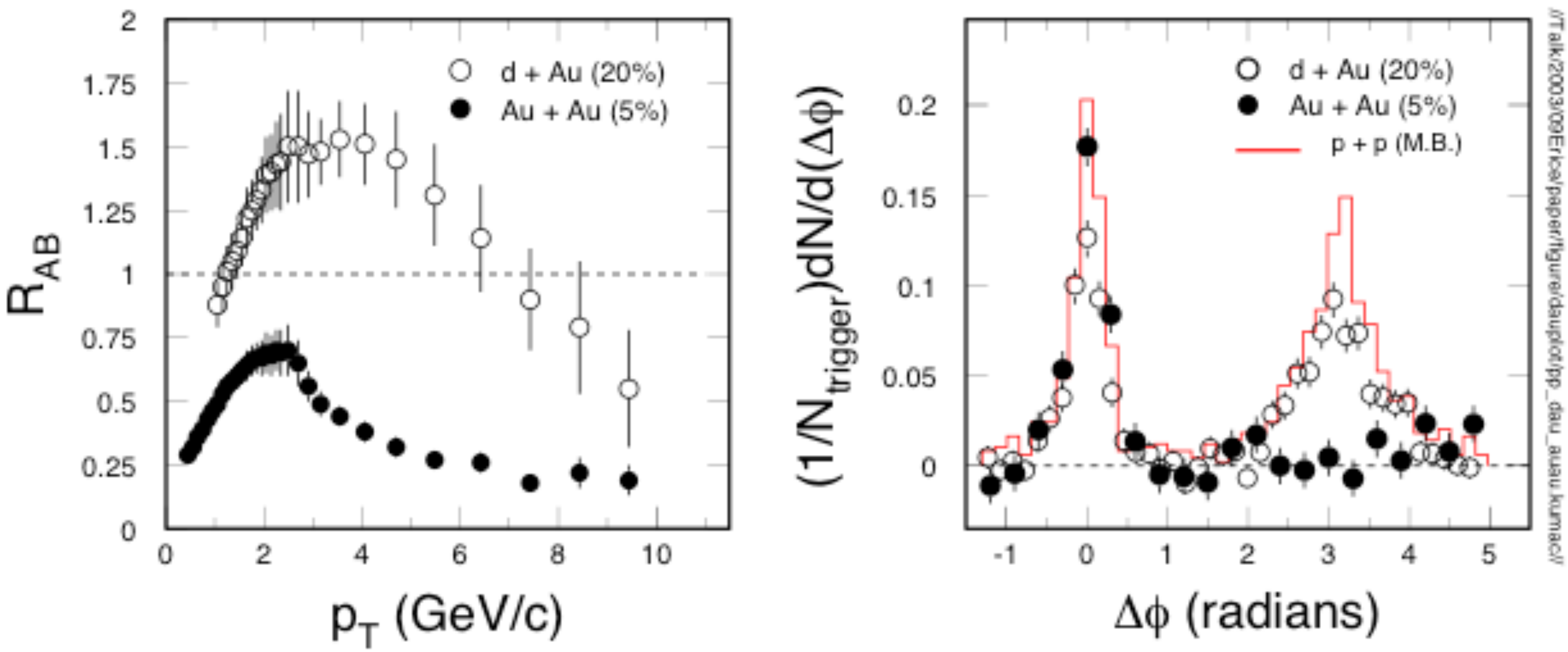
- Fluid velocities are set to zero
- Boost-invariance: all hydro quantities only depend on

proper time $\tau = \sqrt{(t^2 - z^2)}$ and transverse space $\mathbf{x}_\perp$.

- Models for energy density distribution Glauber/Color-Glass-Condensate
- Starting time τ_0: Should be of order 1 fm, precise value unknown


(a)
x
P
T
z
(b)
x
1 1 1 1
2 2 2
3 3
4
4
3 3
2 2 2
1 1 1 1
z
(c)
p_x, x
p_z, z
(d)
⟨p_x⟩,⟨x⟩
Rapidity
1
2
3
4
1
2
3
4

Suppression and Correlation



In central Au+Au collisions: hadrons are suppressed and back-to-back 'jets' are disappeared. Different from p+p and d+Au collisions.

Energy density at RHIC: ε > 5 GeV/fm^3 ~ 30ε_0

Parton energy loss:	Bjorken	1982
("**Jet quenching**")	Gyulassy & Wang	1992

…