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 and N. Xu for exciting discussions !

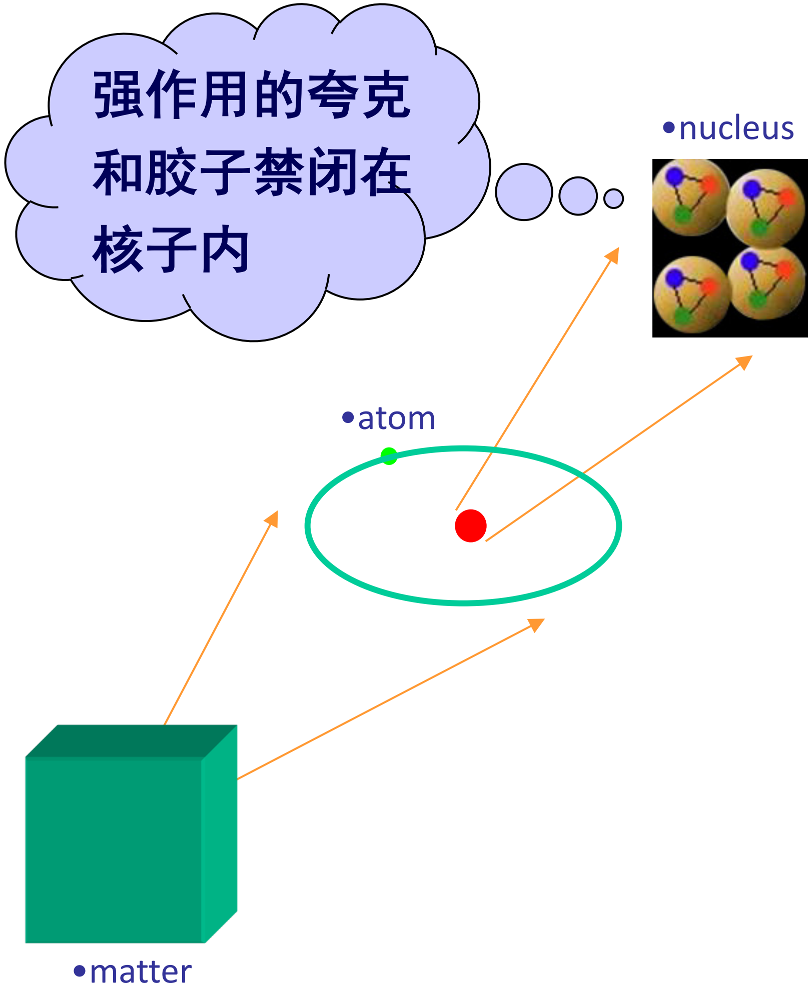
2022年8月14-15日 复旦

Outline

- Introduction
- Collectivity
- Criticality
- Summary and Outlook

Two Puzzles of Modern Physics

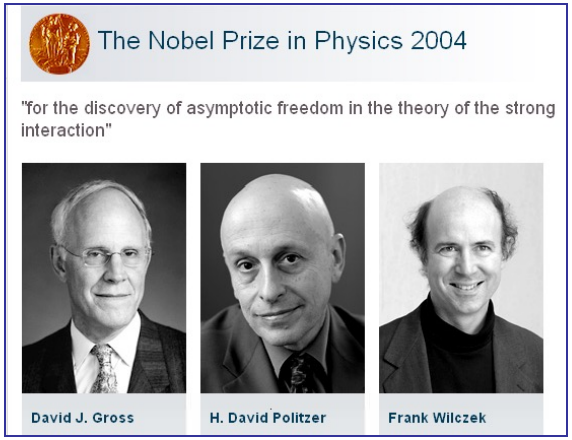
-- T.D.Lee



强作用的夸克和胶子禁闭在核子内

- 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)



The Nobel Prize in Physics 2004

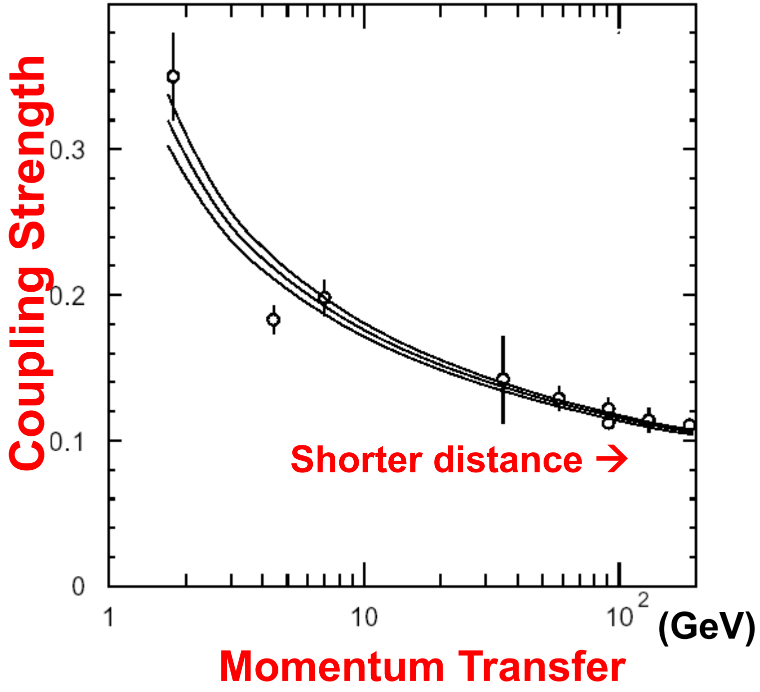
"for the discovery of asymptotic freedom in the theory of the strong interaction"

David J. Gross

H. David Politzer

Frank Wilczek

Asymptotic Freedom

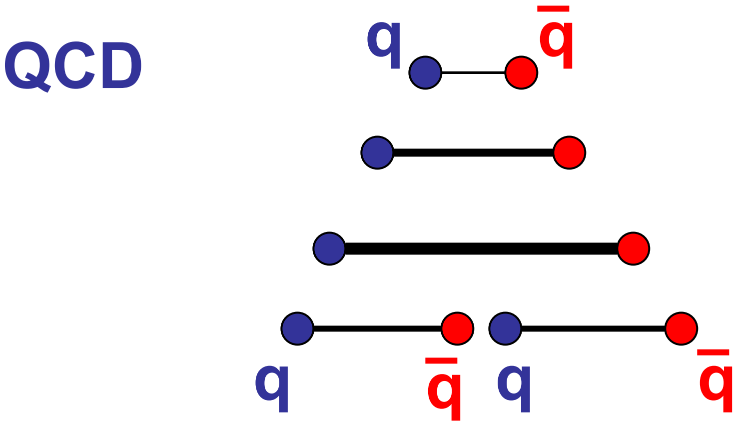


Quark Confinement:

庄子天下篇 ~ 300 B.C.

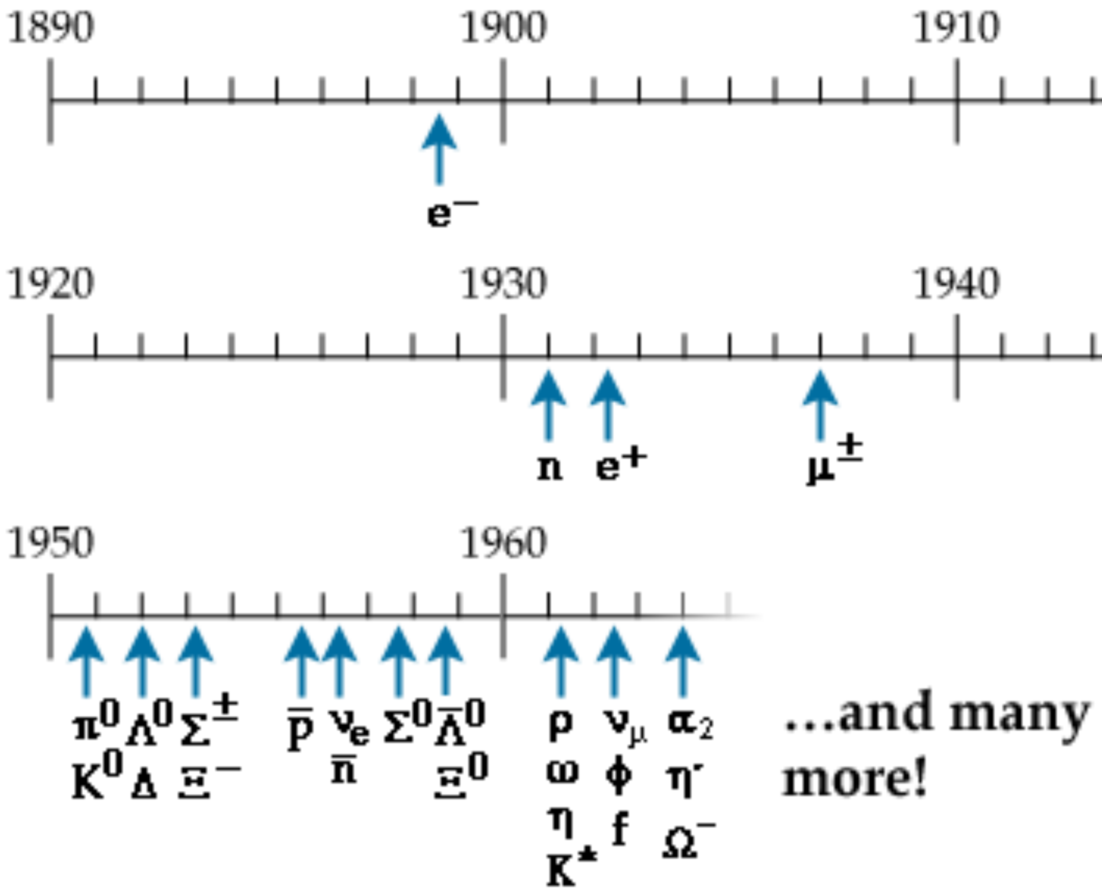
一尺之棰，日取其半，万世不竭

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



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

Particles discovered 1898 - 1964



…and many more!

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

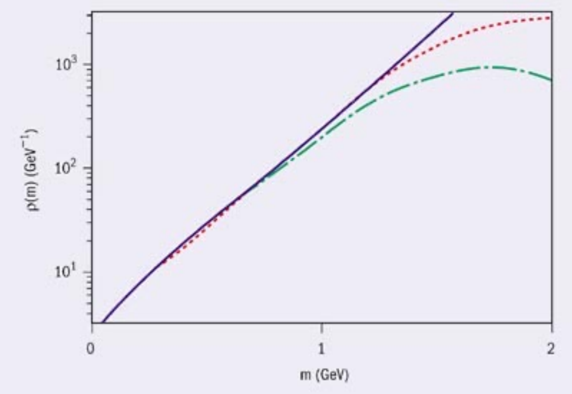
$$N(T) \sim \int_0^\infty \rho(m)\, e^{-\frac{m}{T}} \mathrm{d}m$$

$\rho(m)\,\mathrm{d}m$ 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!)

Federico Antinori QM2022

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

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

- inserting Hagedorn’s spectrum:

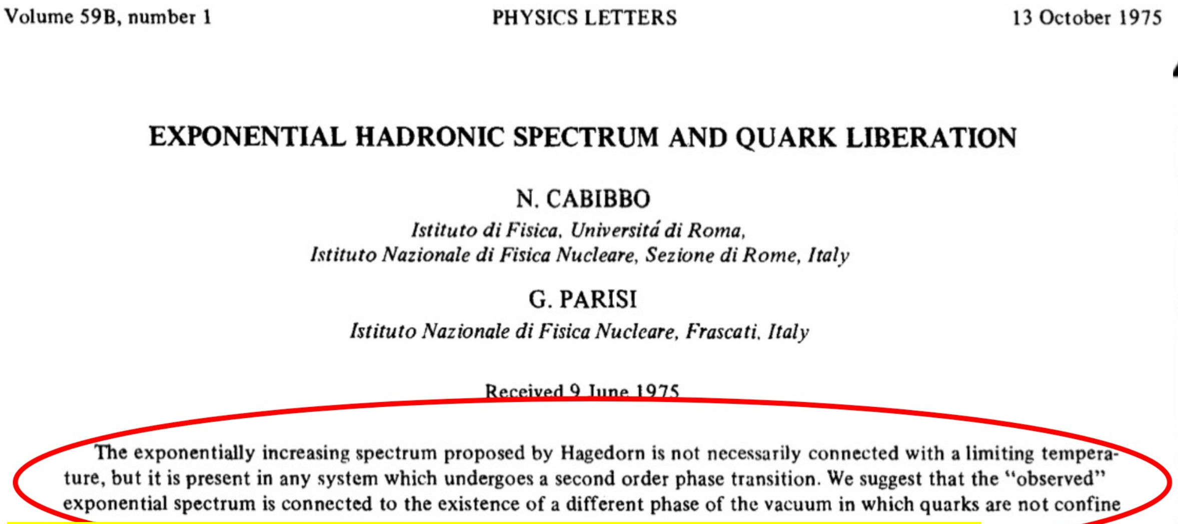
$$lnZ(T,V) \approx V\left[\frac{T}{2\pi}\right]^{3/2} \int \frac{dm}{m^{3/2}} e^{-\left[\frac{m}{T}-\frac{m}{T_H}\right]} \leftarrow$$ divergesforT→T_H

  - ○ 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。

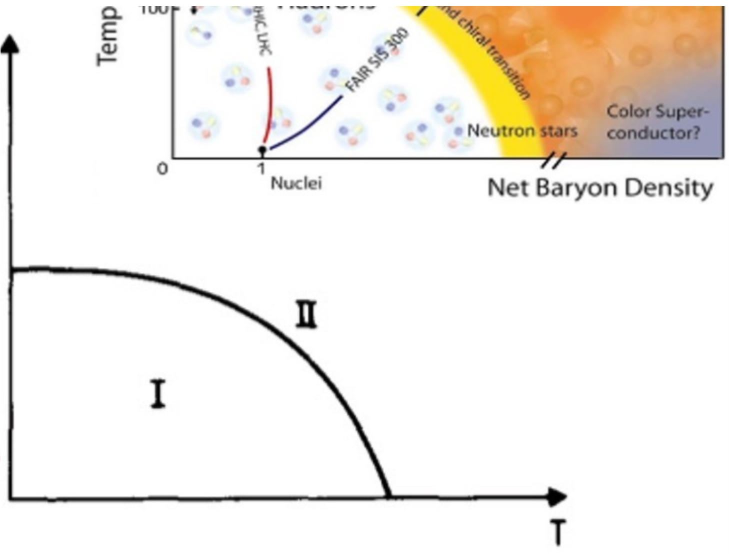
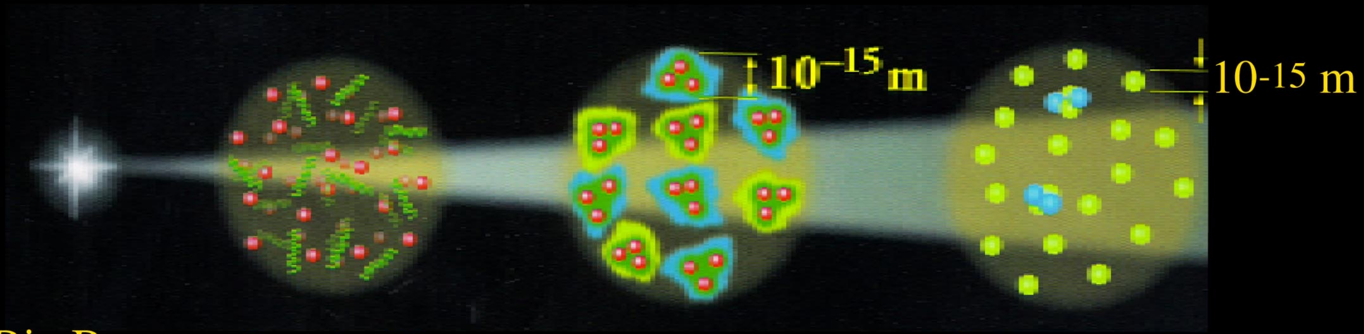


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

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

History of the Universe

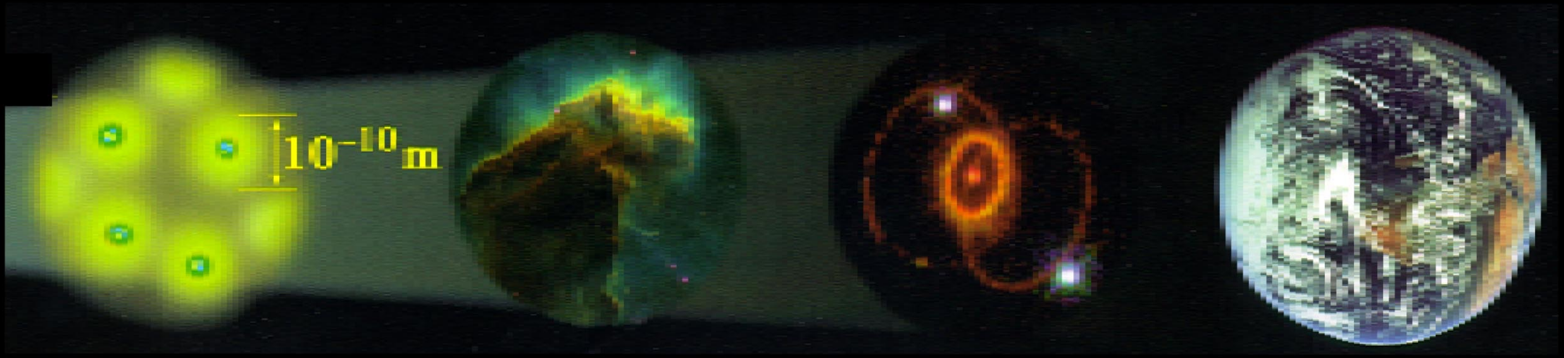


Big Bang

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

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

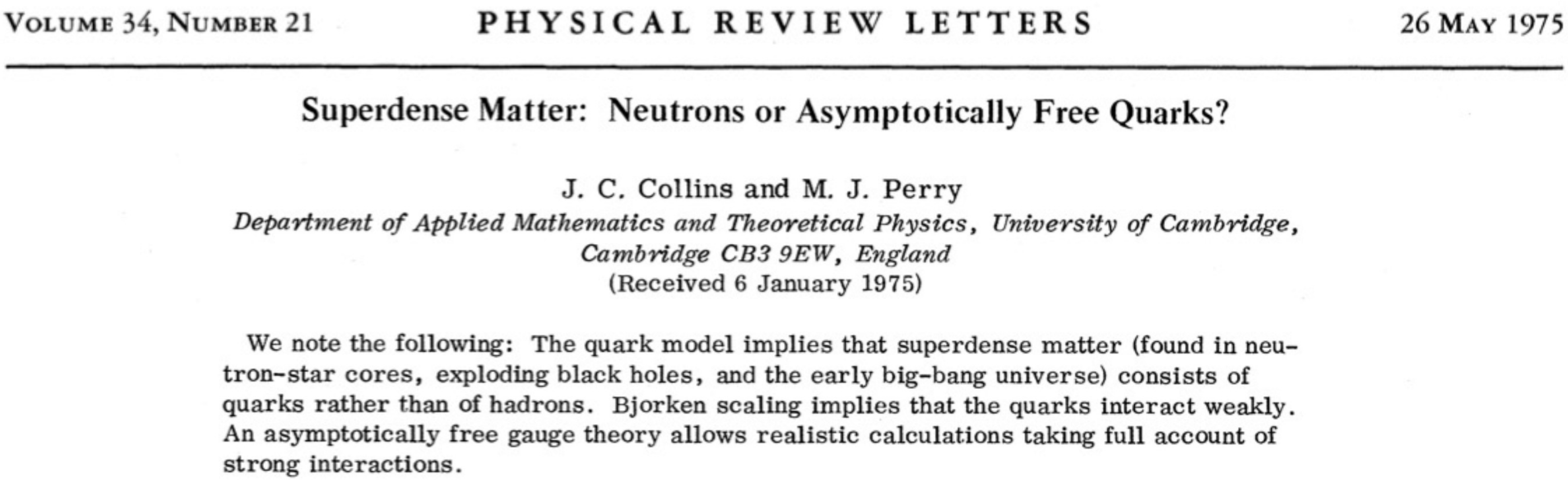
由夸克和胶子组成的等离子体。

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

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



VOLUME 34, NUMBER 21 PHYSICAL REVIEW LETTERS 26 MAY 1975

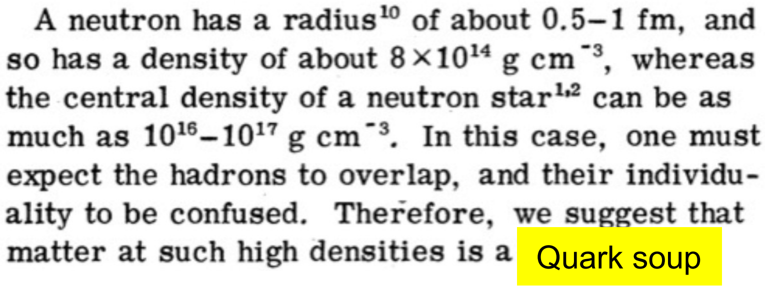
Superdense Matter: Neutrons or Asymptotically Free Quarks?

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.

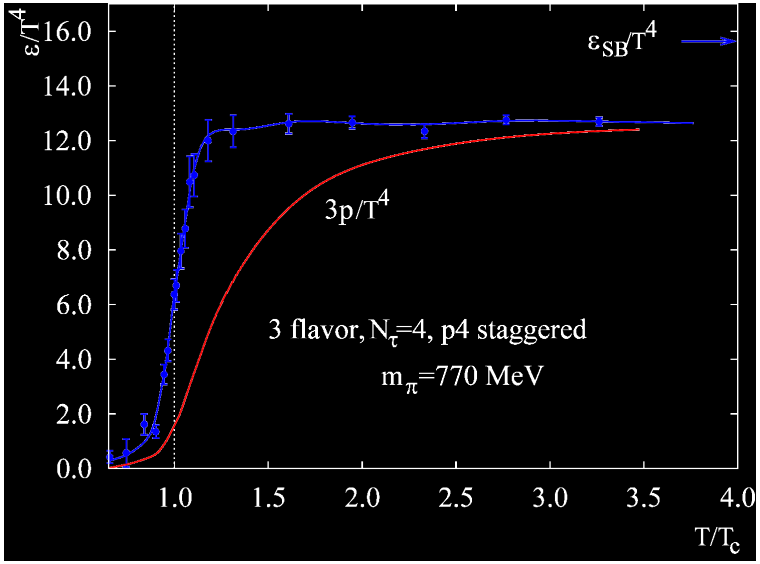
the basic argument is contained in only a few lines...



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

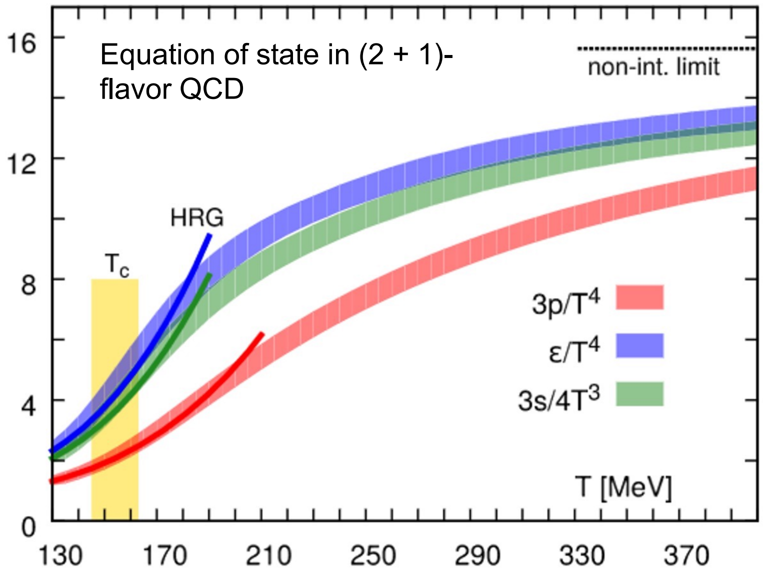
中子的半径约0.5~1fm,密度约 8x10^{14}gcm^{-3}, 中子星的中心约 10^{16}~10^{17}gcm^{-3}.在这种情况下,强子重叠，它们的个性被混淆，我们认为如此高密度的物质是“**夸克汤**”

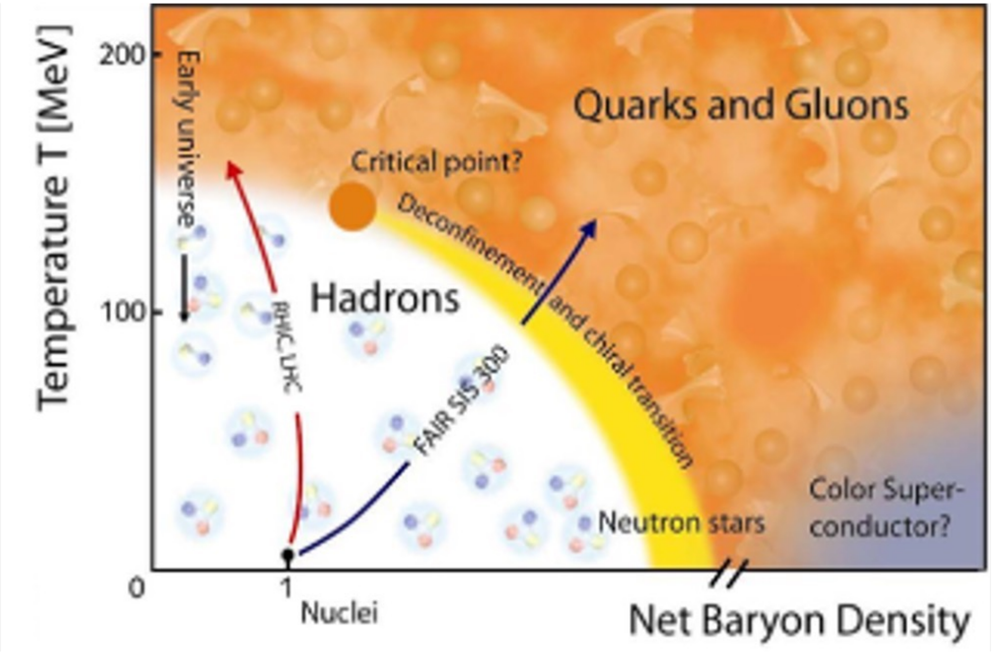
Lattice QCD



- 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!!
- $T_c \sim 170$ MeV, $\varepsilon_C = 0.6$ GeV/fm^3

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





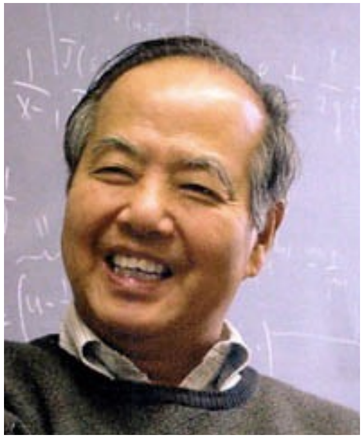
How to Address the Problem?

The confinement:

Quarks are the basic building blocks of matter.

No free quarks are seen, confined within hadron:

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



T.D. Lee

重要的科学问题：

夸克能否解除禁闭，产生新物质形态—夸克胶子等离子体（QGP）？

QCD 相结构 ？相变临界点是否存在 ？

Heavy ion collisions: Large, hot/dense system

$\Delta v \sim 1000\ \mathrm{fm}^3 = 1000\ v_0$

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

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

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

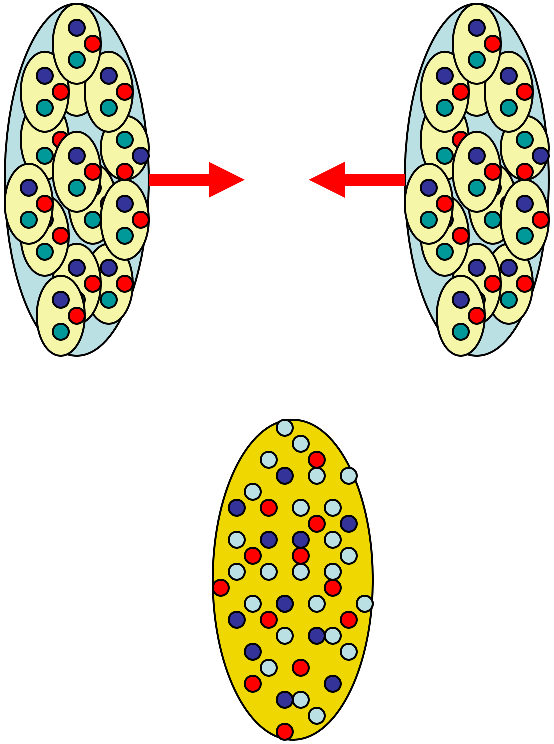
New form of ***matter with partonic degrees of freedom***

QCD Phase Structure

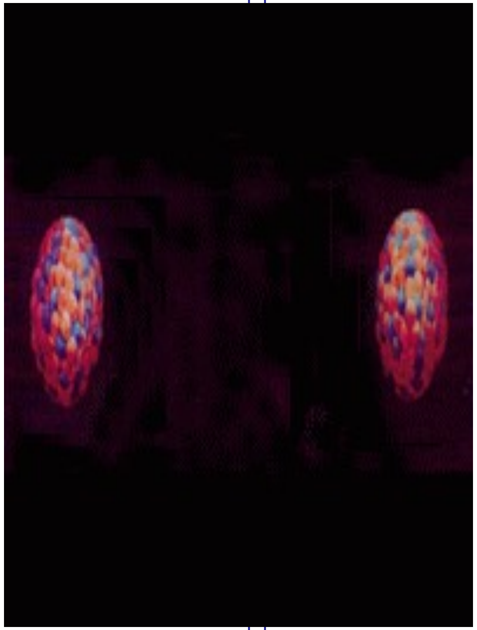
- Connection with other fields，cosmology, origin of the universe, evolution of the universe
  quantum statistics with partons

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

Matter Compression:

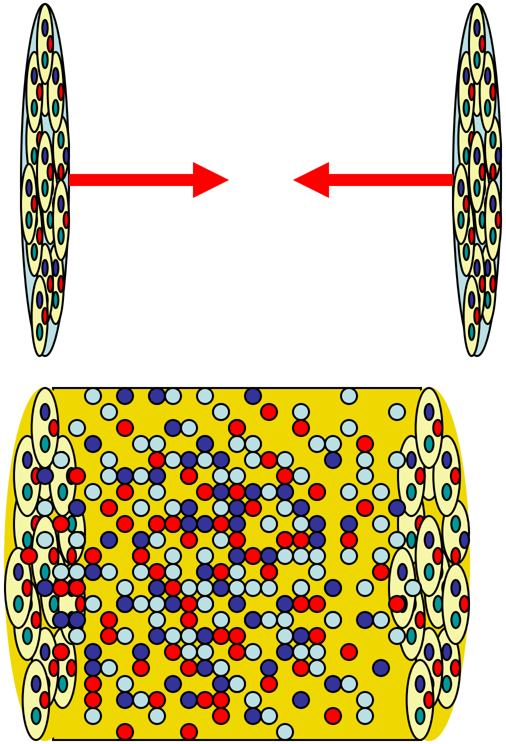


High Baryon Density
-- low energy heavy ion collisions
-- neutron star→quark star



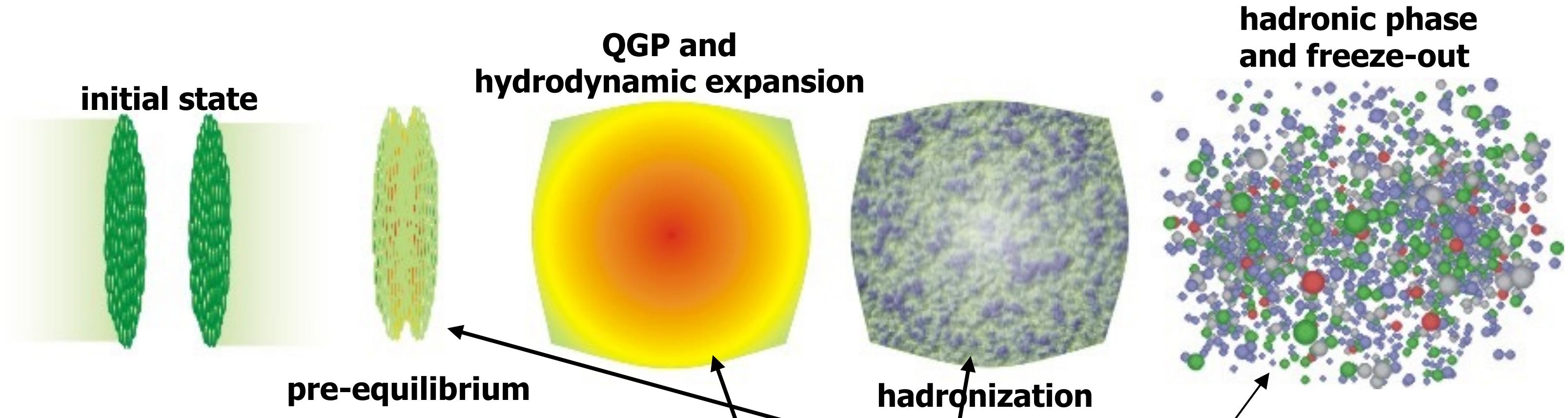
Deconfinement

Vacuum Heating:



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

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.

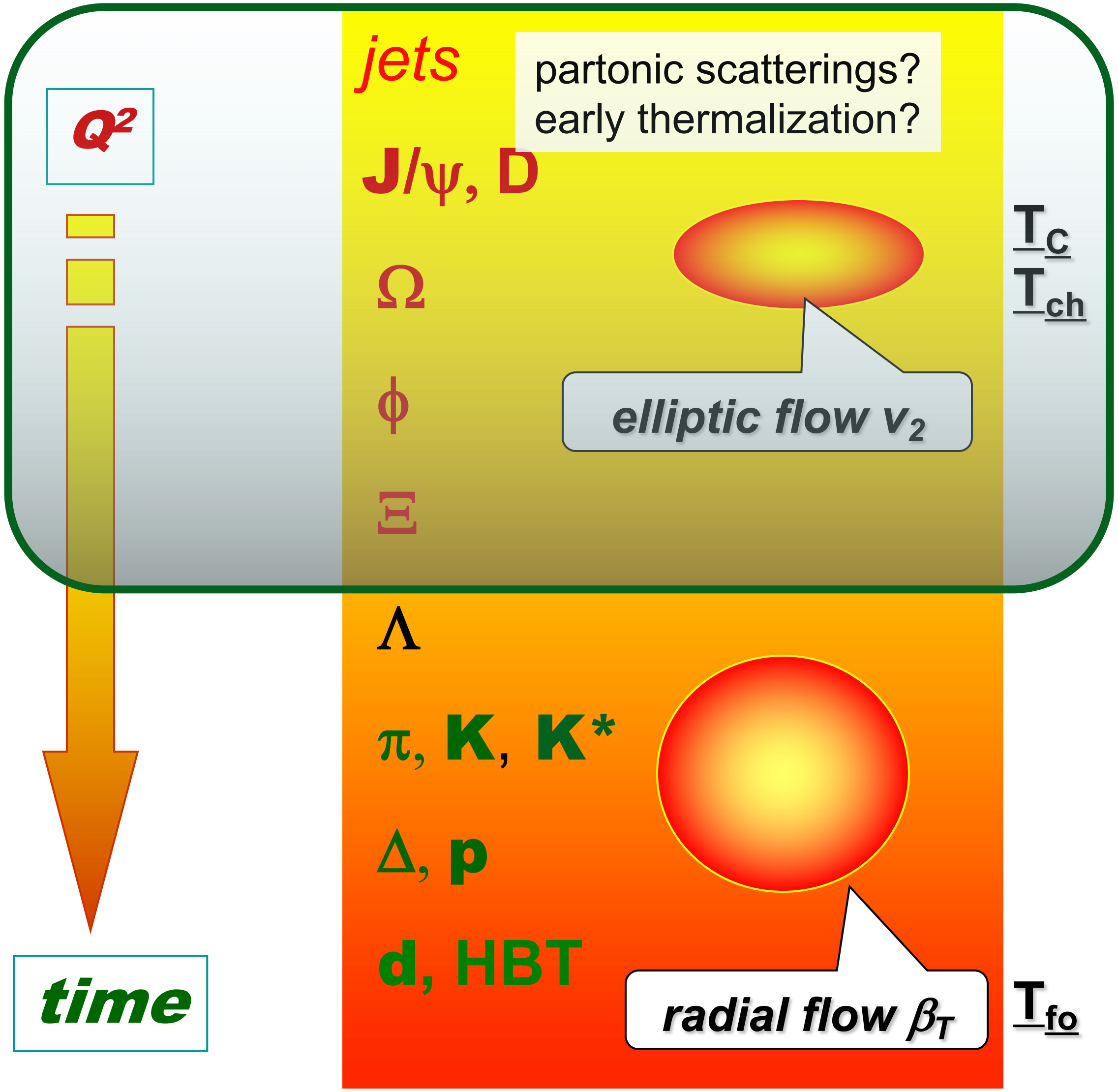
Experimental probes:
1) ***Penetrating probes:*** "jets" **Energy loss**
2) ***Bulk probes*** **:Elliptic flow, radial flow**
3) ***Fluctuation*****:**

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



Q^2

time

jets

partonic scatterings?
early thermalization?

J/ψ, D

Ω

φ

Ξ

Λ

π, K, K*

Δ, p

d, HBT

elliptic flow v_2

radial flow β_T

T_C

T_{ch}

T_{fo}

1980's: the hunt is on ...

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

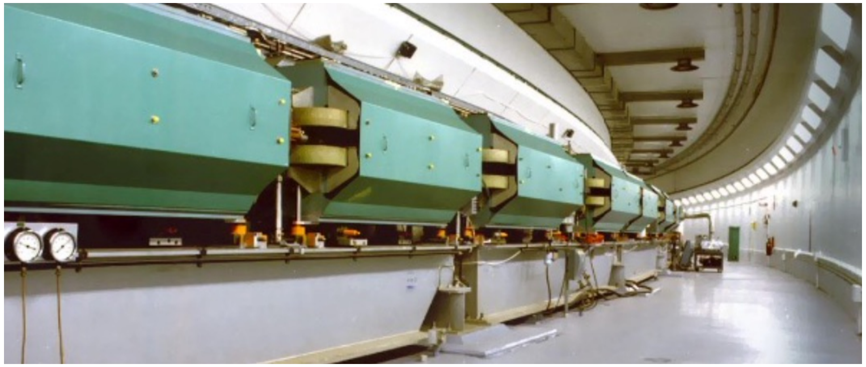
$\sqrt{s_{NN}} \sim$ 5 GeV , O (1986), Si (1987), Au (1993)

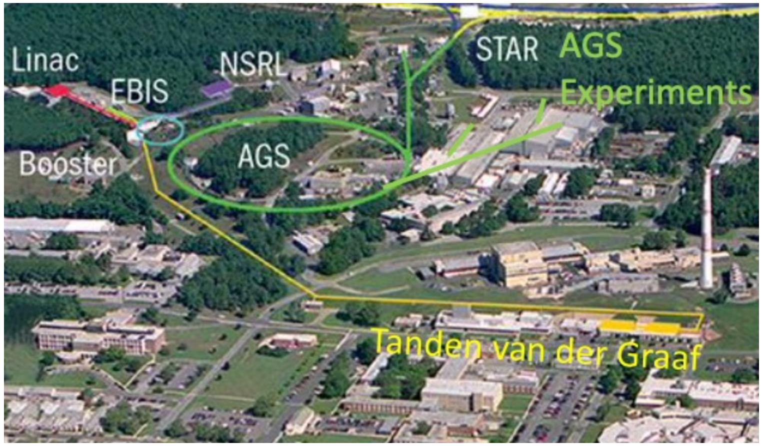
○ at the Super-Proton Synchrotron (SPS) at CERN (Geneva)

$\sqrt{s_{NN}}$ ~ 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

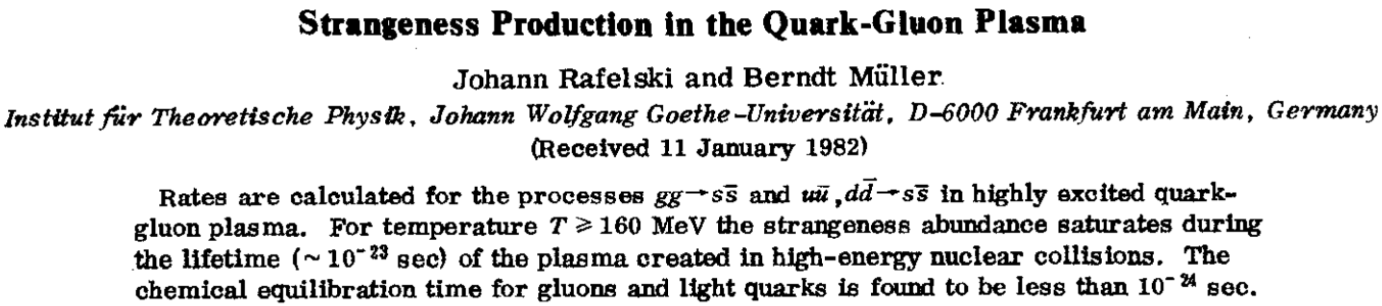
Two historic predictions...

- 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)

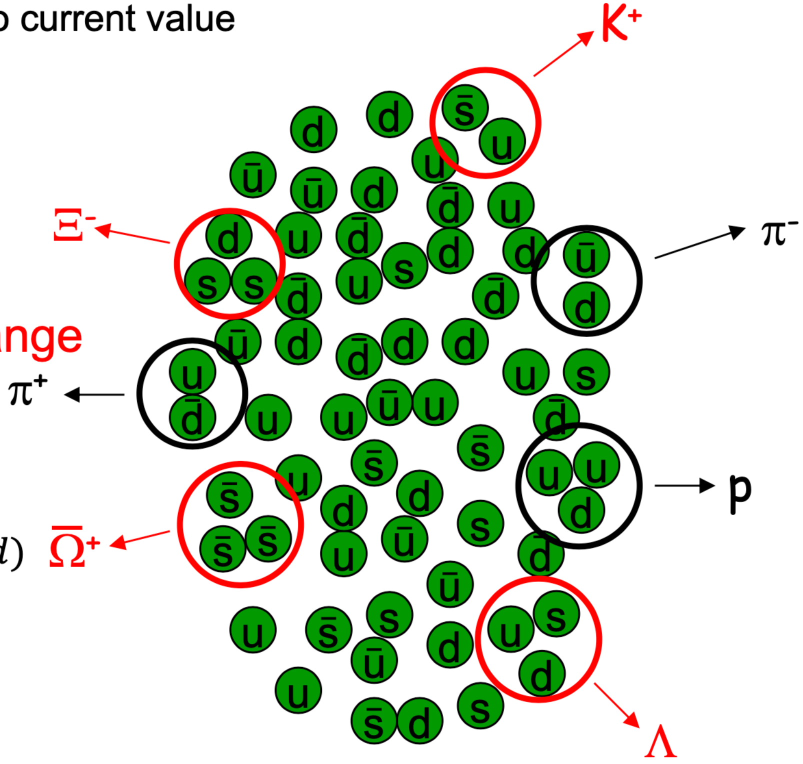
Rates are calculated for the processes $gg \to s\bar{s}$ and $u\bar{u}, d\bar{d} \to s\bar{s}$ in highly excited quark-gluon plasma. For temperature $T \gtrsim 160$ MeV the strangeness abundance saturates during the lifetime ($\sim 10^{-23}$ sec) of the plasma created in high-energy nuclear collisions. 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 ~ 150 MeV ~ Tc
  - → copious production of $s\bar{s}$ pairs, mostly by gg fusion

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

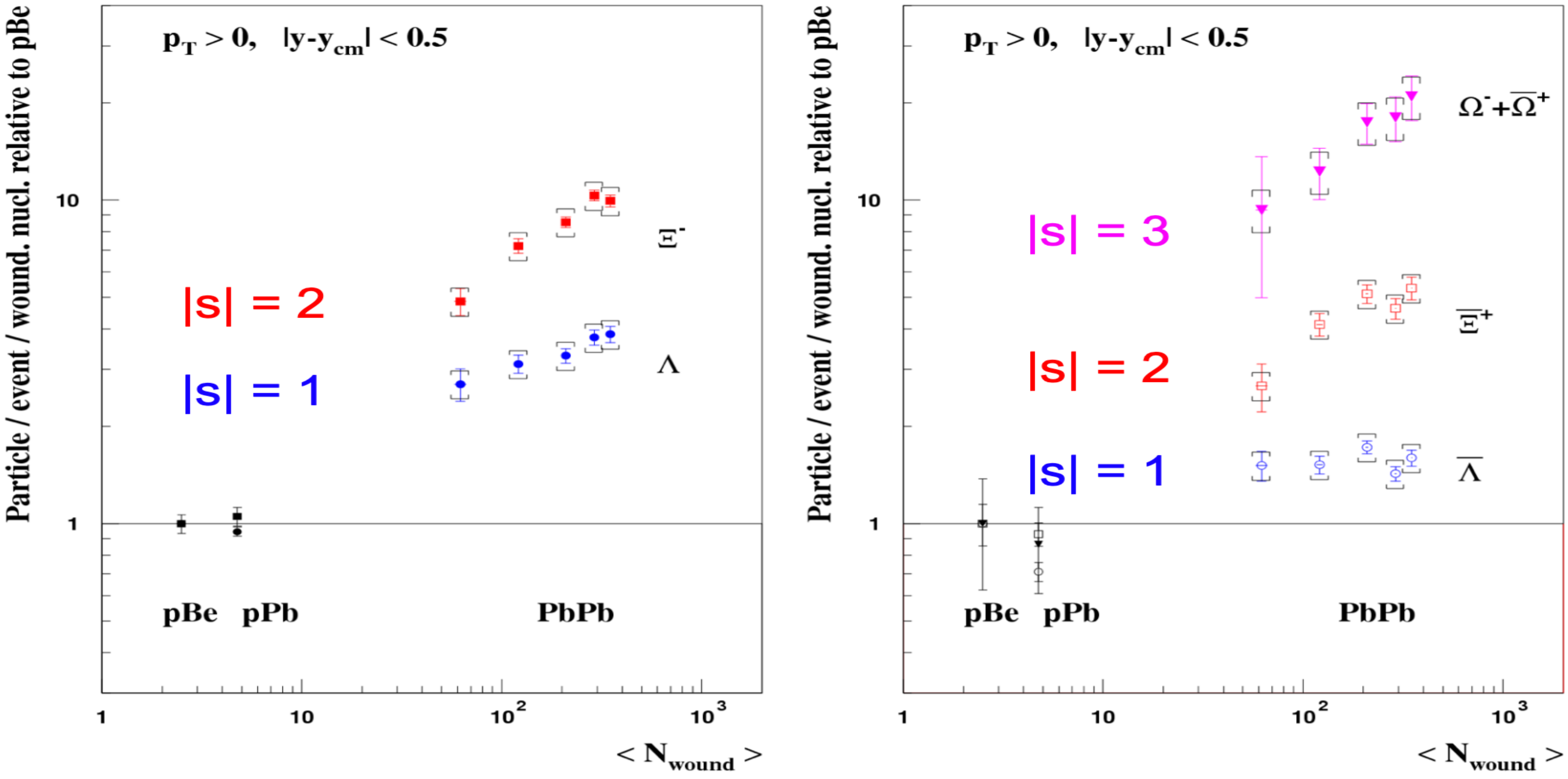
    [J Rafelski and B Müller: Phys. Rev. Lett. 48 (1982) 1066]
- deconfinement → stronger effect for multi-strange
  - ○ can be built recombining s quarks
  - → strangeness enhancement increasing with strangeness content
  - → expect larger for $\Omega(sss)$ than for $\Xi(ssd)$ than for $\Lambda(sud)$

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



Strangeness enhancement at the SPS

WA97/NA57

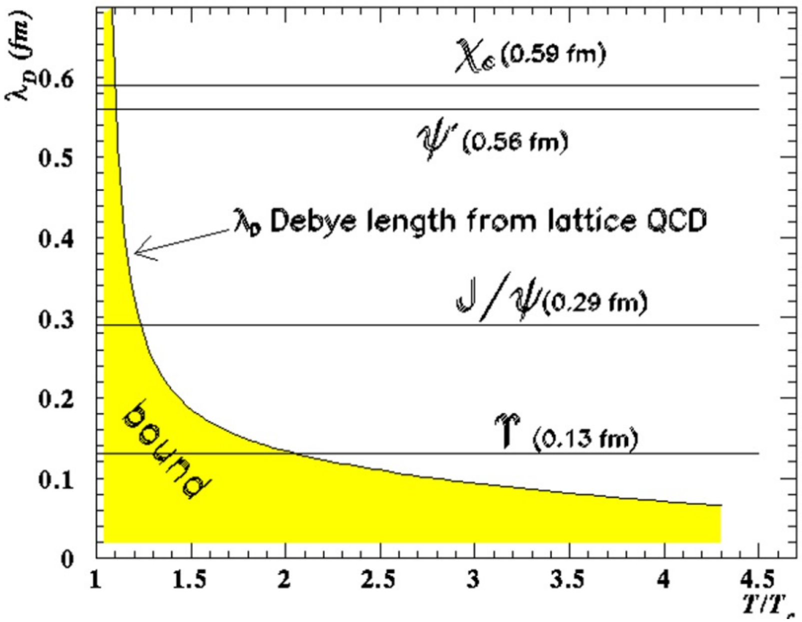


- enhancement relative to p-Be, p-Pb
- increasing with |S|
- up to ~ x 20 for the Ω

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



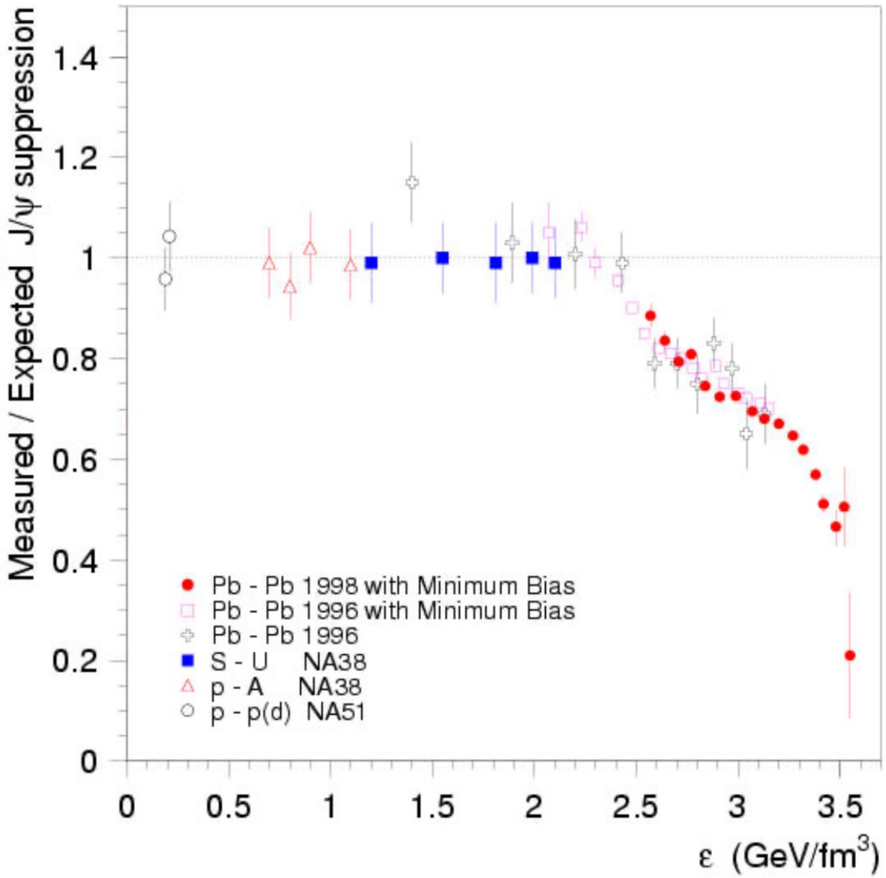
states with radius > λ_D
will not bind ♋ suppressed

- $J/\psi, \psi', \chi'$ → $c\bar{c}$ states
- Υ → $b\bar{b}$ states

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

J/ψ suppression at the SPS

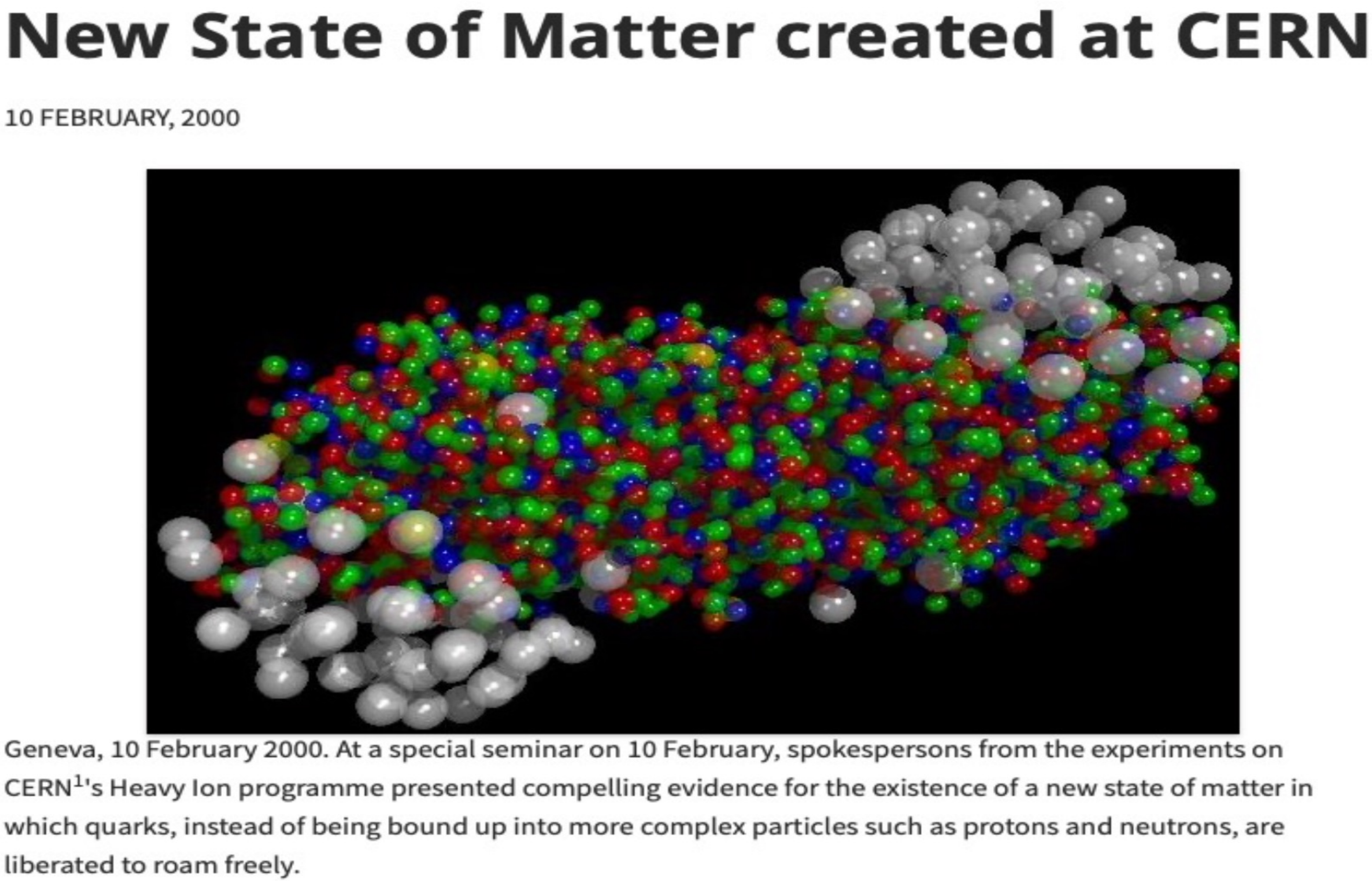
NA50: “anomalous” suppression



- 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



New State of Matter created at CERN

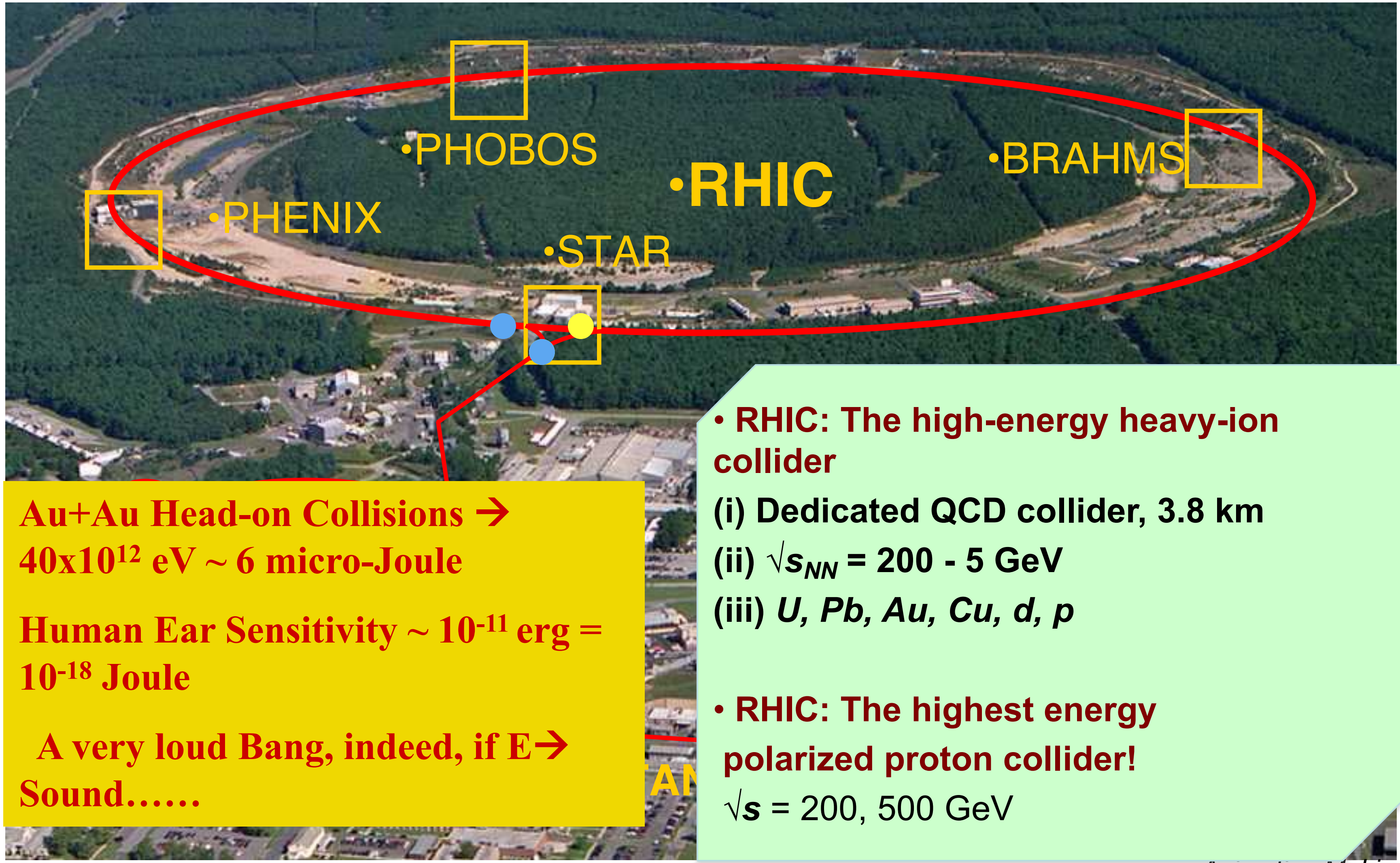
10 FEBRUARY, 2000

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!**

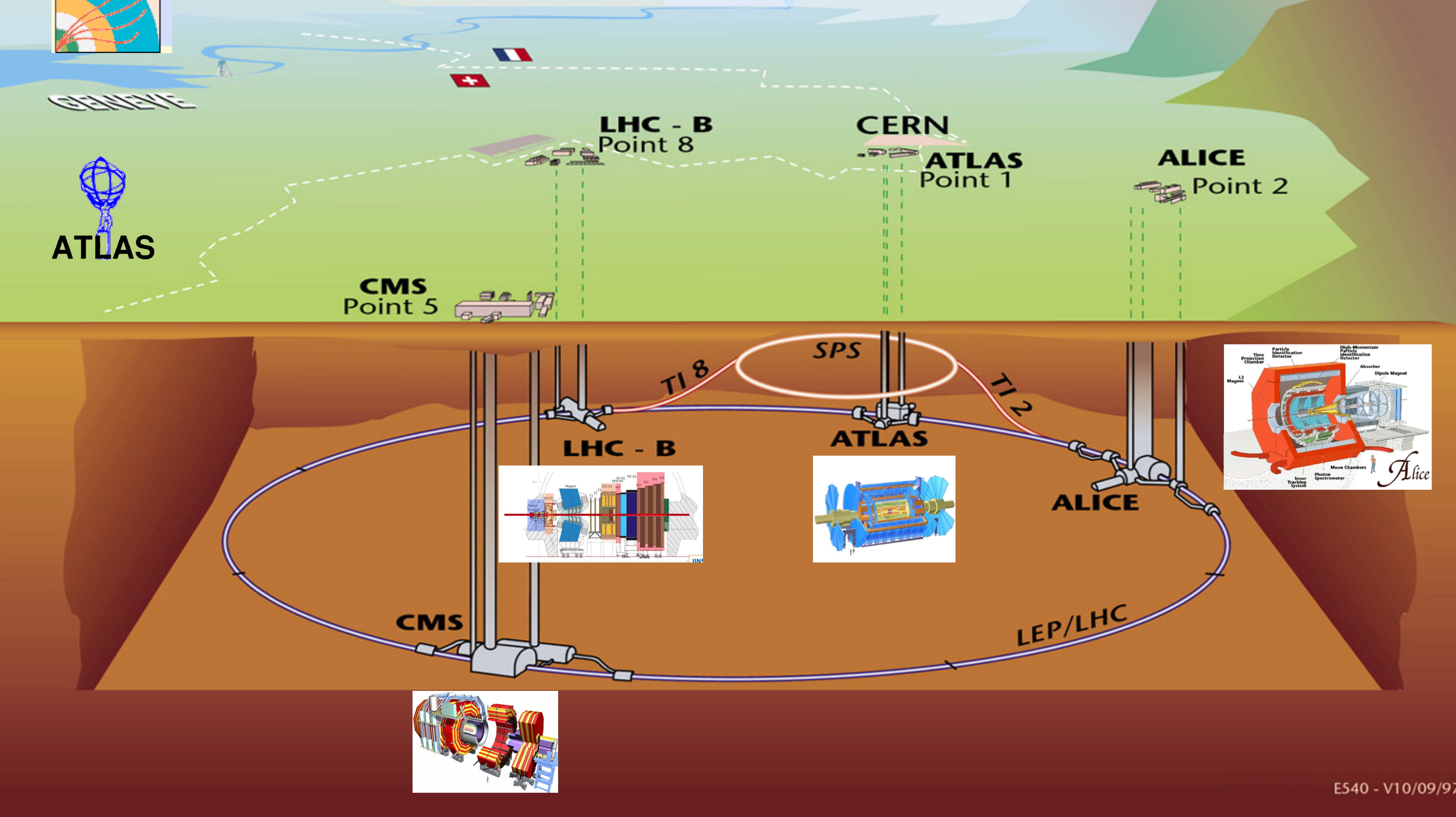
$\sqrt{s}$ = 200, 500 GeV

•*Animation M. Lisa*

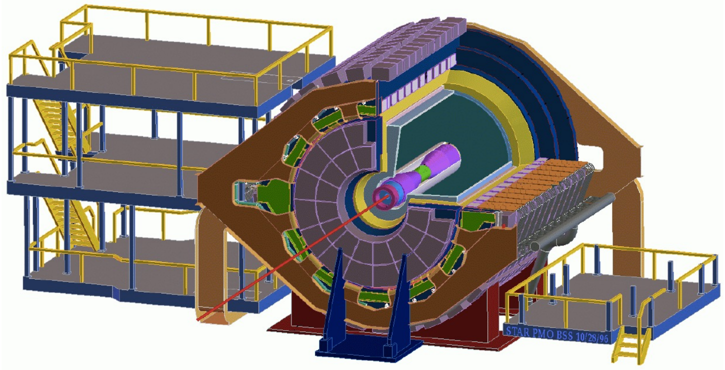
Overall view of the LHC experiments.

One dedicated HI experiment: ALICE

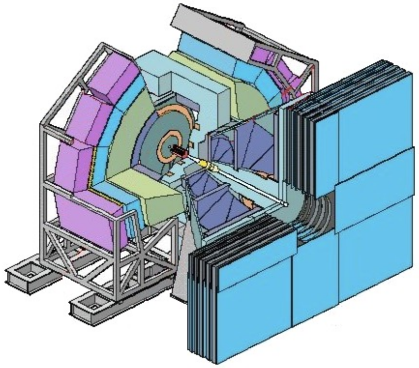
Two pp experiments with HI program: ATLAS and CMS



High-Energy Nuclear Collider Experiments

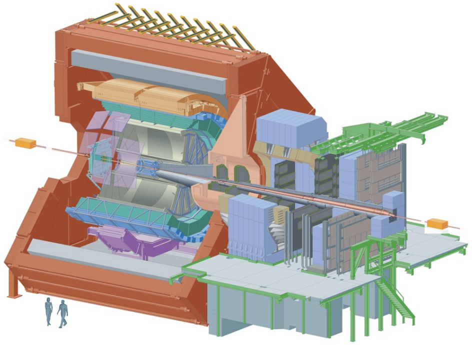


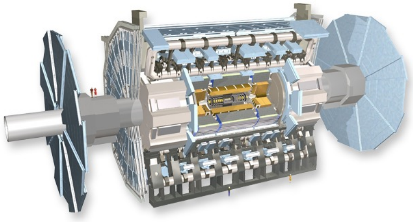
STAR (Solenoidal Tracker At RHIC)



PHENIX (Pioneering High Energy Nuclear Ion Experiment)

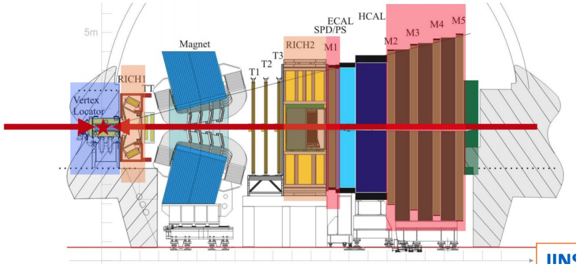
ALICE (A Large Ion Collider Experiment)

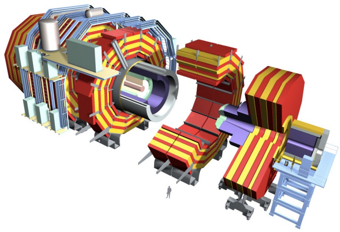




•**ATLAS** (A Toroidal LHC Apparatus)

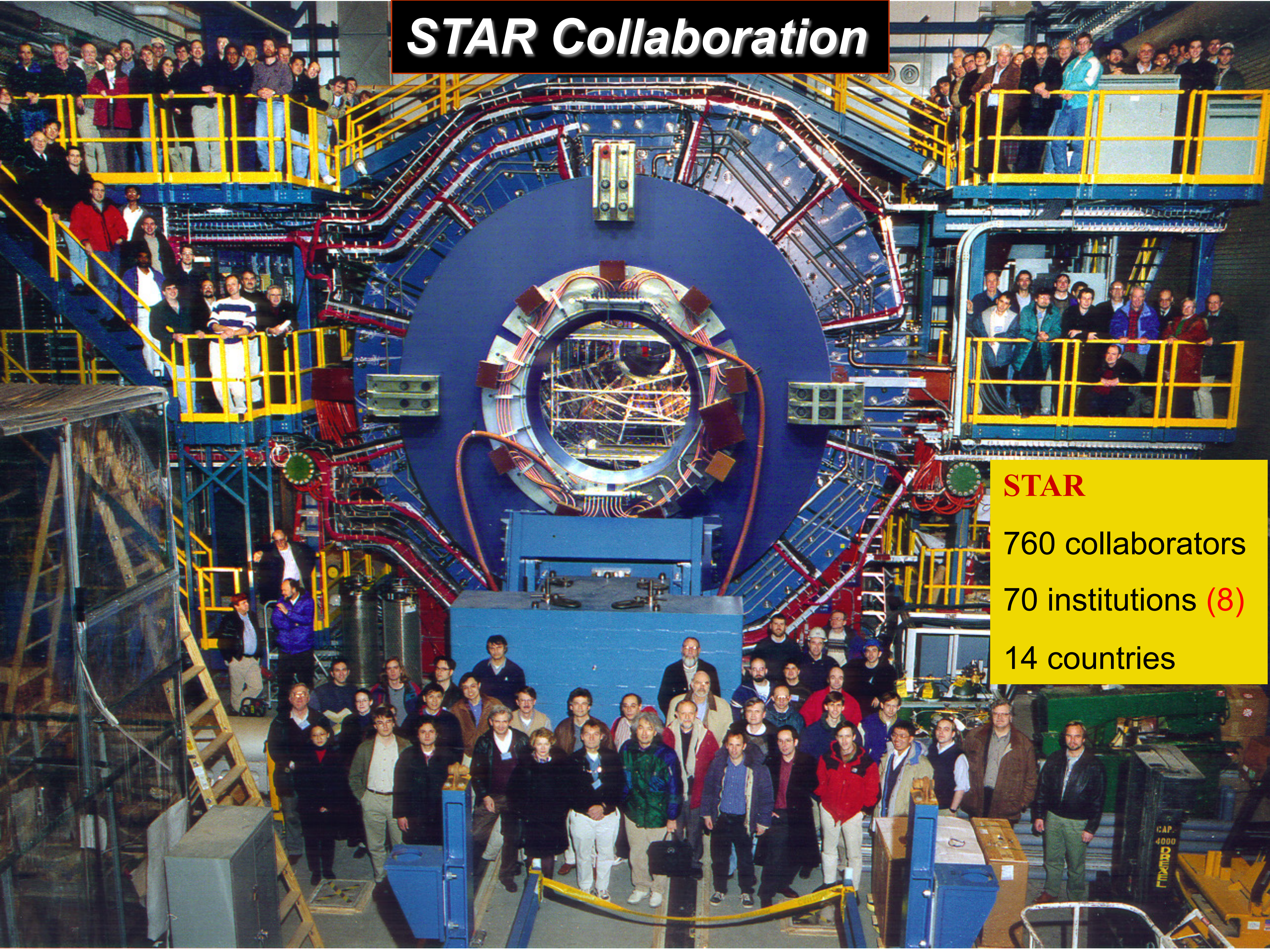
LHCb





CMS (Compact Muon Solenoid)

STAR Collaboration



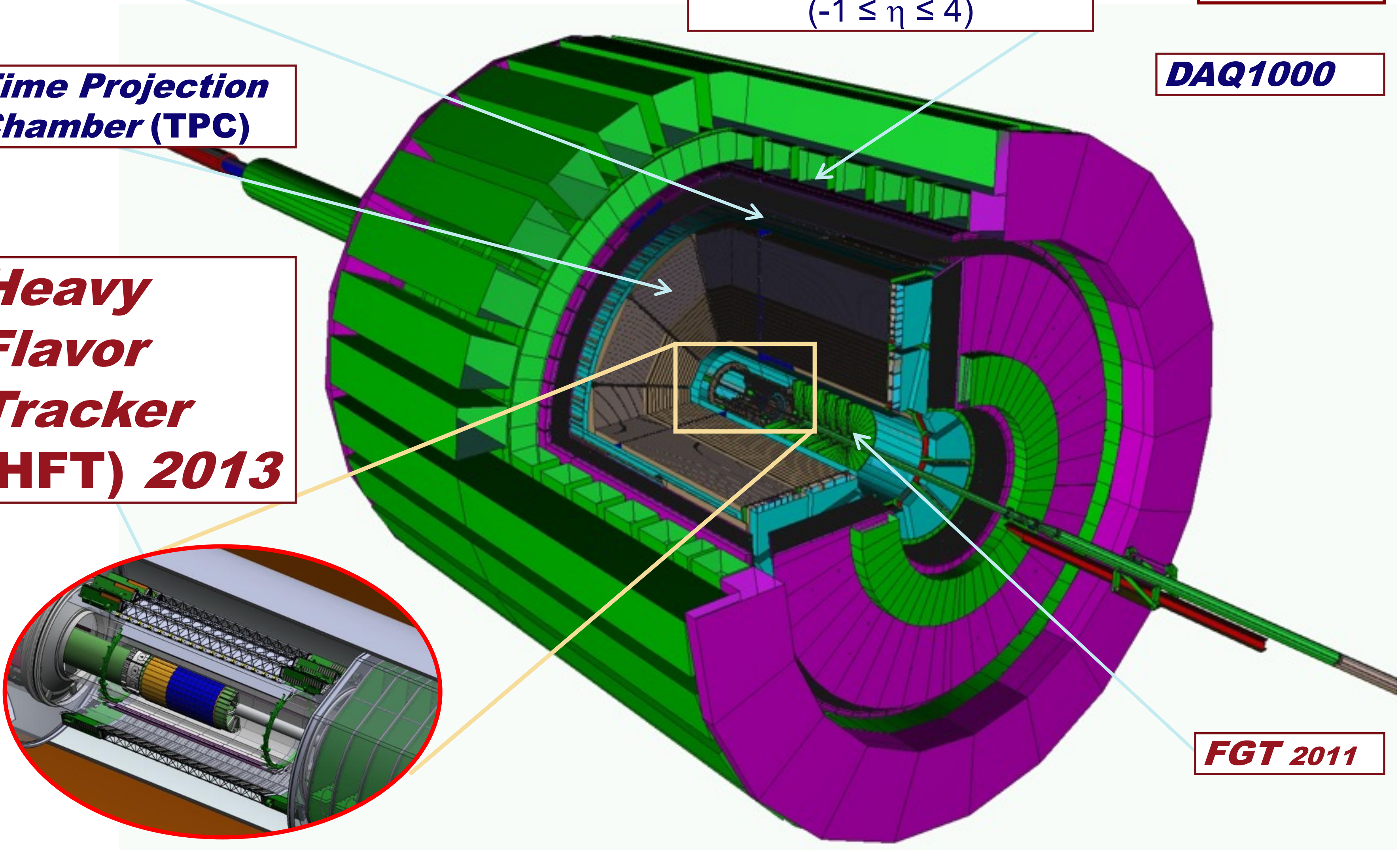
STAR

760 collaborators

70 institutions (8)

14 countries

STAR Detectors *Fast and Full azimuthal particle identification*



MRPC Time Of Flight

EMC+EEMC+FMS
(-1 ≤ η ≤ 4)

***MTD** 2013*

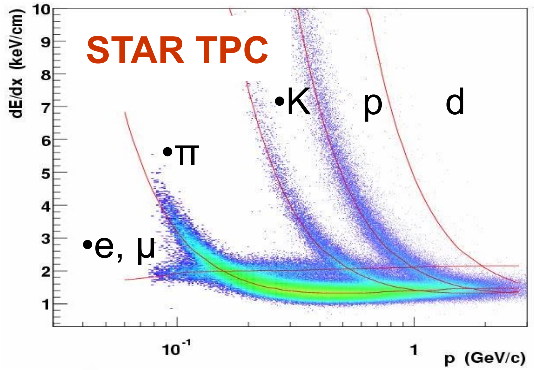
DAQ1000

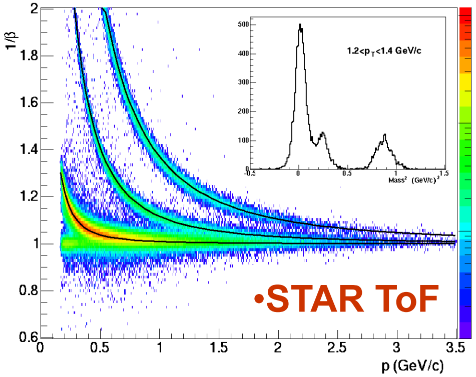
***Time Projection Chamber* (TPC)**

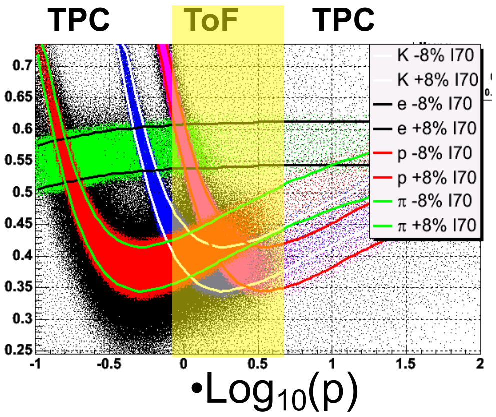
Heavy Flavor Tracker* (HFT)** ***2013

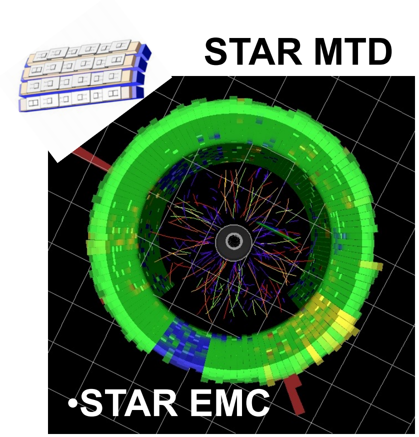
***FGT** 2011*

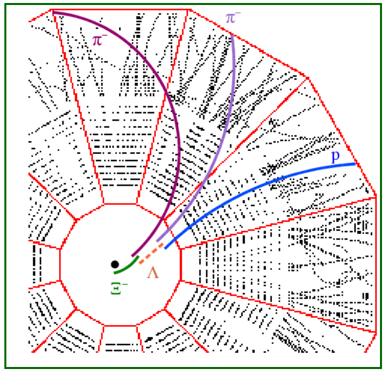
Particle Identification at STAR

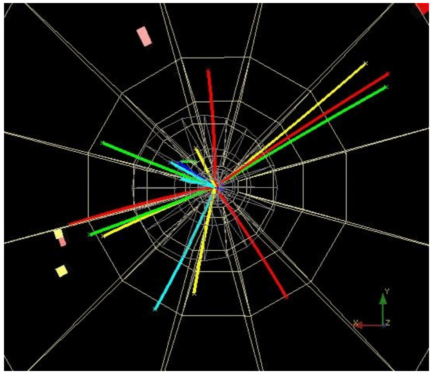


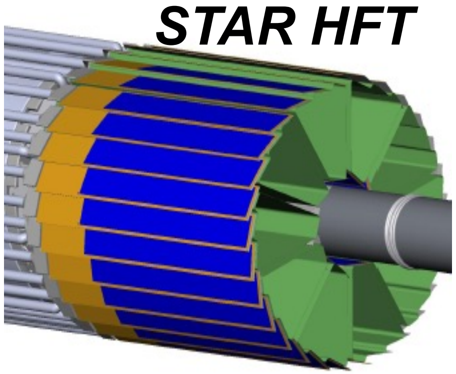












Neutral particles

Strange hyperons Hadrons

Jets

Heavy Quark

Particle Identification

Rest are constructed: Invariant Mass + Decay Topology

V0 decay vertices

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

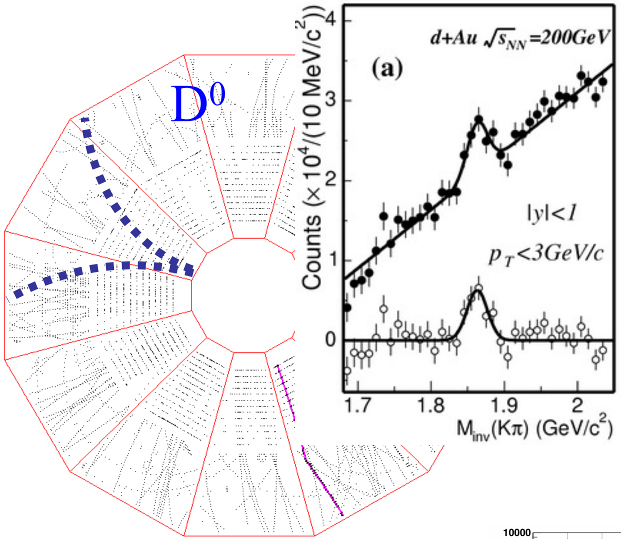
$\Lambda \rightarrow p + \pi^-$

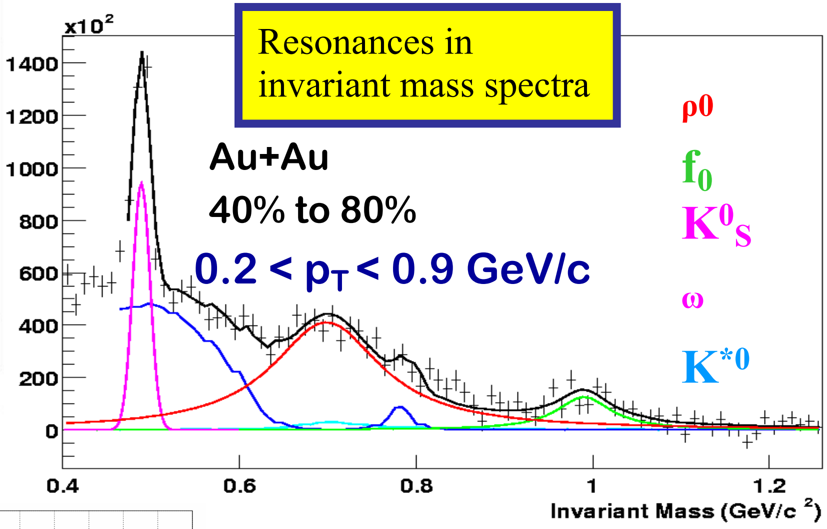
$\bar{\Lambda} \rightarrow \bar{p} + \pi^+$

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

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

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



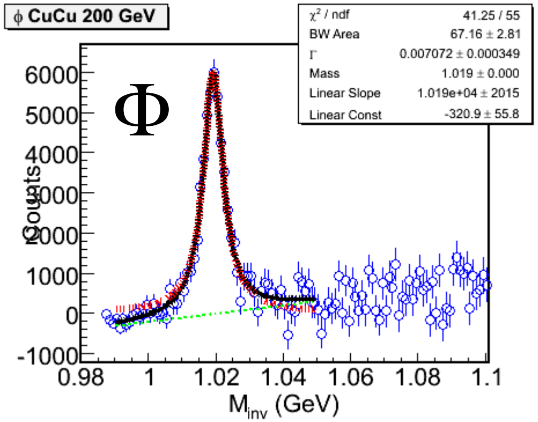


Resonances in invariant mass spectra

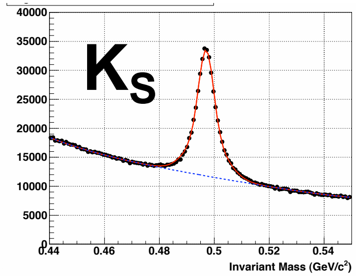
Au+Au

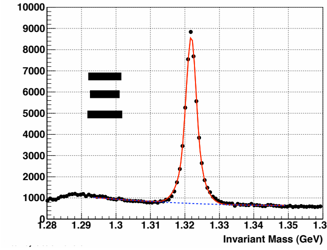
40% to 80%

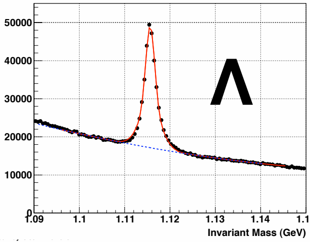
$0.2 < p_T < 0.9$ GeV/c

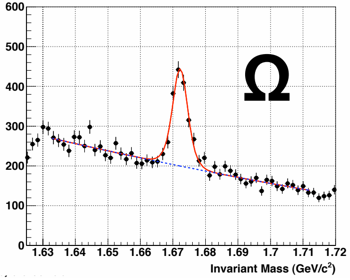


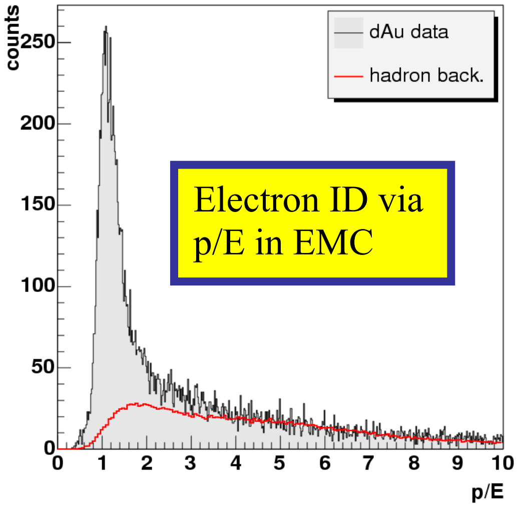
$$M^2 = E^2 - p^2$$











Electron ID via p/E in EMC

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

ALICE Experiment

Future scientists are prepared!

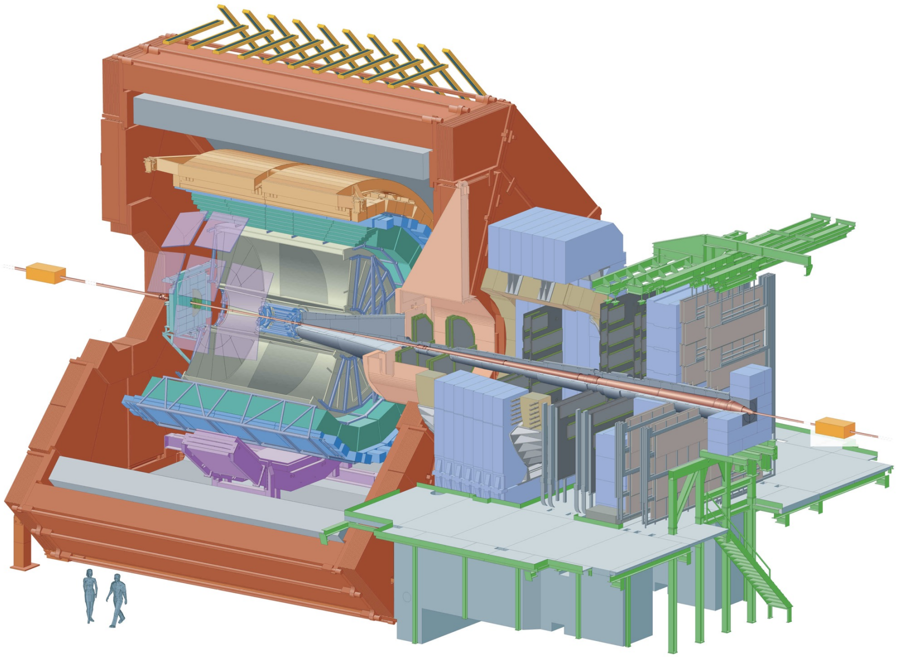
ALICE

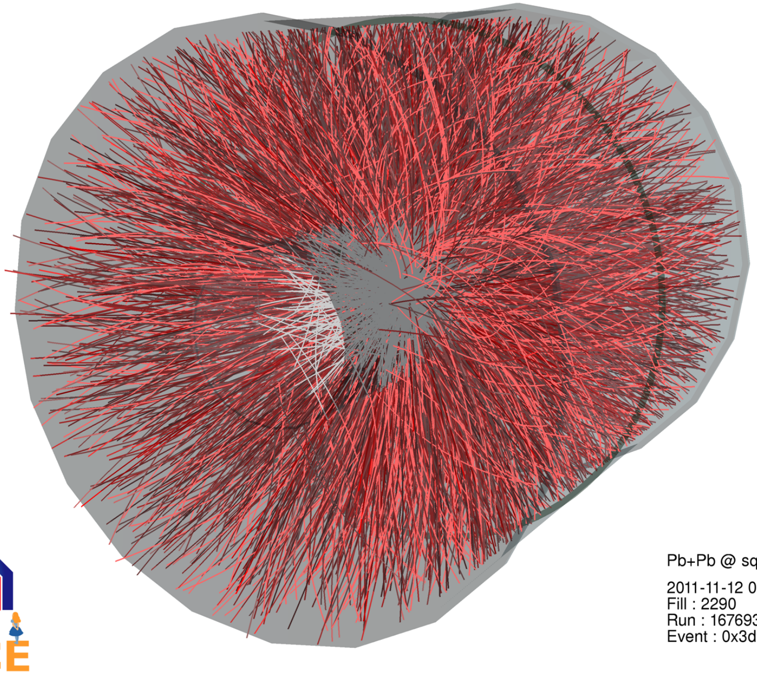
1978 collaborators

169 institutions (4)

40 countries

ALICE





Pb+Pb @ sqrt(s) = 2.76 ATeV

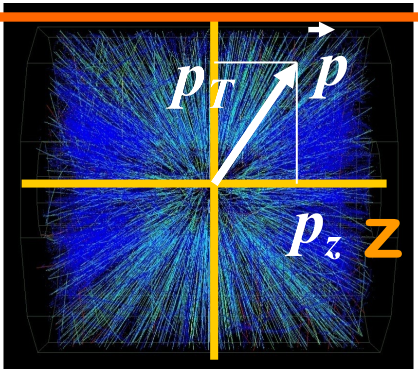
2011-11-12 06:51:12
Fill : 2290
Run : 167693
Event : 0x3d94315a

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:

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

$$E = m_T \cosh y$$

$$p_z = m_T \sinh y$$

Pseudo-rapidity :

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

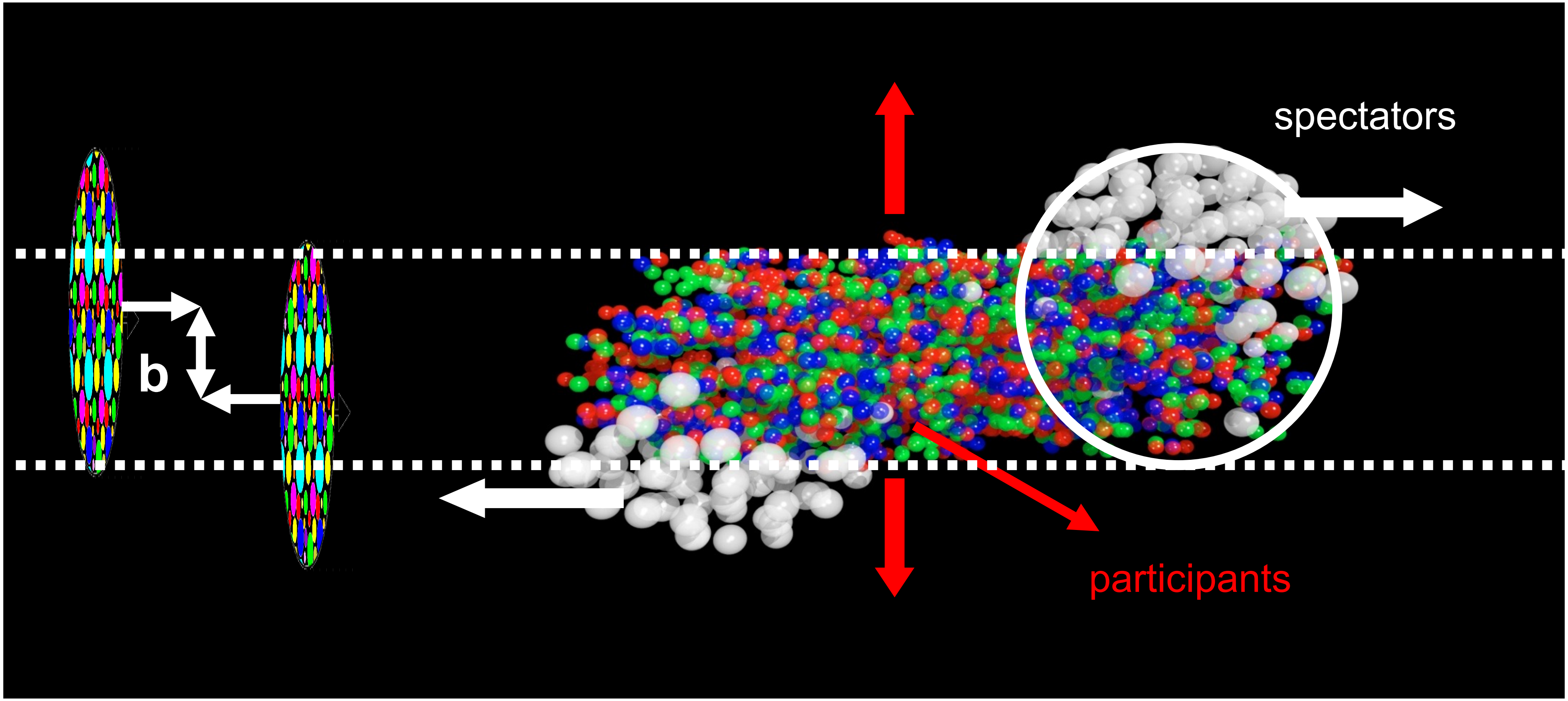
$$p = p_T \cosh\eta$$

$$p_z = p_T \sinh\eta$$

p=100 GeV/c, y=5.36
p=1380 GeV/c. y=7.99

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

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

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

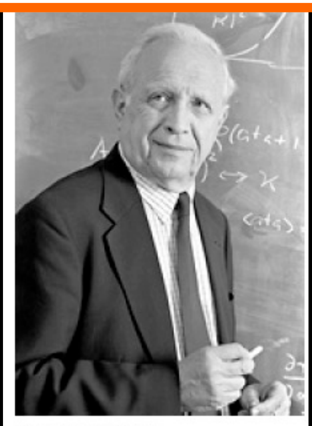
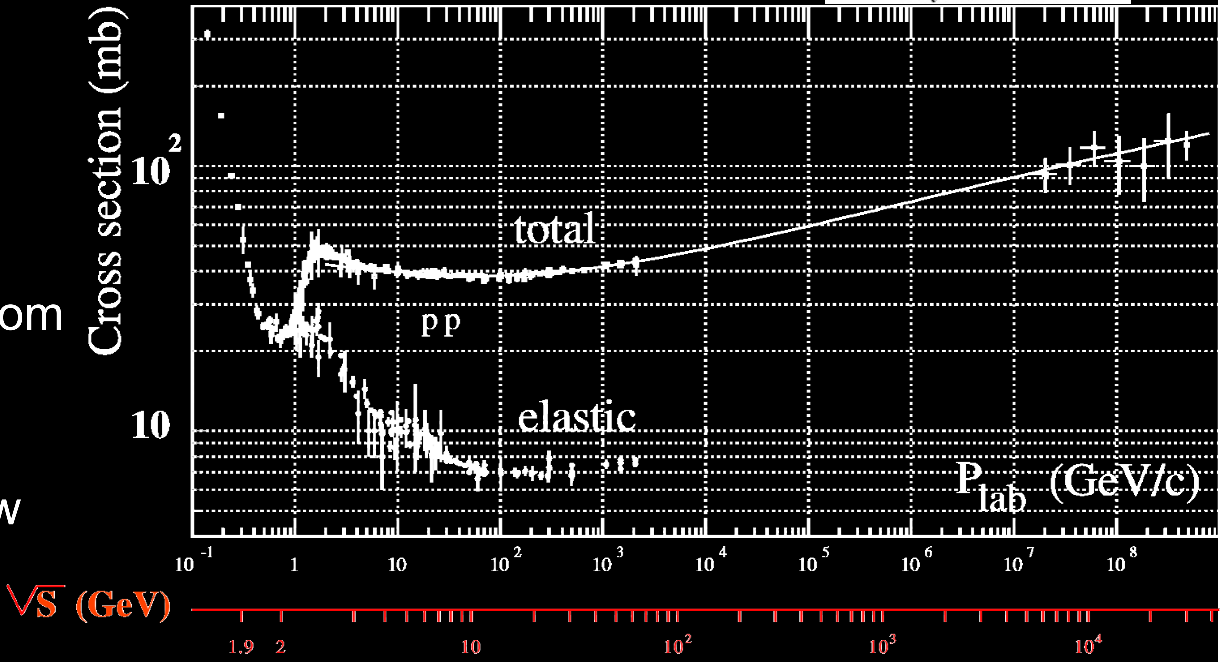


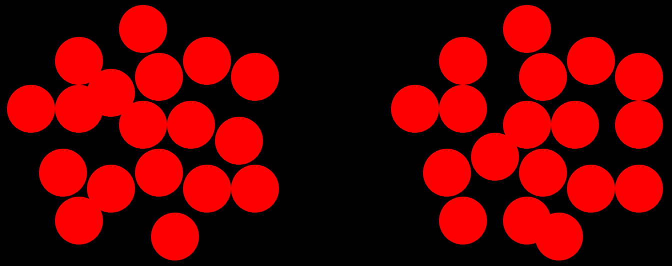
Photo: J.Reed

Roy J. Glauber



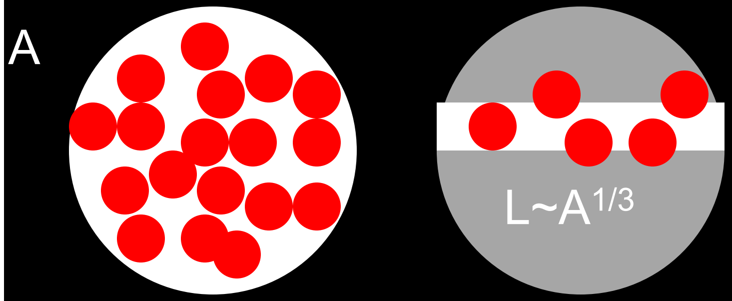
Wounded nucleons and binary collisions

Wounded nucleon scaling

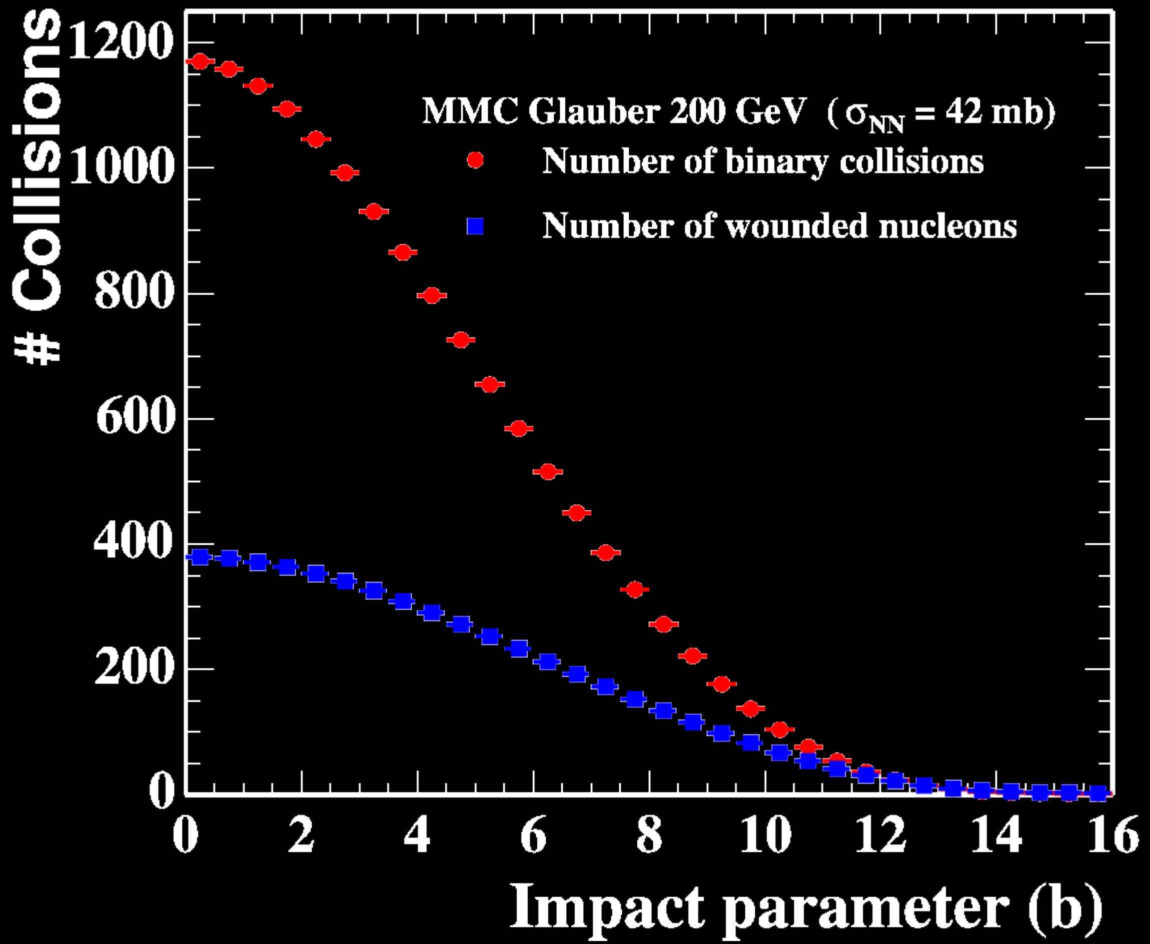


Number of participating nucleons scales with volume ~ 2A

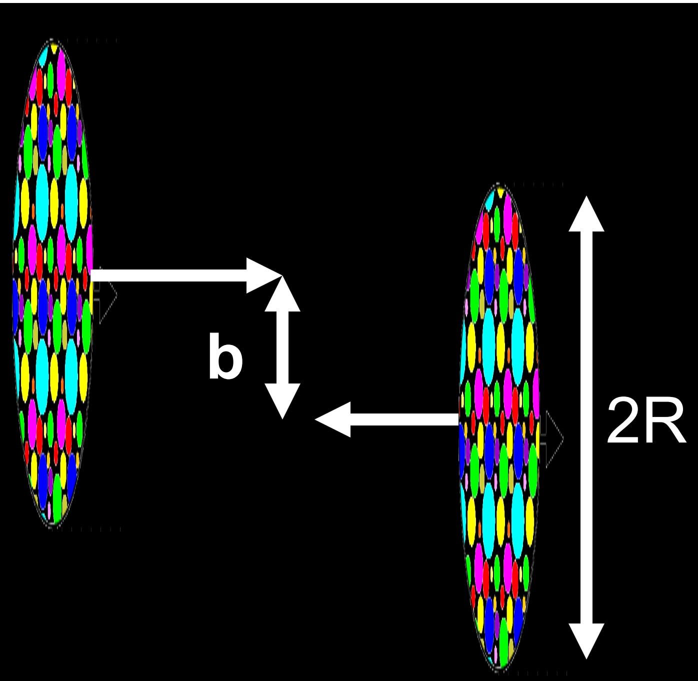
Binary scaling

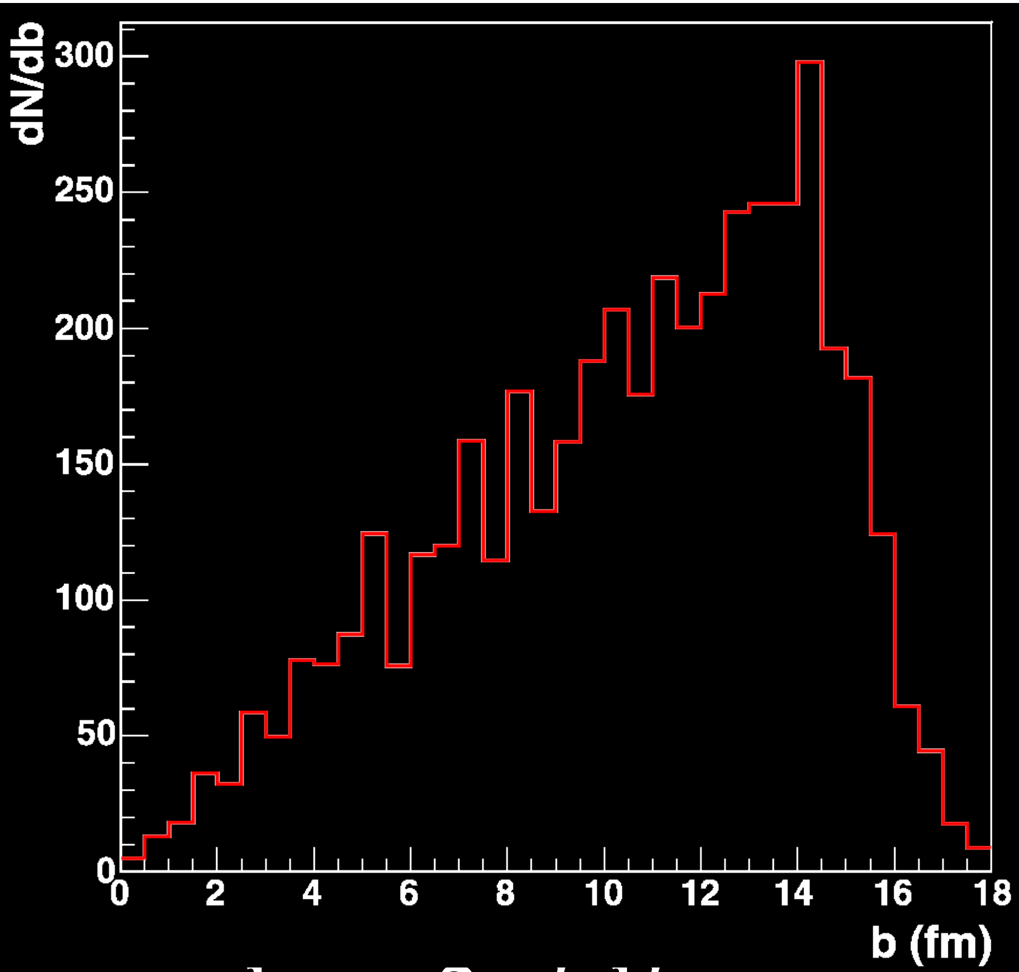


Number of NN collisions, point like, scales with ~ $A^{4/3}$



Impact parameter distribution

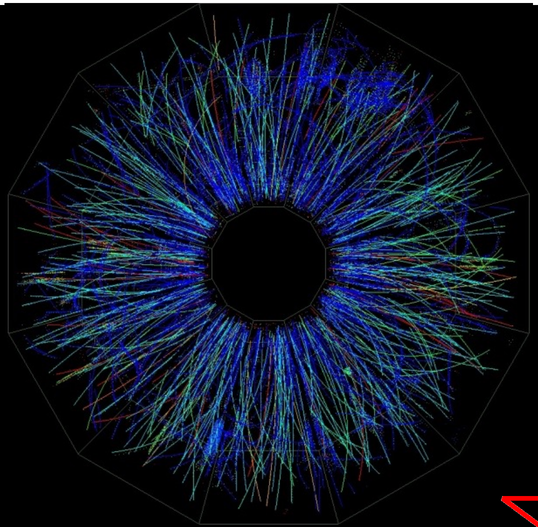




- impact parameter **b**
  - perpendicular to beam direction
  - connects centers of the colliding ions

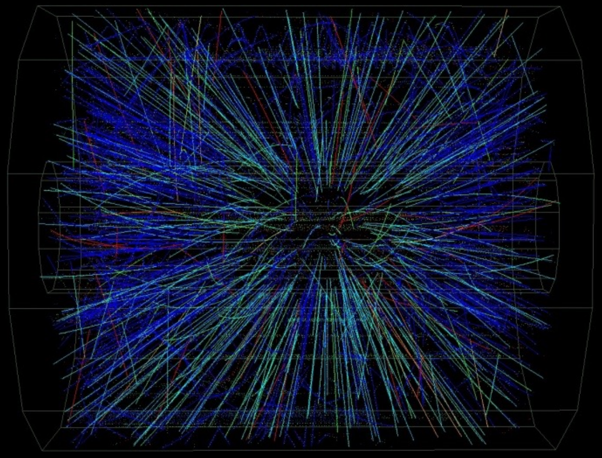
$$\mathrm{d}\sigma = 2\pi b\,\mathrm{d}b$$

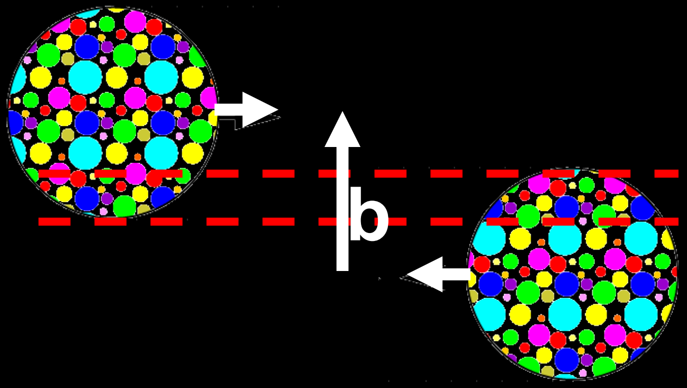
Centrality determination (II)



Peripheral Event

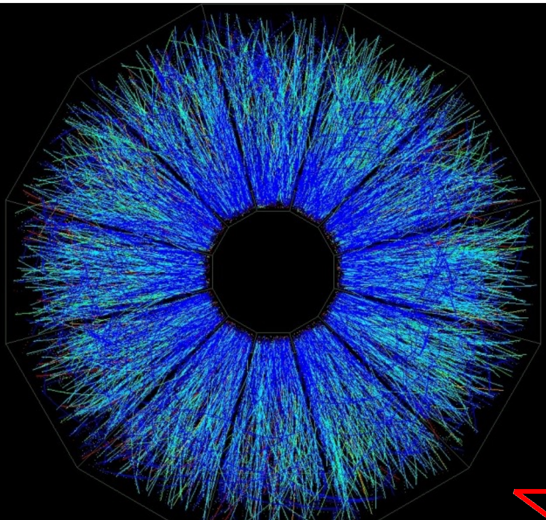
From real-time Level 3 display





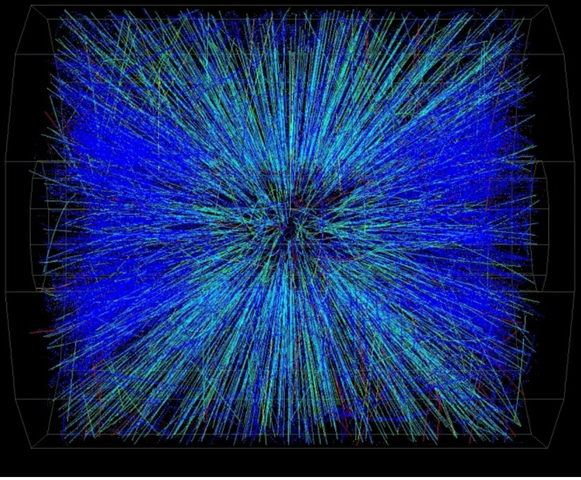
- peripheral collisions, largest fraction cross section
- many spectators
- “few” particles produced

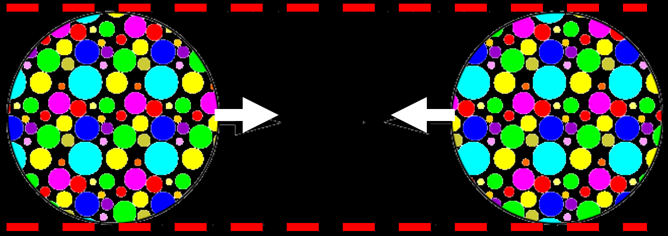
Centrality determination (III)



Central Event

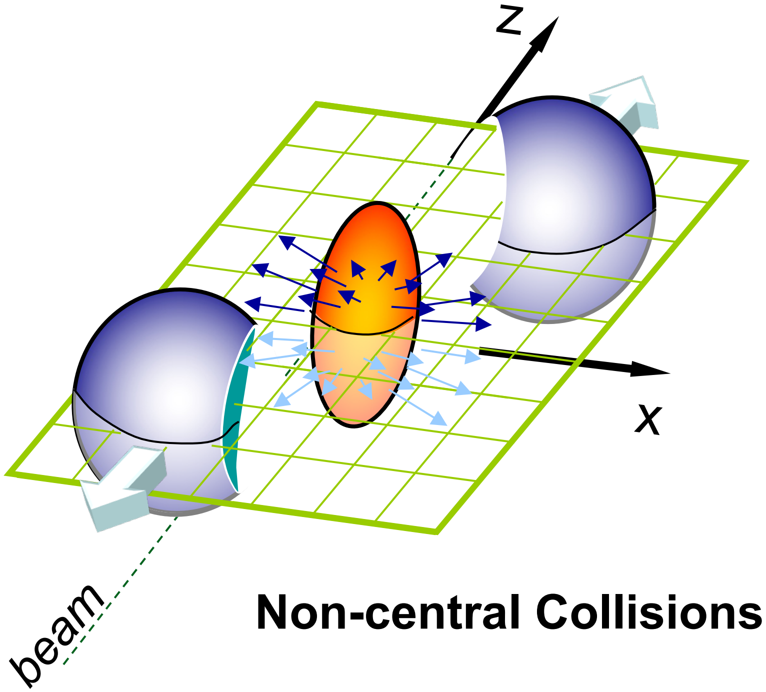
From real-time Level 3 display



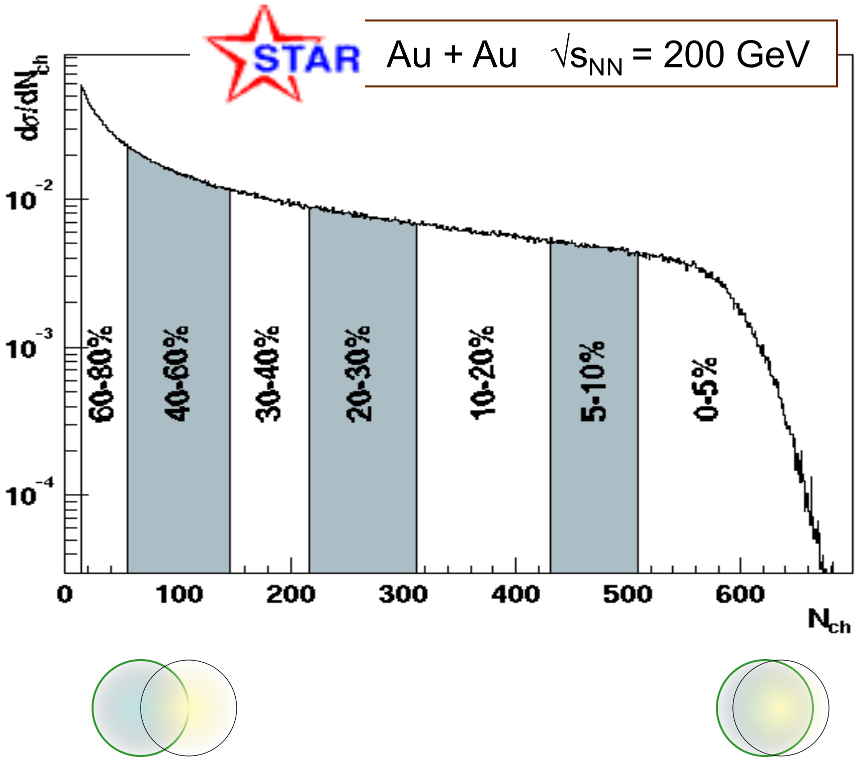


- impact parameter **b** = 0
- central collisions, small cross section
- no spectators
- many particles produced

Collision Geometry



Non-central Collisions



Number of participants: number of incoming nucleons in the overlap region
Number of binary collisions: number of inelastic nucleon-nucleon collisions

Charged particle multiplicity ⇔ collision centrality
Reaction plane: x-z plane

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:

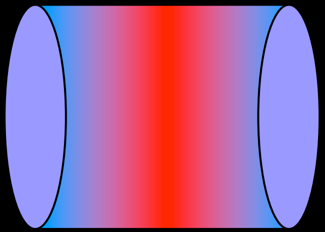
“In the quest for evidence of the quark-gluon plasma, there are two levels to which one might aspire. At the first level, one might hope to observe phenomena that are very difficult to explain from a hadronic perspective but have a simple qualitative explanation based on quarks and gluons.

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.”

Transverse Energy and Energy Density

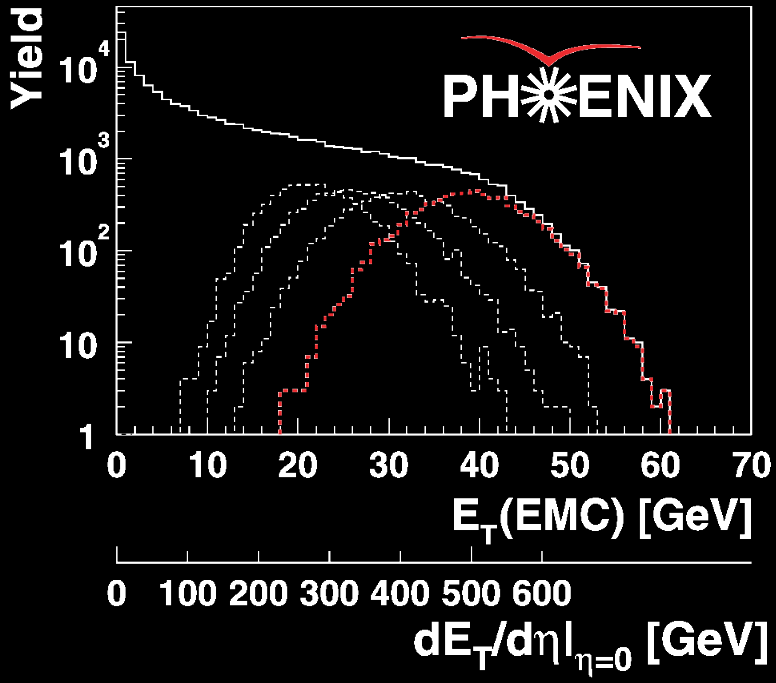
- Bjorken energy density estimate

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



$dz = \tau_0 dy$

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

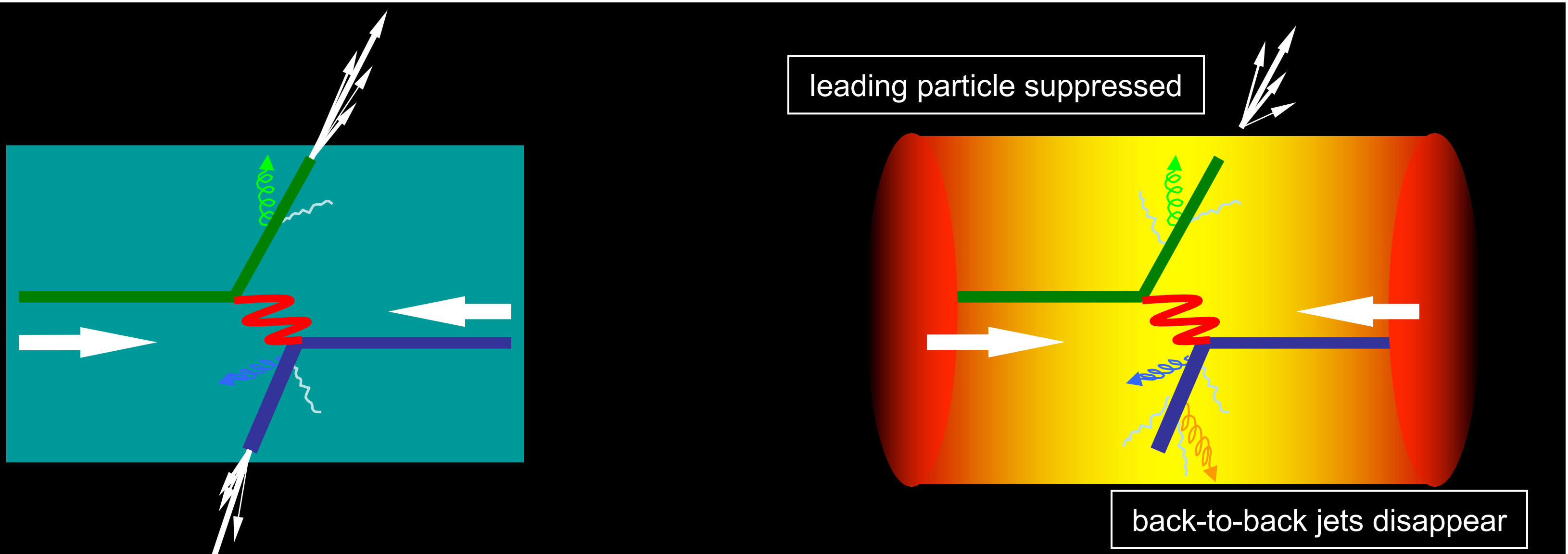


$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\ \mathrm{GeV}$$

- Much larger than the critical energy density !!

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

Energy Loss in A+A Collisions

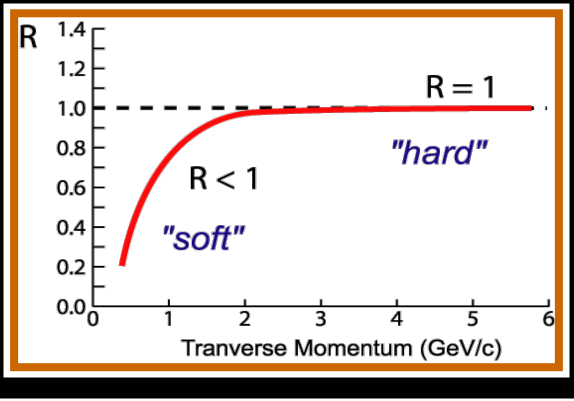


leading particle suppressed

back-to-back jets disappear

p+p

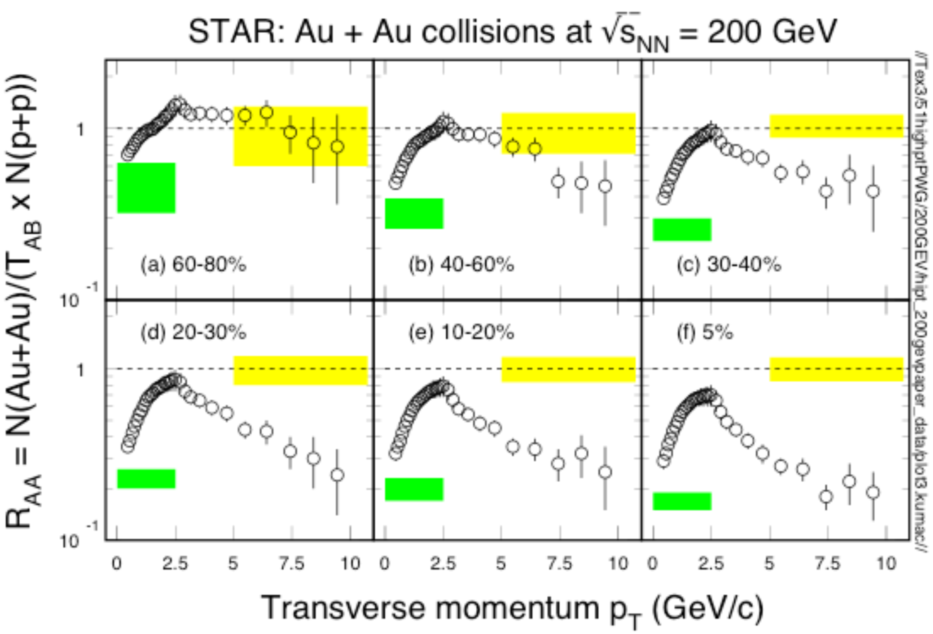
Au + Au

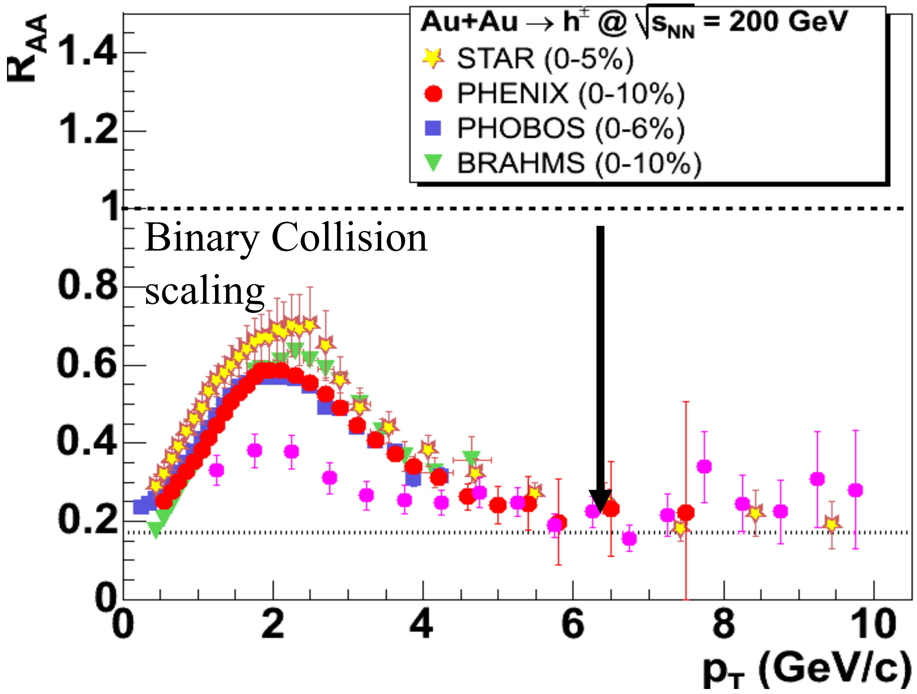


Nuclear Modification Factor:

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

Hadron Suppression at RHIC



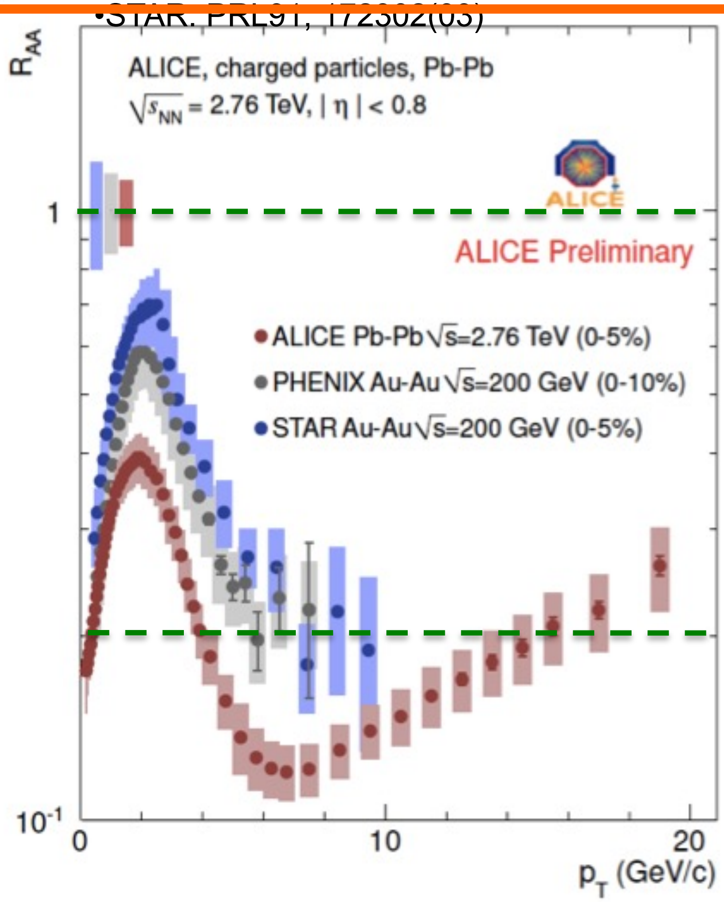


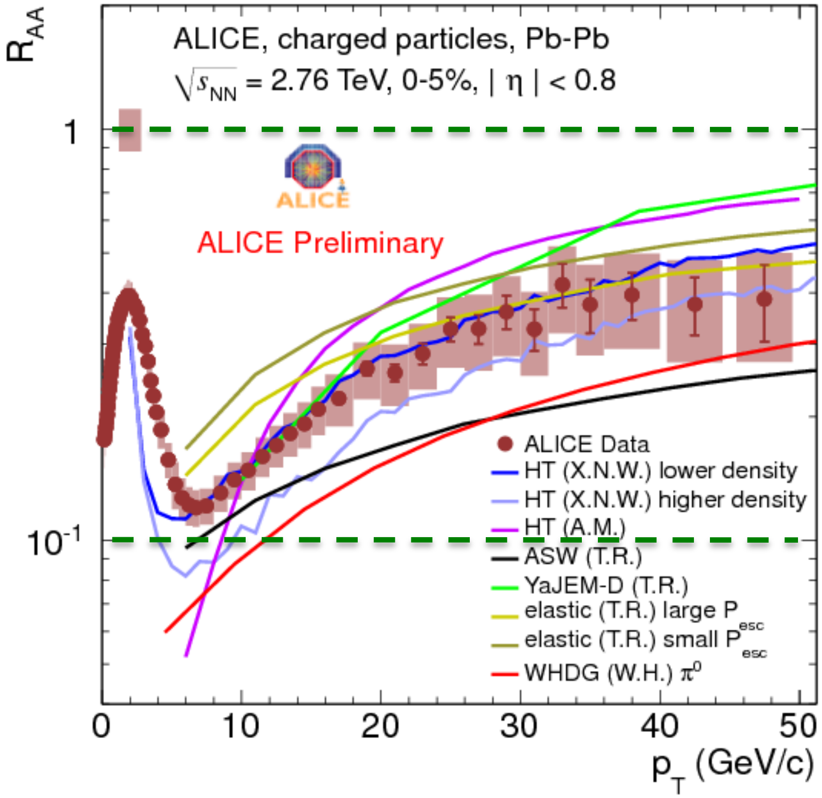
$$R_{AA}(p_T) = \frac{(dN/dp_T)_{AA}}{\langle N_{coll}\rangle (dN/dp_T)_{pp}}$$

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

Nuclear Modification Factor

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



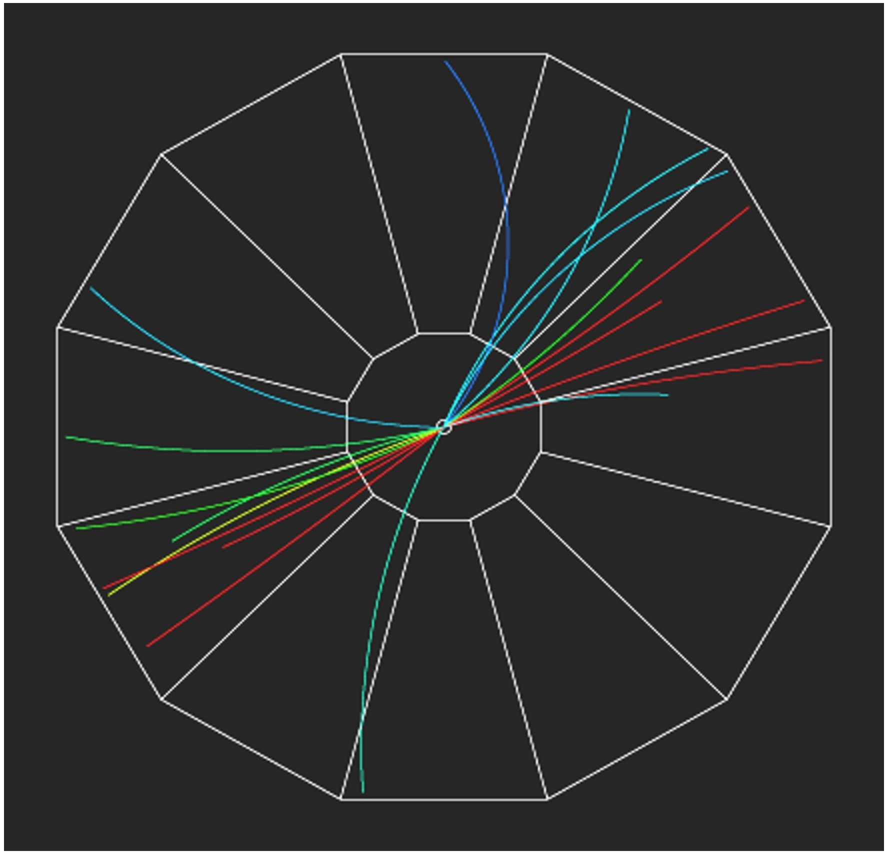


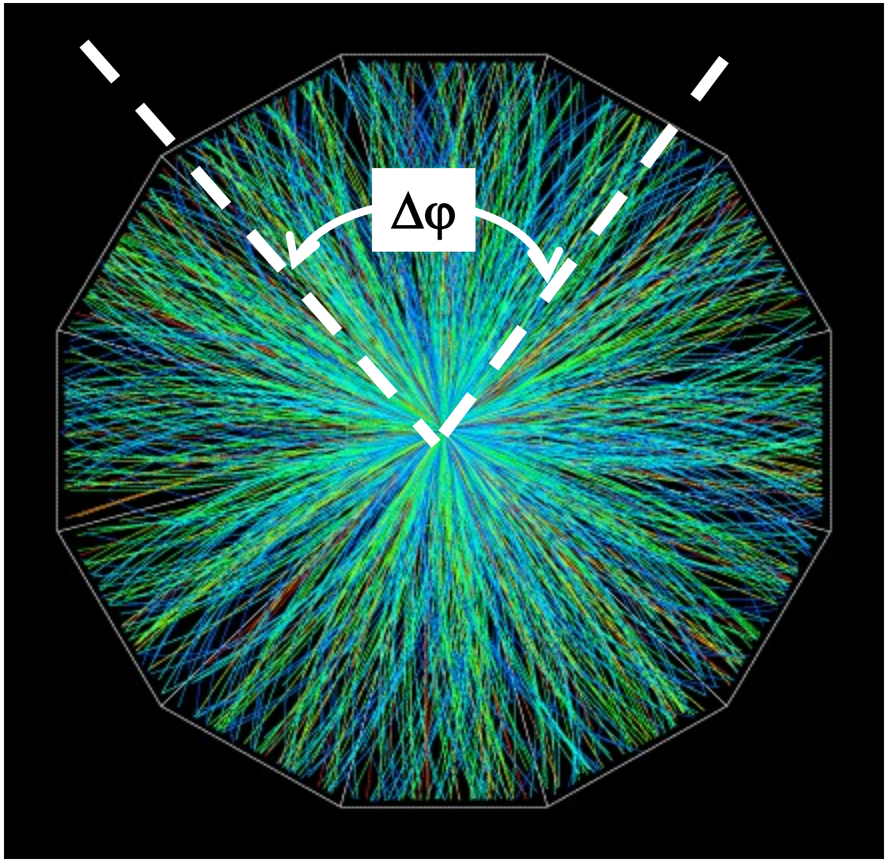
1) At LHC(2.76TeV), the energy loss is stronger than that from RHIC (0.2TeV)

➔ hotter/denser medium created at higher collision energy

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

Jets Observation at RHIC



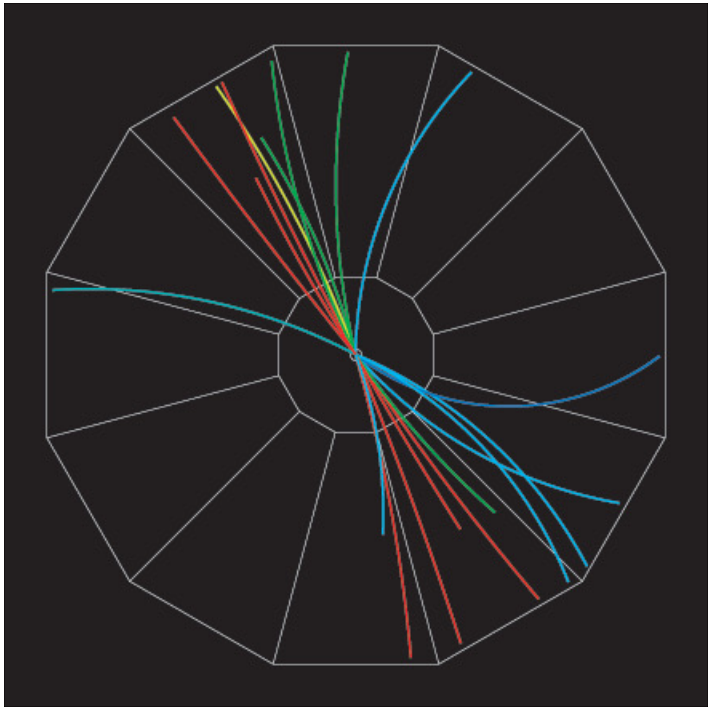


p+p collisions at RHIC
Jet like events observed

Au+Au collisions at RHIC
Jets?

Jets

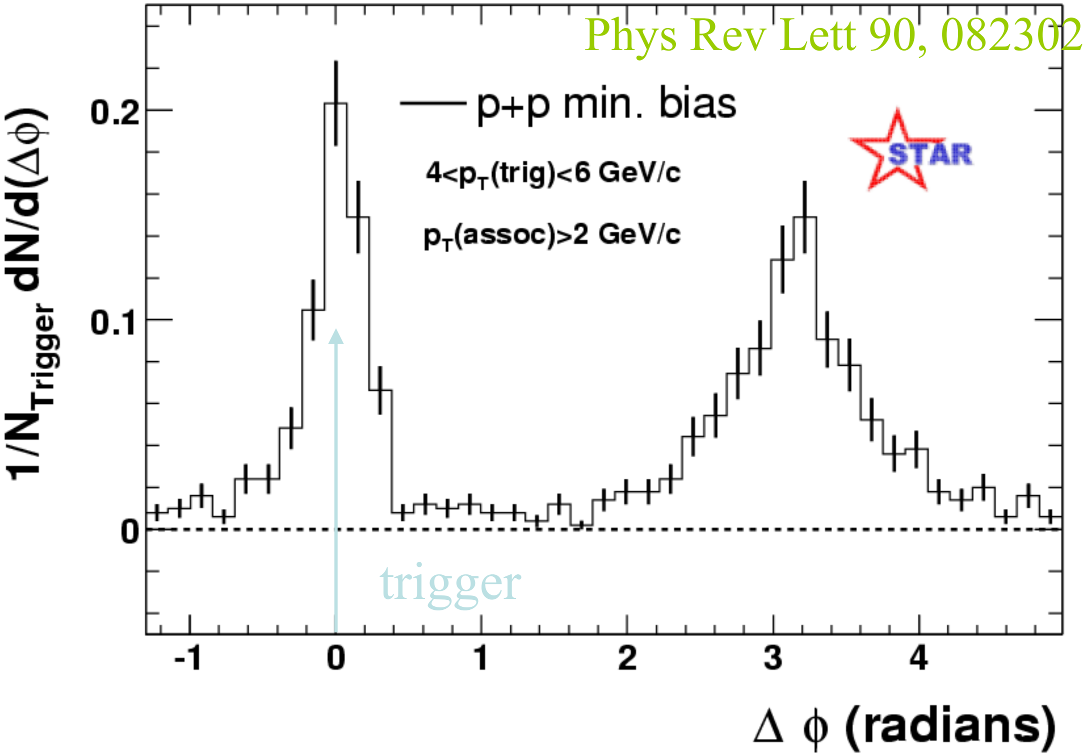
$p+p \rightarrow$ dijet



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

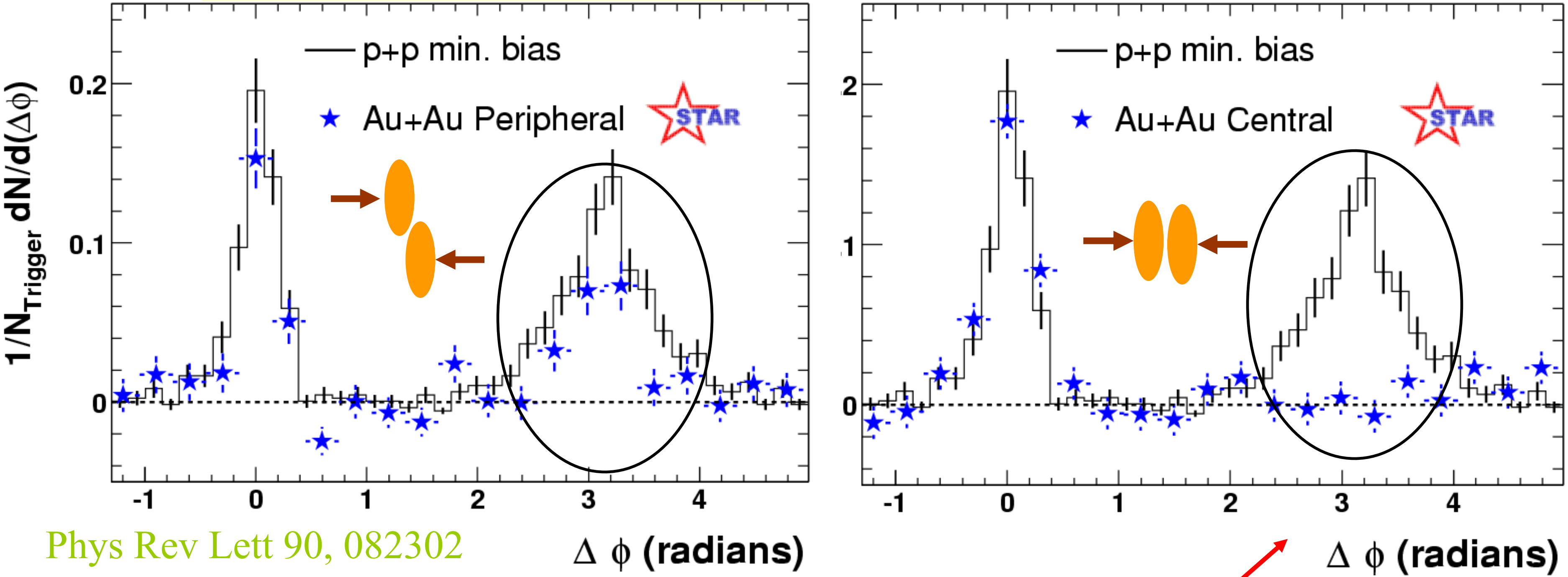


Phys Rev Lett 90, 082302

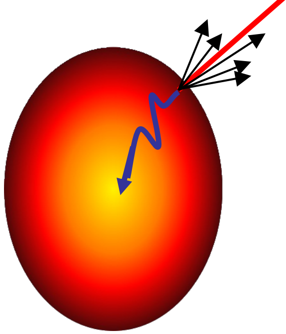
Dihadrons in Au+Au vs p+p

Au+Au peripheral
(large impact parameter)

Au+Au central (head-on)

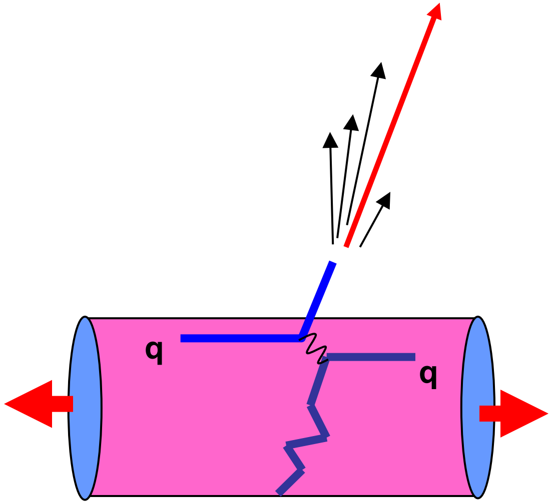


Phys Rev Lett 90, 082302

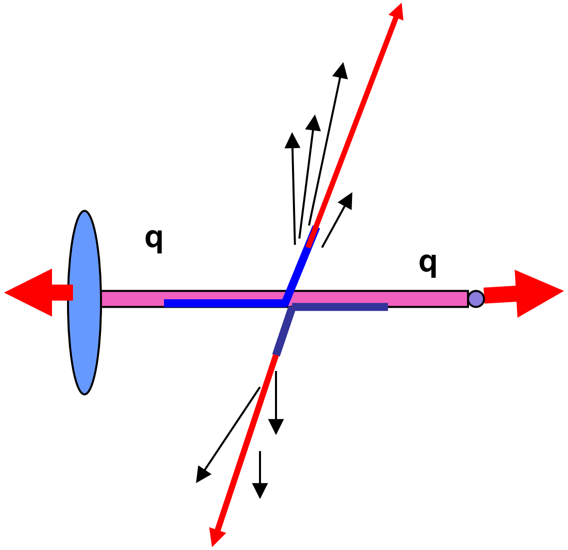


Strong suppression of back-to-back correlations in central Au+Au

d+Au Collisions



Au+Au Geometry

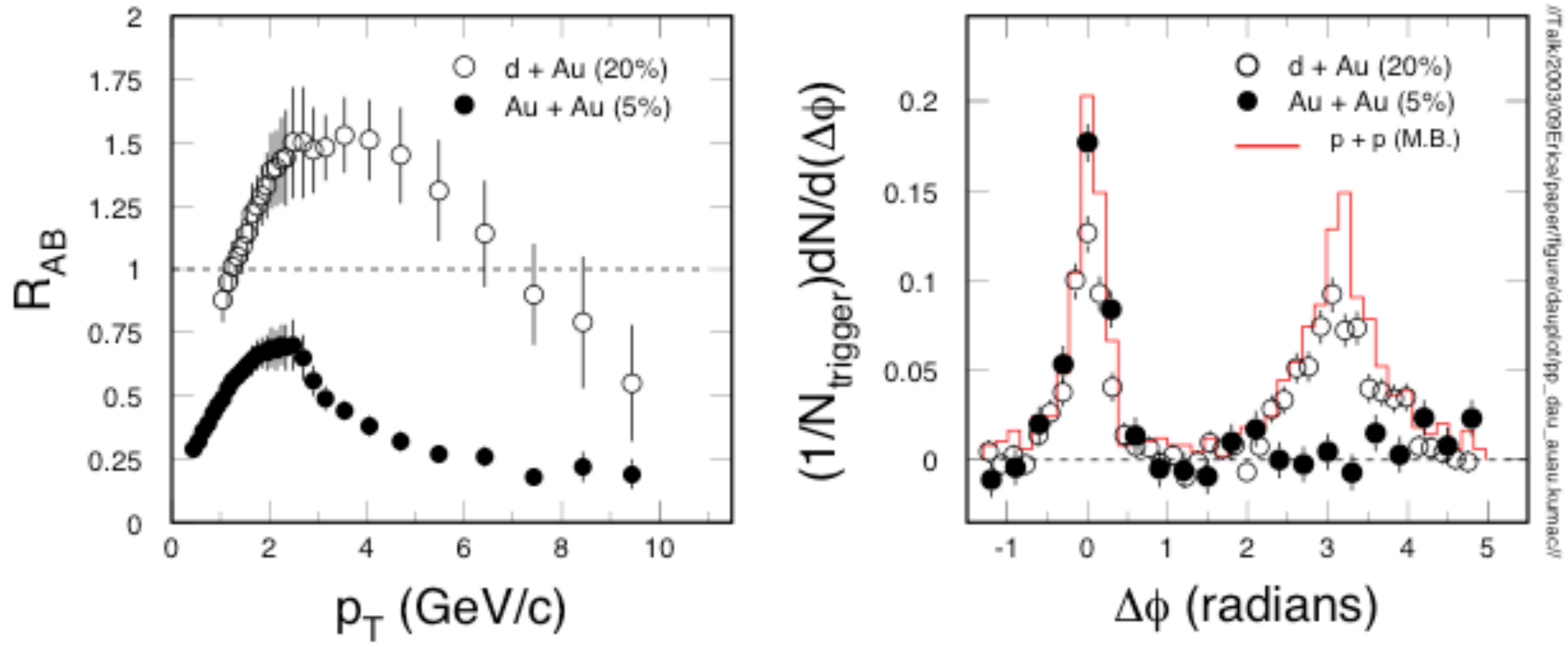


d+Au Geometry

d+Au collisions:

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

Suppression and Correlation



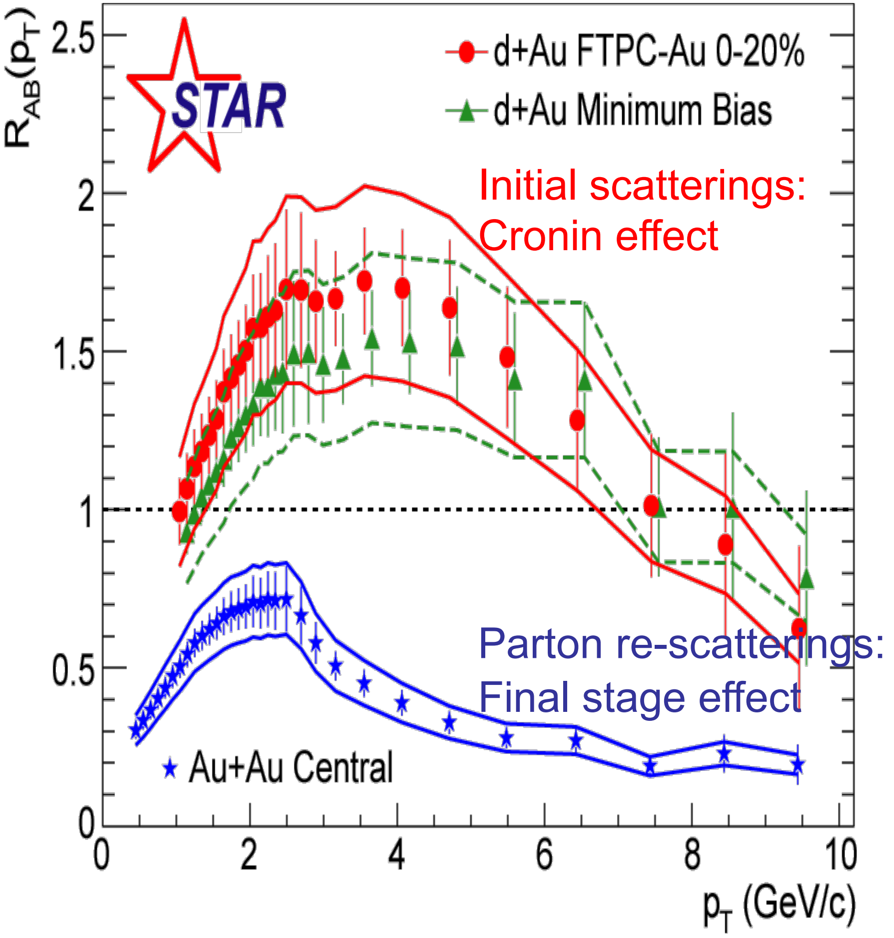
In central Au+Au collisions: hadrons are suppressed and back-to-back 'jets' are disappeared. Different from p+p and d+Au collisions.

Energy density at RHIC: $\varepsilon > 5$ GeV/fm^3 ~ $30\varepsilon_0$

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

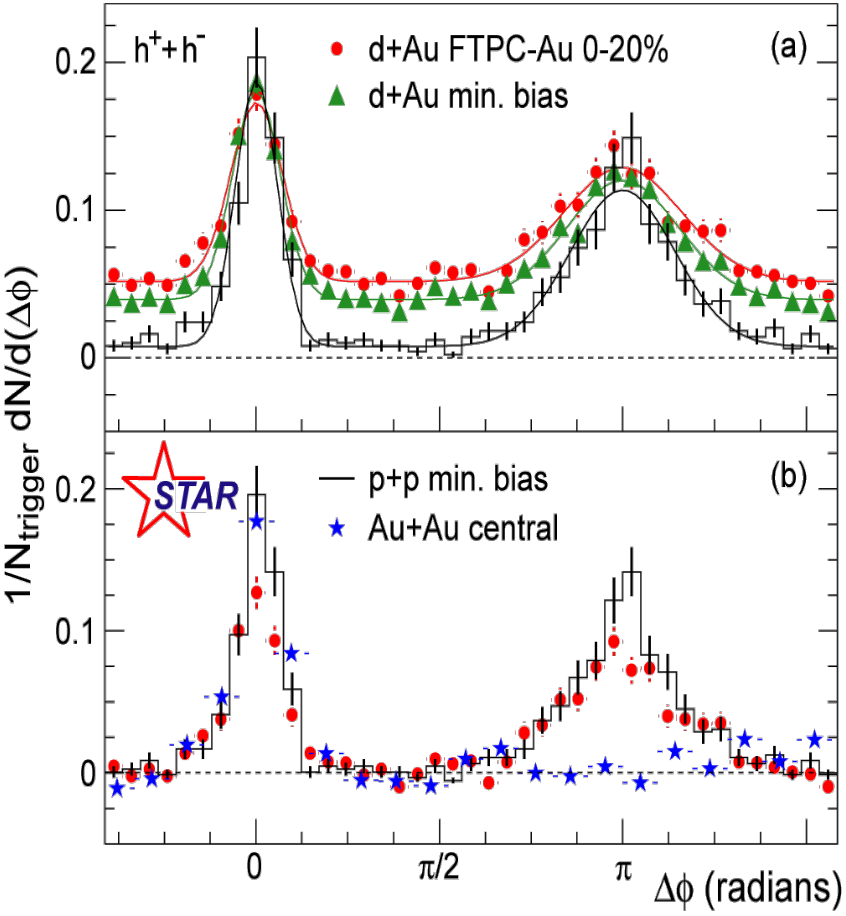
…

Data from d+Au collisions



Initial scatterings: Cronin effect

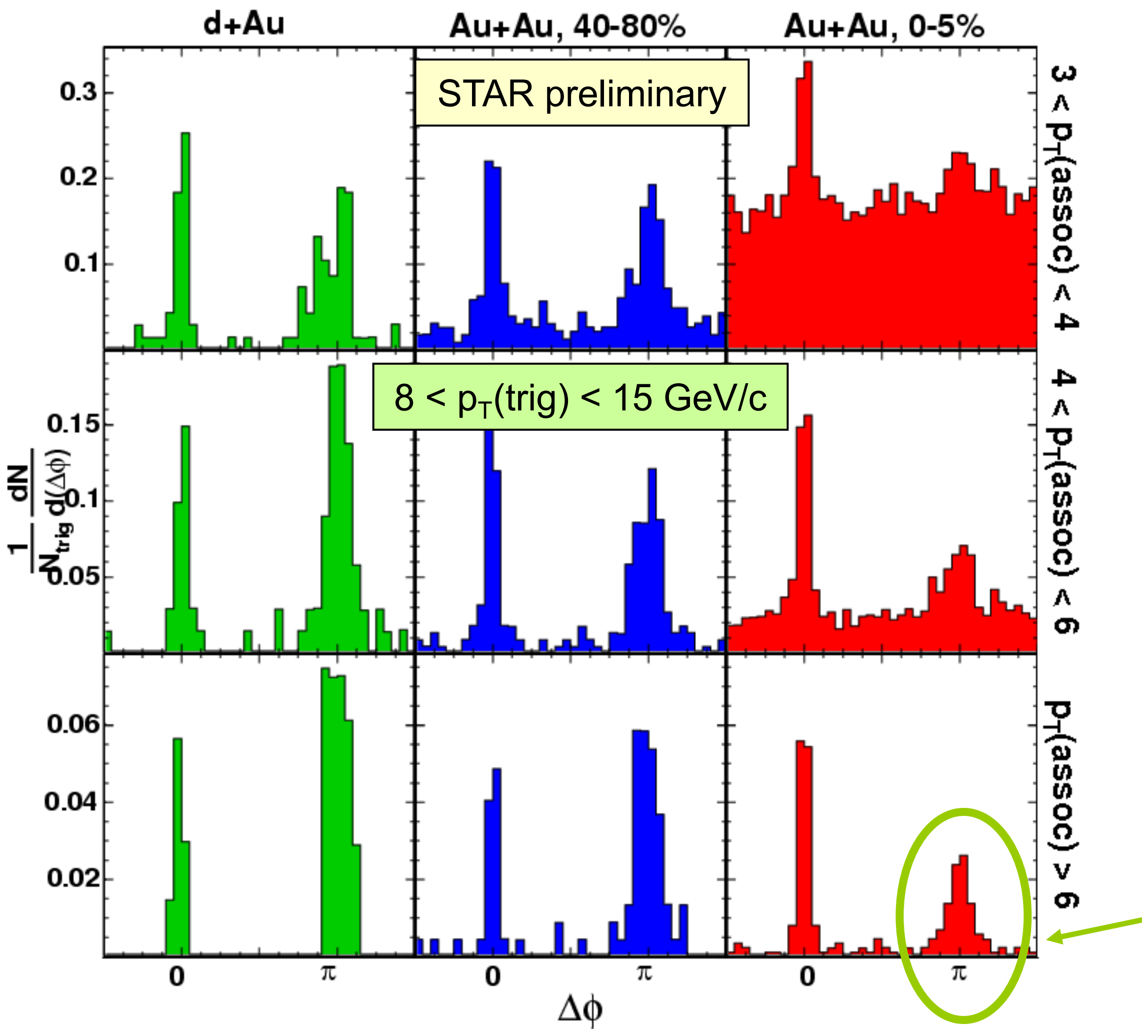
Parton re-scatterings: Final stage effect



No high p_T suppression !

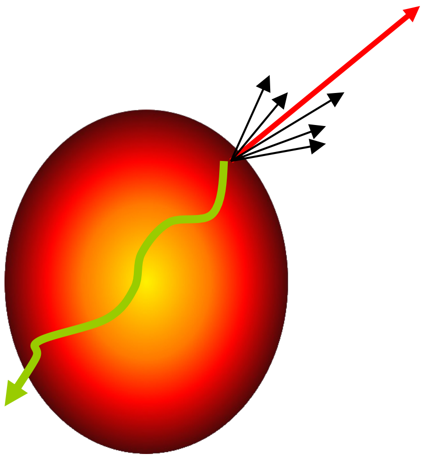
No disappearance of back-to-back correlations!

Di-hadron Measurements at Higher p_T



STAR preliminary

$8 < p_T(\text{trig}) < 15$ GeV/c



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
- Collectivity
  - Spectra
  - Freeze out
  - 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: $v_n = \cos n\varphi$

- 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***.

Basics of hydrodynamics: ideal

Energy-momentum conservation

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

Charge conservation

$$\partial_\mu N^\mu = 0$$

System always in local equilibrium: ideal hydrodynamics

$$\begin{aligned} T^{\mu\nu} &= (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu} \\ N^\mu &= n u^\mu \end{aligned}$$

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

Closed by the equation-of-state (EOS) :* ε=ε(P)

Hydro-response controlled by QCD EoS

Taken from JY Jia. QM2018

Equation of State and degrees of freedom

ideal QGP:

$$P_{\mathrm{QGP}} = \frac{1}{3}\varepsilon_{\mathrm{QGP}} = g\frac{\pi^2}{90}T^4$$

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

- 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)

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

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

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

Basics of hydrodynamics: viscous

Energy-momentum conservation

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

Charge conservation

$$\partial_\mu N^\mu = 0$$

Include near-equilibrium corrections: viscous hydrodynamics

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

Bulk pressure

Shear tensor

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

Charge diffusion

Basics of hydrodynamics:1st order

Energy-momentum conservation

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

Charge conservation

$$\partial_\mu N^\mu = 0$$

Include near-equilibrium corrections: viscous hydrodynamics

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

Bulk pressure

Shear tensor

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

Charge diffusion

Include 1st-order gradient expansion:

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

η: shear viscosity coefficient

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

ζ : bulk viscosity coefficient

Basics of hydrodynamics: 2st order

Energy-momentum conservation

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

Charge conservation

$$\partial_\mu N^\mu = 0$$

Include near-equilibrium corrections: viscous hydrodynamics

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (P + \underbrace{\Pi}_{\text{Bulk pressure}})\Delta^{\mu\nu} + \underbrace{\pi^{\mu\nu}}_{\text{Shear tensor}}$$

$$N^\mu = n u^\mu + \underbrace{n^\mu}_{\text{Charge diffusion}}$$

Include 2st-order gradient expansion:

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

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

Taken from 1712.05815

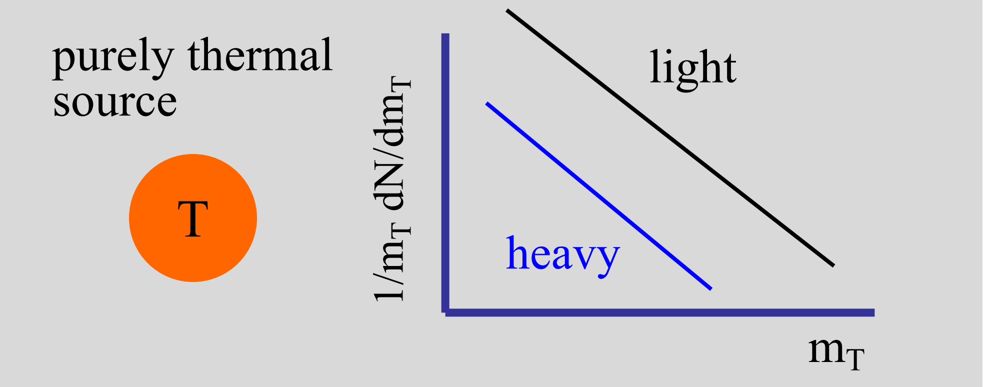
Many transport coeff.→ probe microscopic theory, QCD

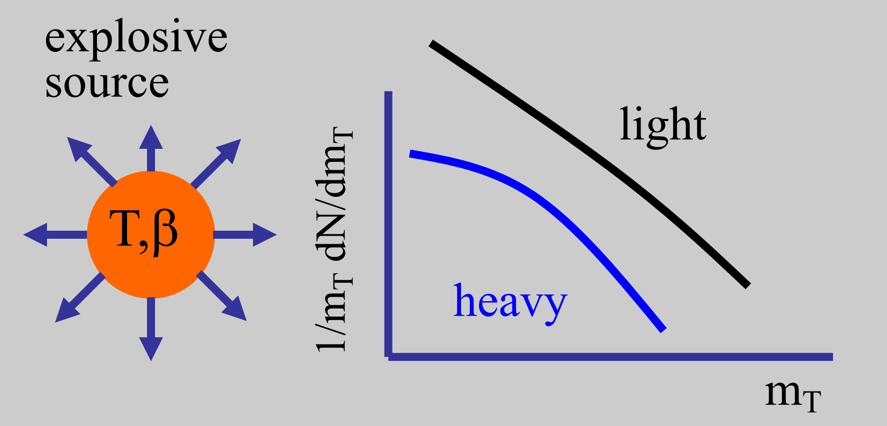
Collective Effects

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

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

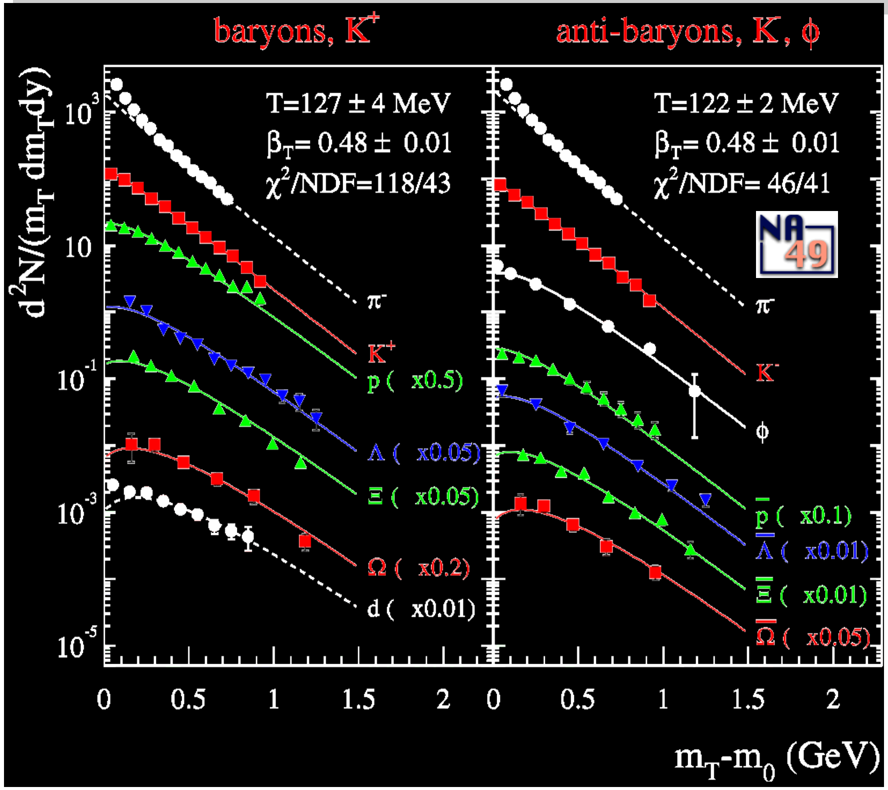
Identified Particle Spectra



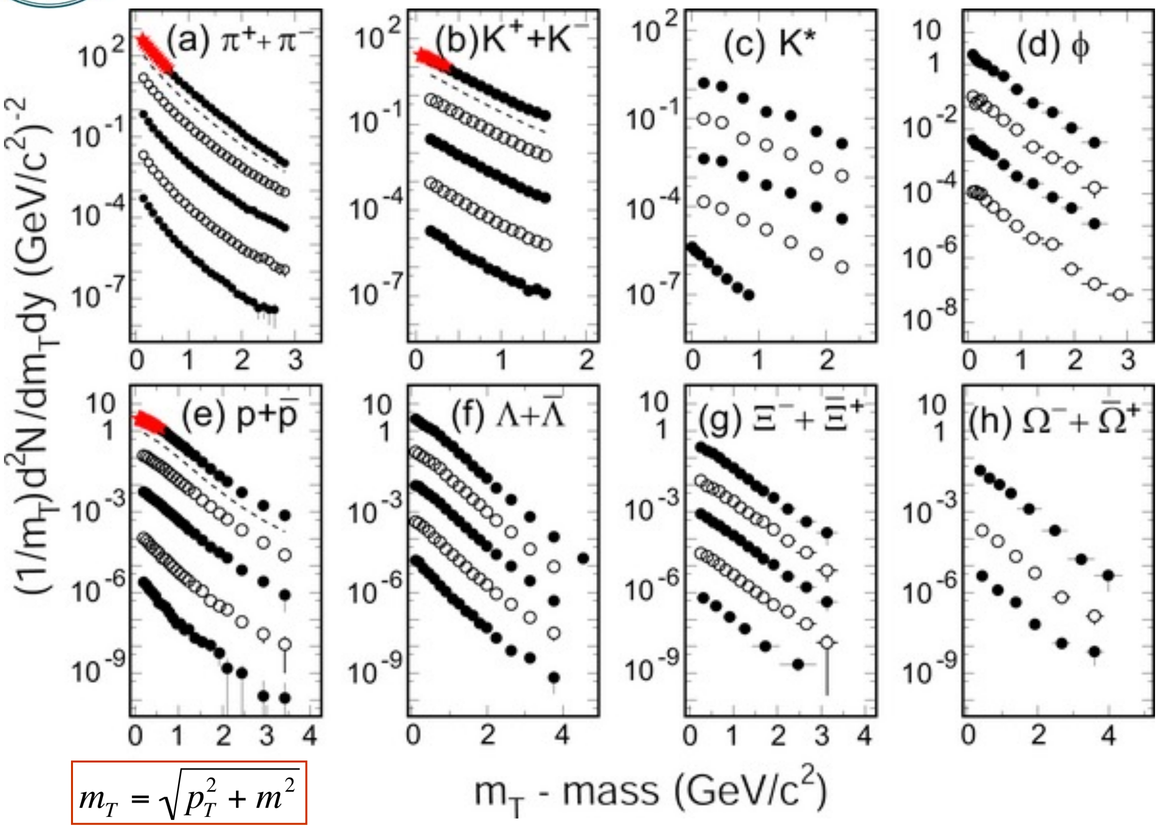


$$\frac{dN}{m_T\ dm_T} \propto e^{-m_T/T}$$

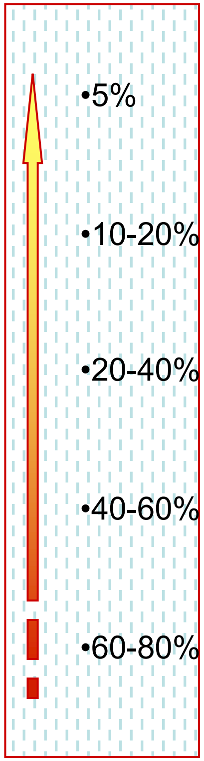
- In p-p at low transverse momenta the particle yields are well described by thermal spectra (m_T scaling)
- Boosted thermal spectra give a very good description of the particle distributions measured in heavy-ion collisions



Hadron Spectra From RHIC



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



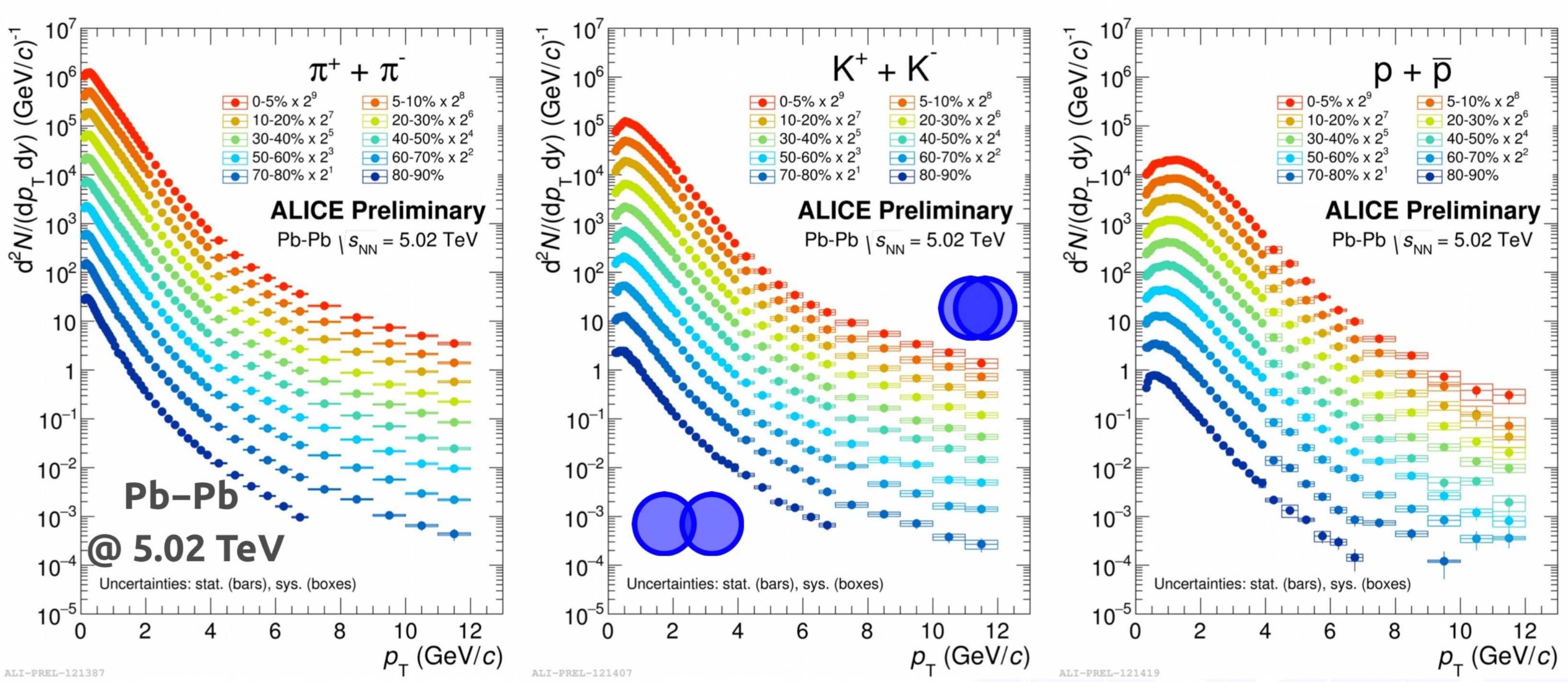
- 5%
- 10-20%
- 20-40%
- 40-60%
- 60-80%

- 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 !

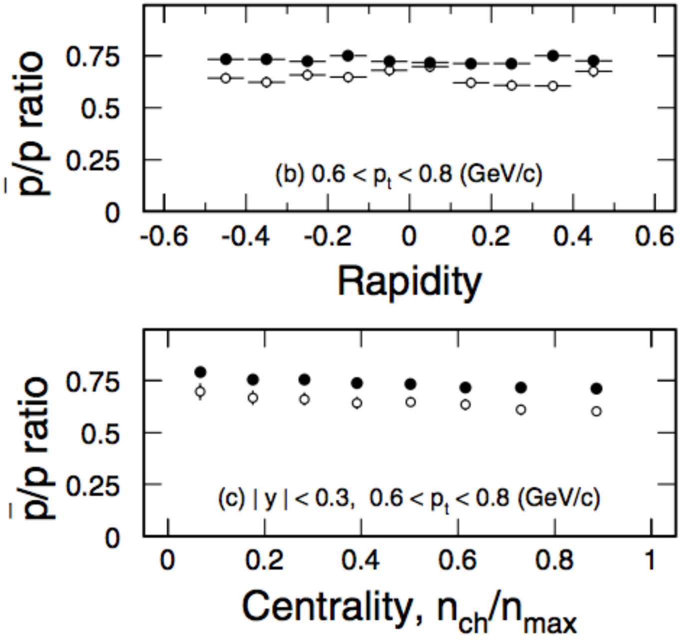
Hadron Spectra From ALICE

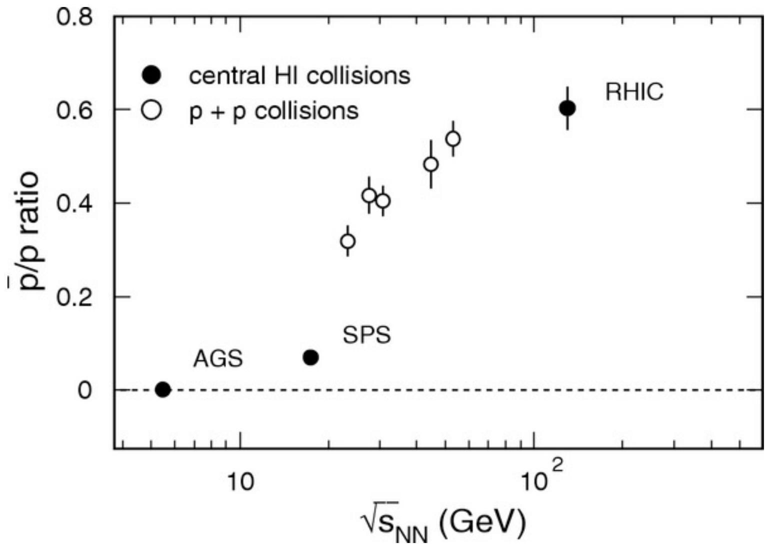


- Measured with different analysis techniques: ITS, TPC, TOF, HMPID and topological identification of K from kinks covering different p_T intervals
- **Mass dependent hardening of the spectra with increasing centrality**

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

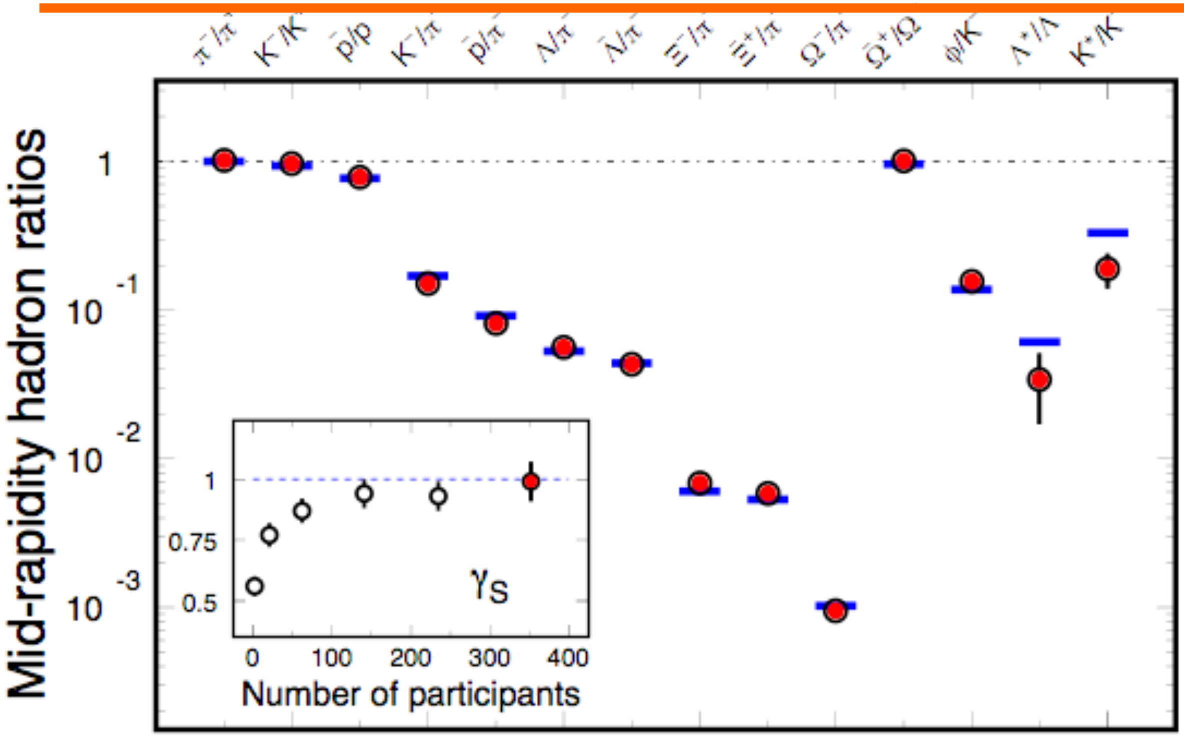
Statistical Model Fits

- 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

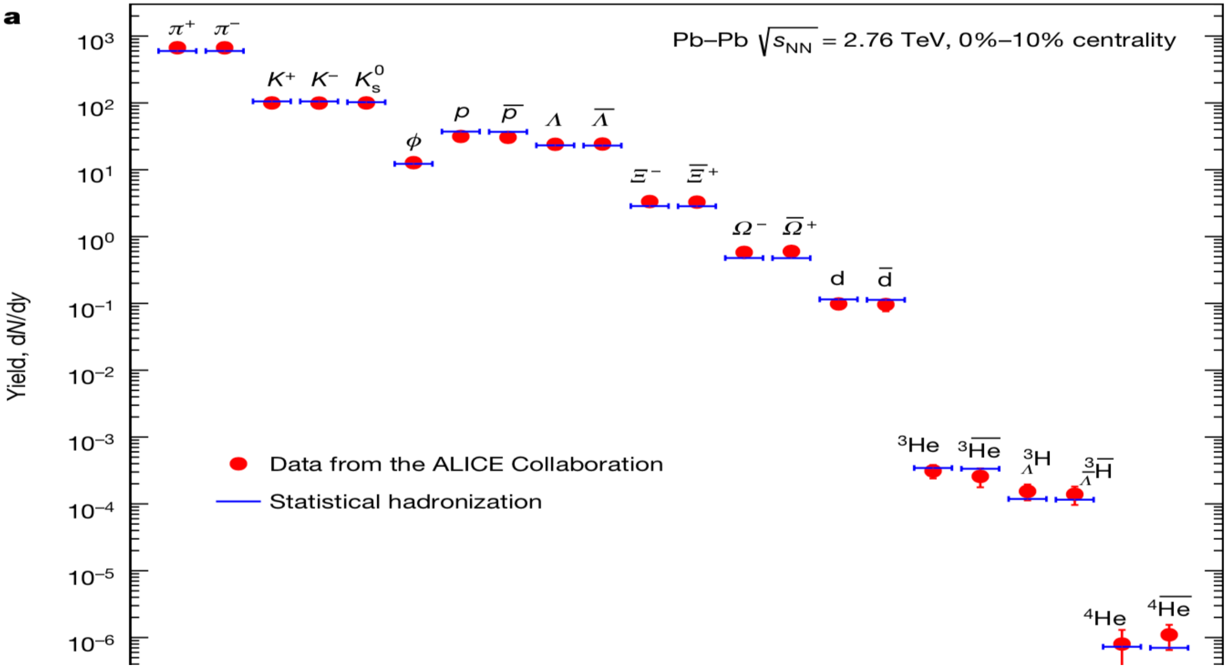
- In central collisions, thermal model fit well with $\gamma_S = 1$.

  → **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.

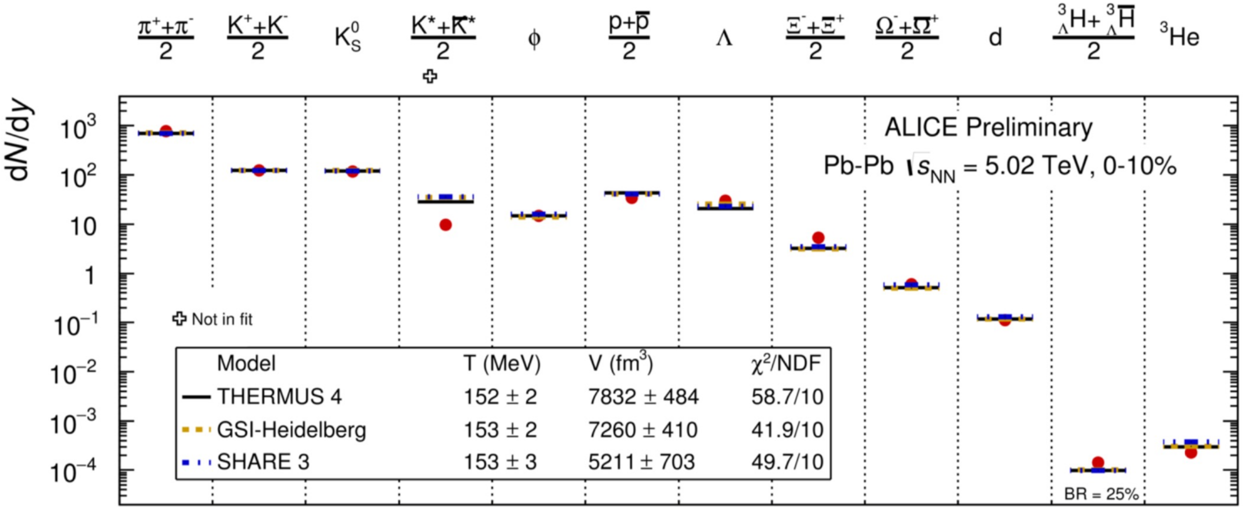
Hadron abundances and predictions of the statistical hadronization model: ALICE



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:

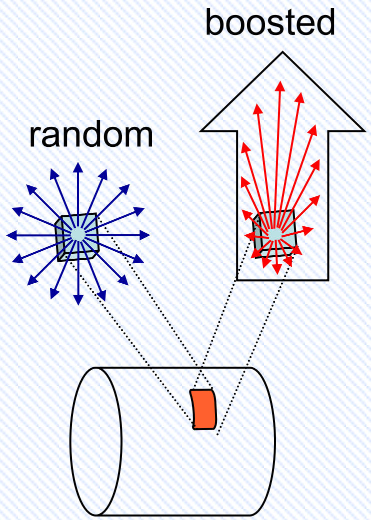
- Local thermal equilibrated
- Boosted radically

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

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

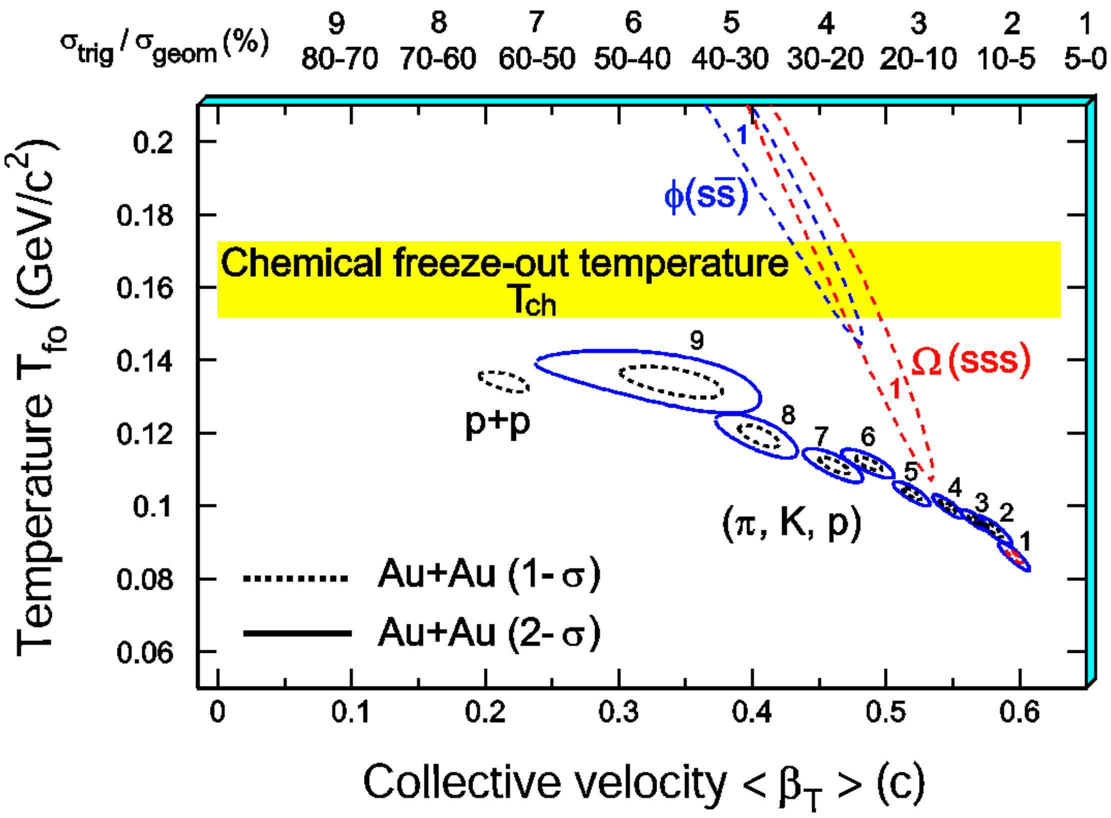
$$\frac{dN}{m_T\,dm_T}\propto\int_0^R r\,dr\,m_T K_1\left(\frac{m_T\cosh\rho}{T_{fo}}\right)I_0\left(\frac{p_T\sinh\rho}{T_{fo}}\right)$$

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



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

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



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

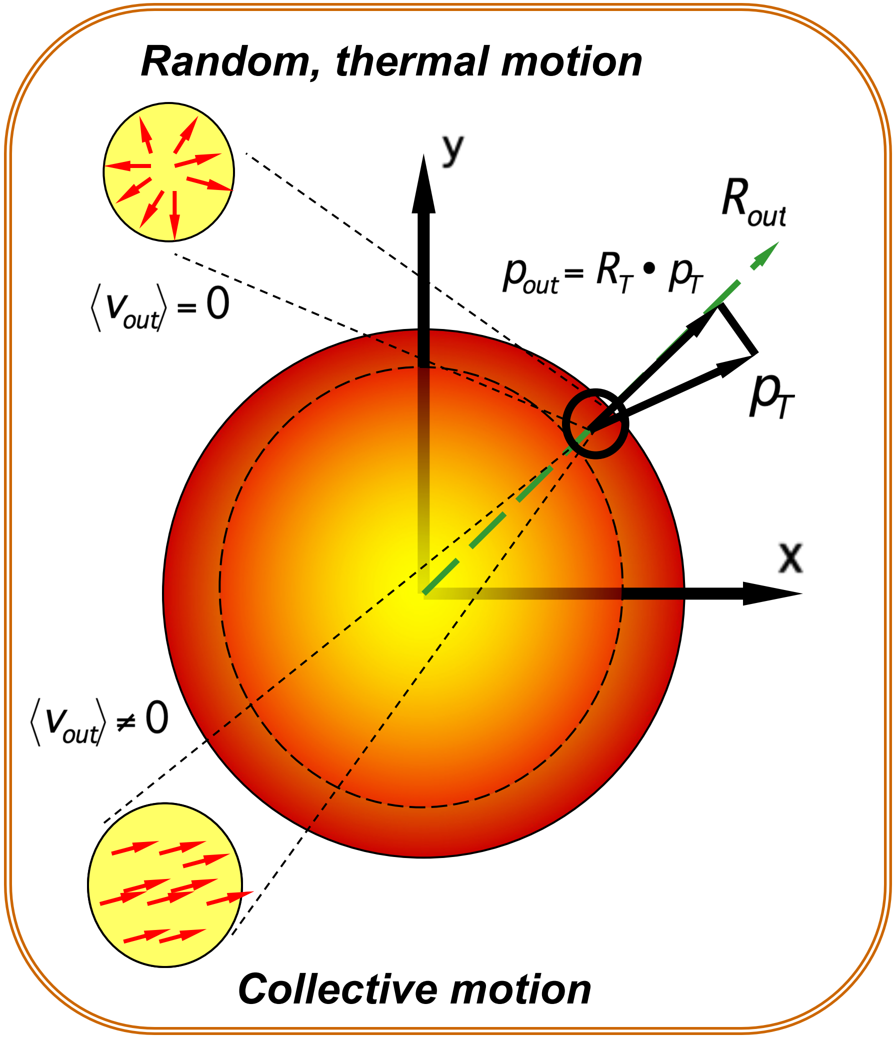
2) At the most central collisions, $<\beta_T>$ reaches 0.6c.

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***

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

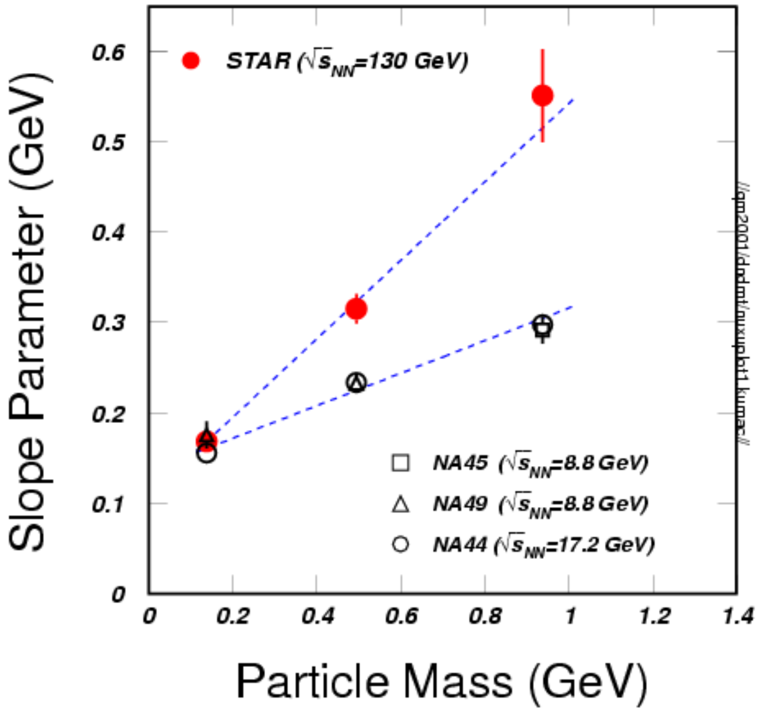
$$T \propto T_{thermal} + mass\,\langle v_T\rangle^2$$

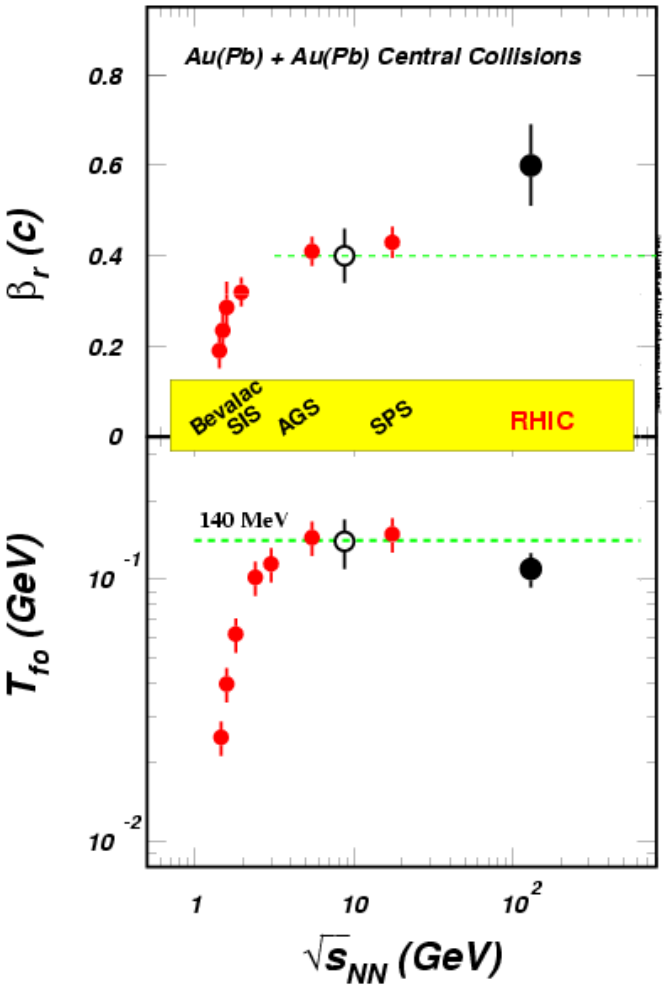
$$\langle p_T\rangle_{thermal} \propto \sqrt{mass\; T_{thermal}}$$

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

Mass Dependence of Slopes

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

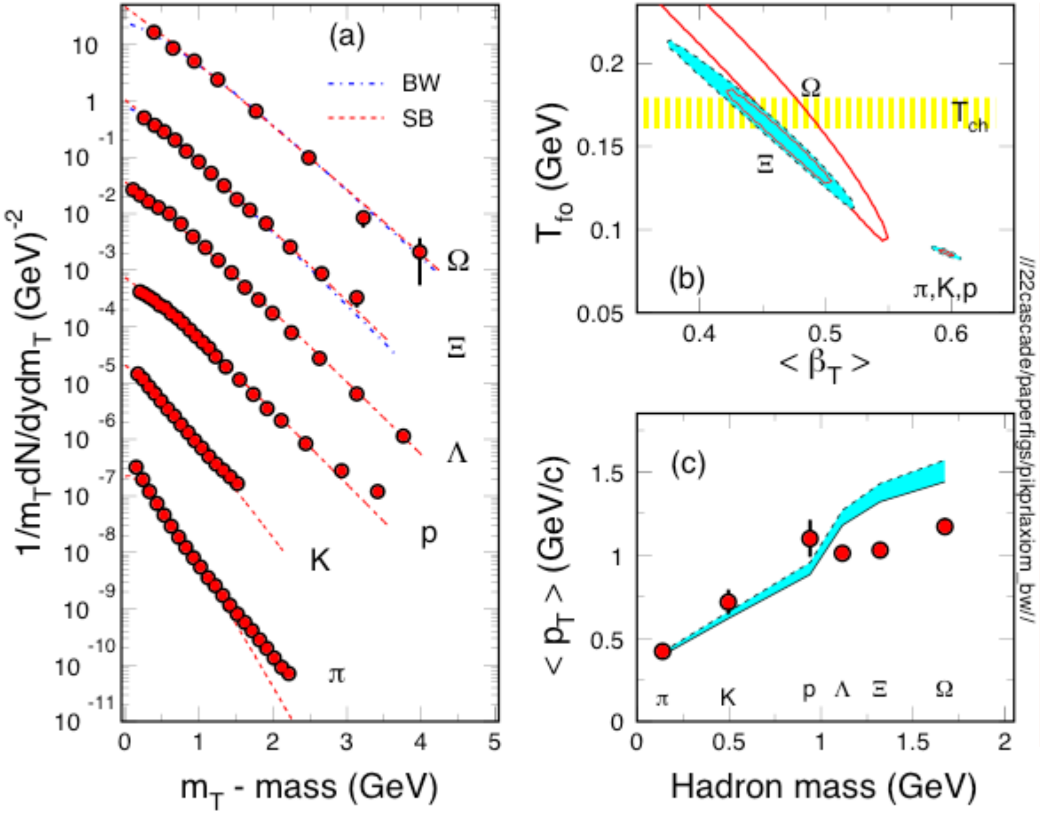




Explosive expansion at RHIC!

Early freeze-out

Central Au+Au collisions at RHIC

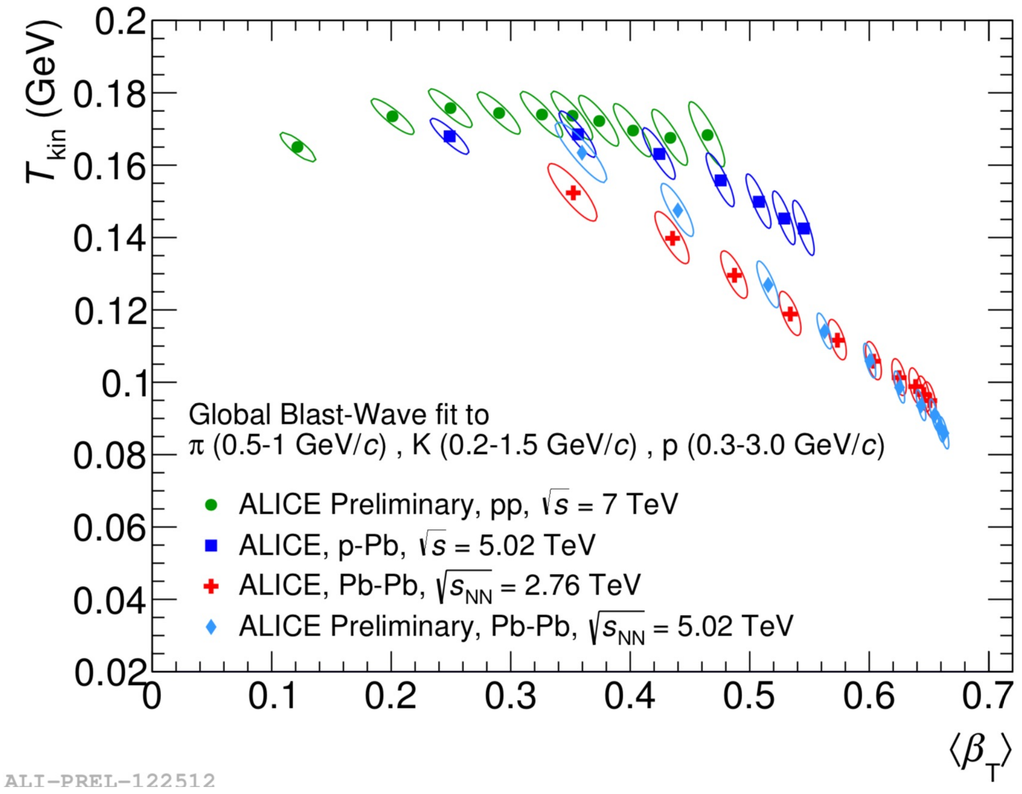


1）Multi-strange hadrons seem to freeze out earlier than others 🡇 sensitive probe for early dynamics

2) Model results fit to π, K, p spectra well, but over predicted $\langle p_T \rangle$ 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

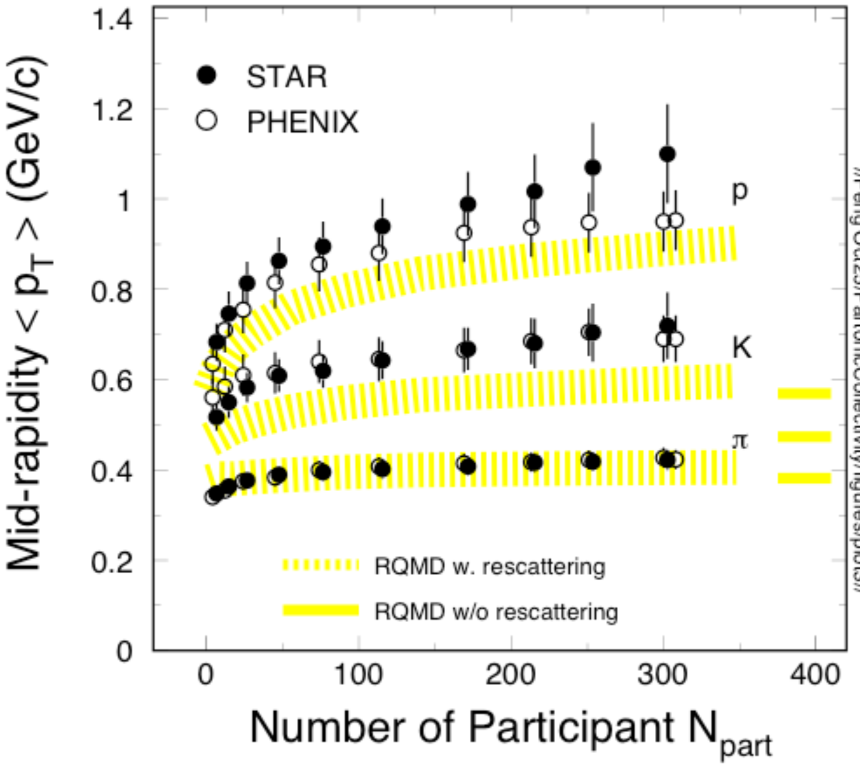


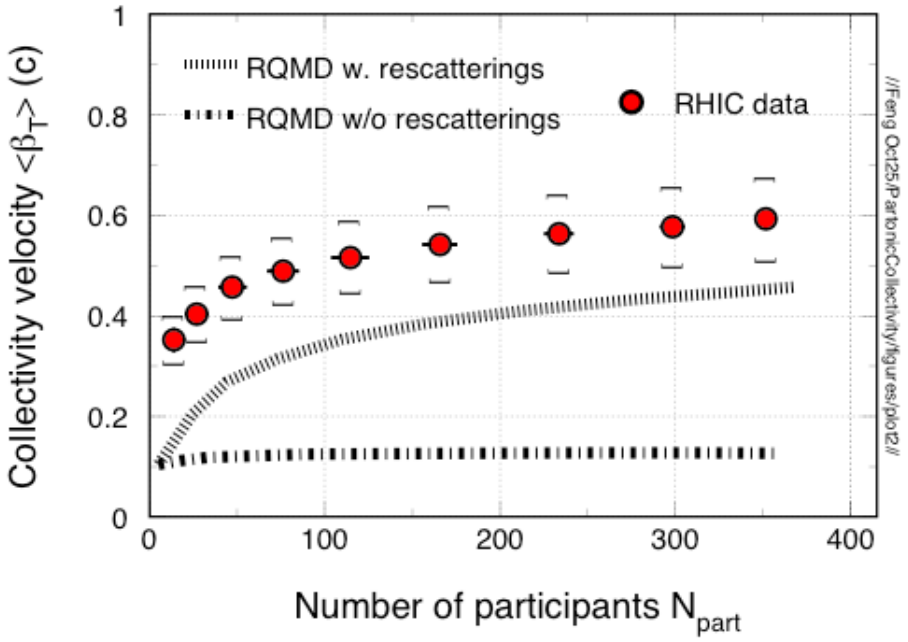
N. Jacazio
ALICE QM2017

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



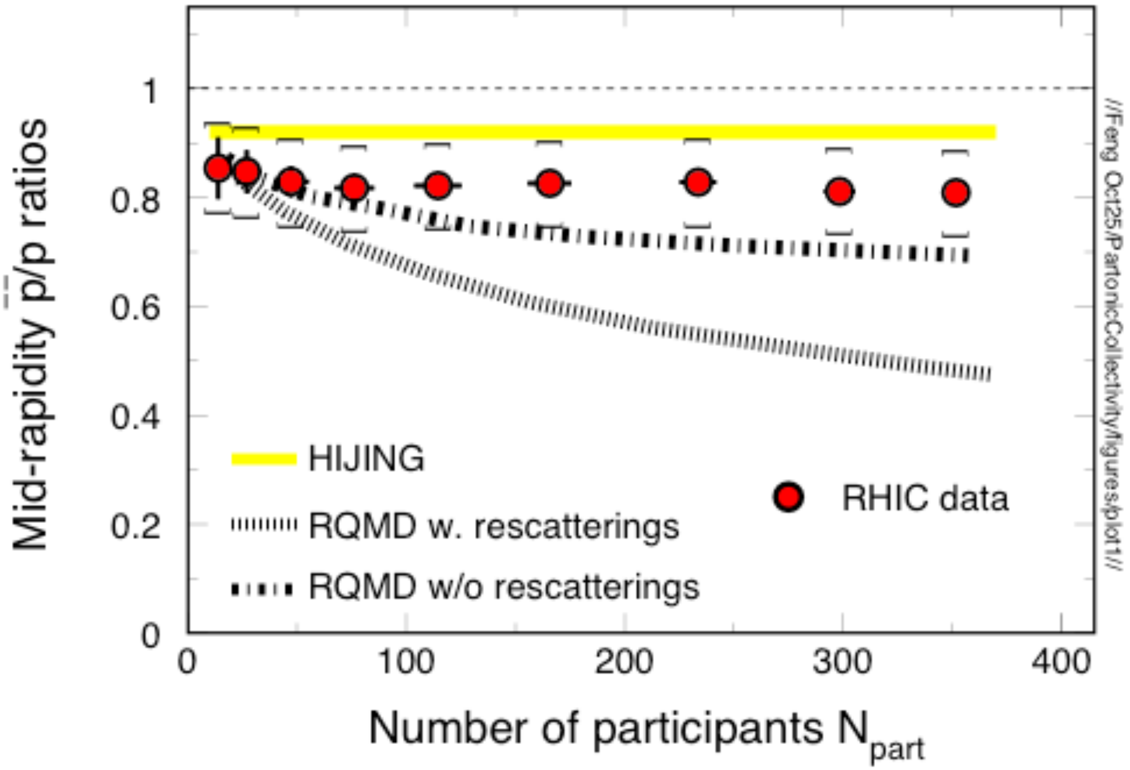


(1) The <pt> increases vs. centrality ⇒ collective expansion

(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?**

Summary II: Radial Flow

1) Copiously produced hadrons freeze-out:

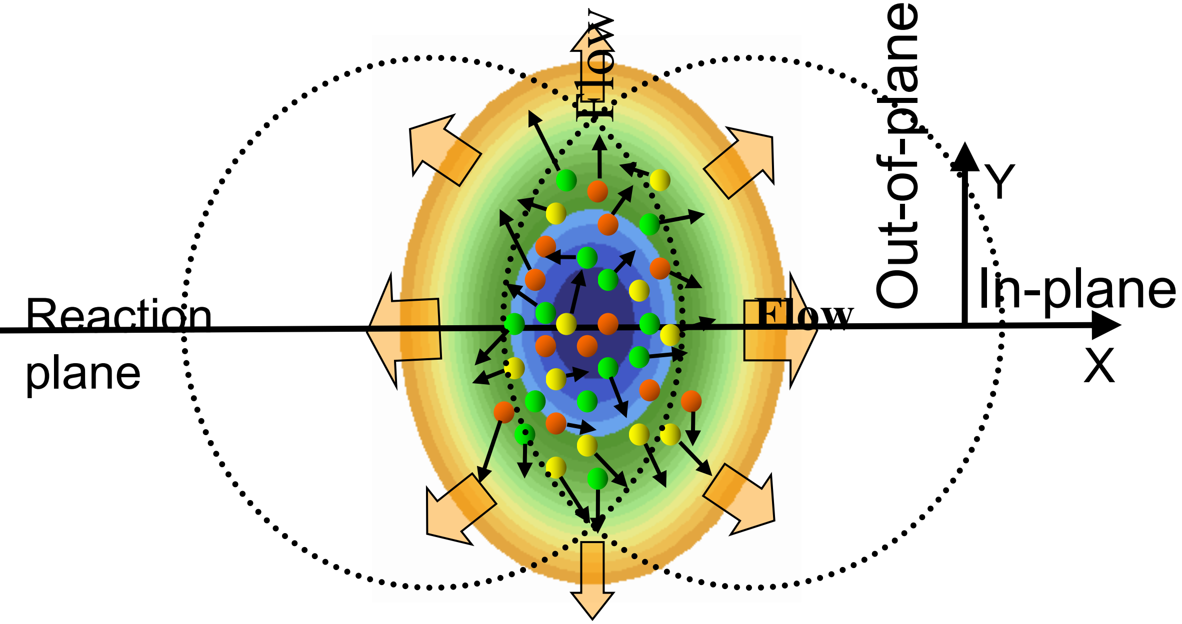
T_{fo} = 100 MeV, β_T = 0.6 (c) > β_T(SPS)

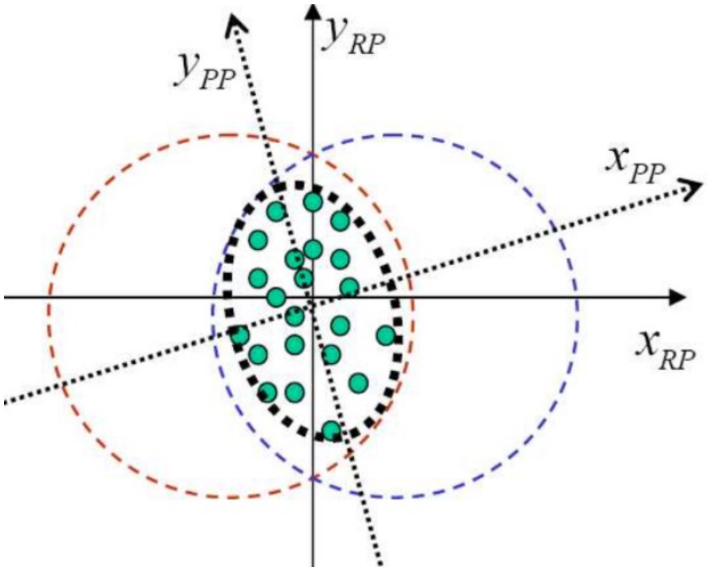
Much stronger collective flow observed in collisions at RHIC than collisions at lower beam energies. ***Early partonic interactions*** are responsible for the increase of pressure gradient at RHIC.

2)* Multi-strange hadrons freeze-out:

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

Azimuthal Distributions

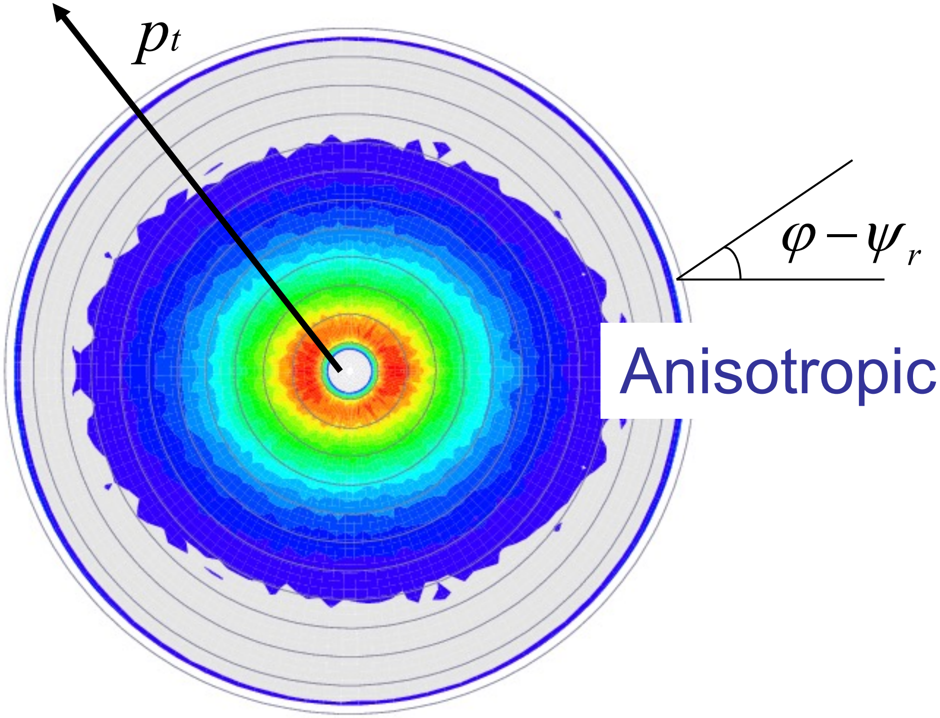




Reaction plane defined by impact parameter and beam direction

X_{PP}: Participant Plane, maximises spatial anisotropy ε_n
Ψ_n: Event plane, maximises anisotropy v_n

Higher harmonics



Anisotropic flow

- Directed flow (v_1)
- Elliptic flow (v_2)
- Higher harmonics

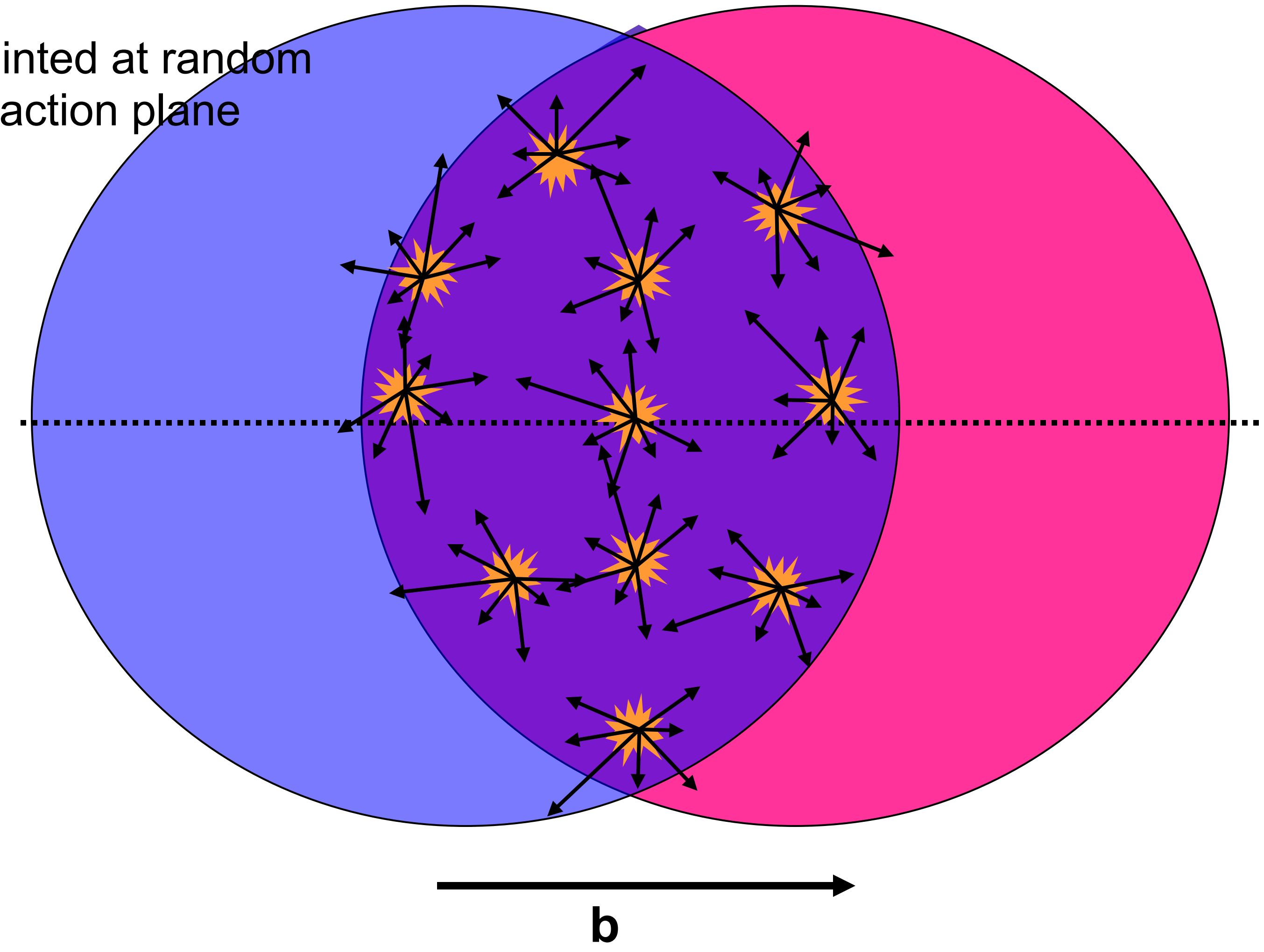
$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\varphi-\psi_r)]\right)$$

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

Forming a system and thermalizing

Animation: Mike Lisa

1) Superposition of independent p+p:

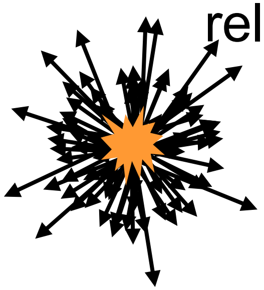


Forming a system and thermalizing

Animation: Mike Lisa

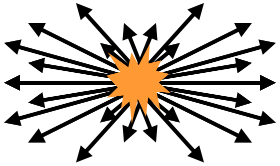
1) Superposition of independent p+p:

momenta pointed at rando
relative to reaction plane

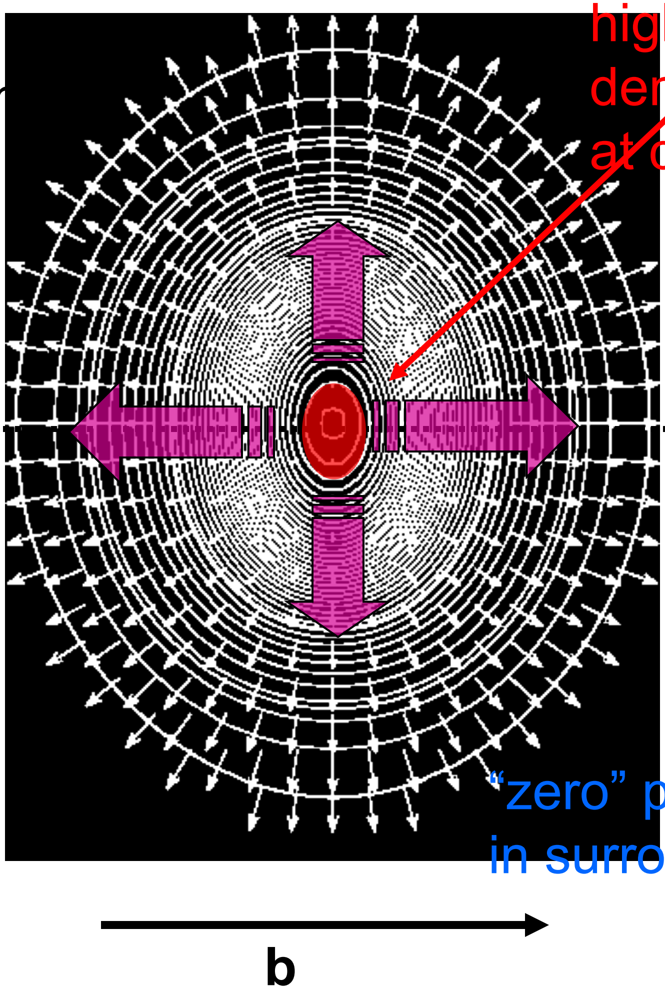


2) Evolution as a **bulk __system__**

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



more, faster particles seen in-plane



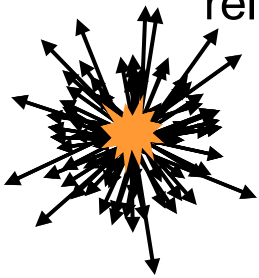
high
density / pressur
at center

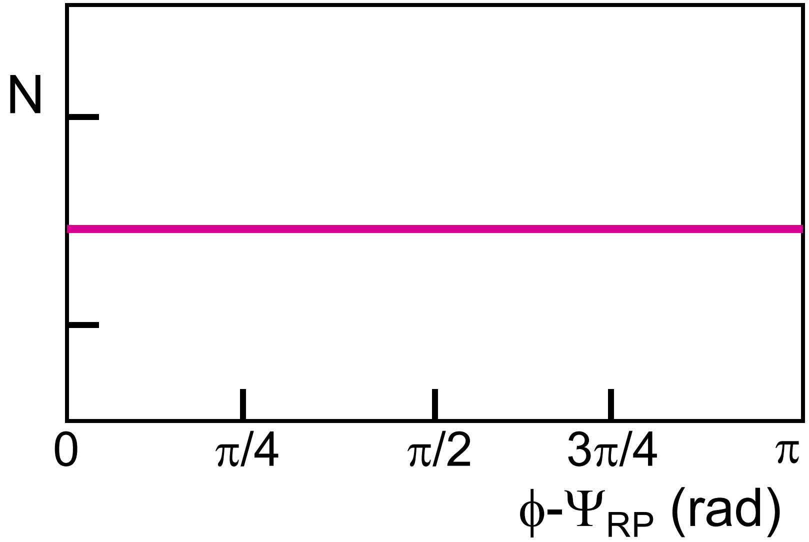
"zero" pressure
in surrounding vacuu

How does the system evolve?

1) Superposition of independent p+p:

momenta pointed at random
relative to reaction plane





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

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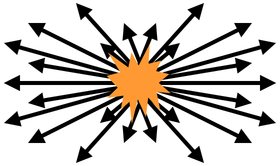
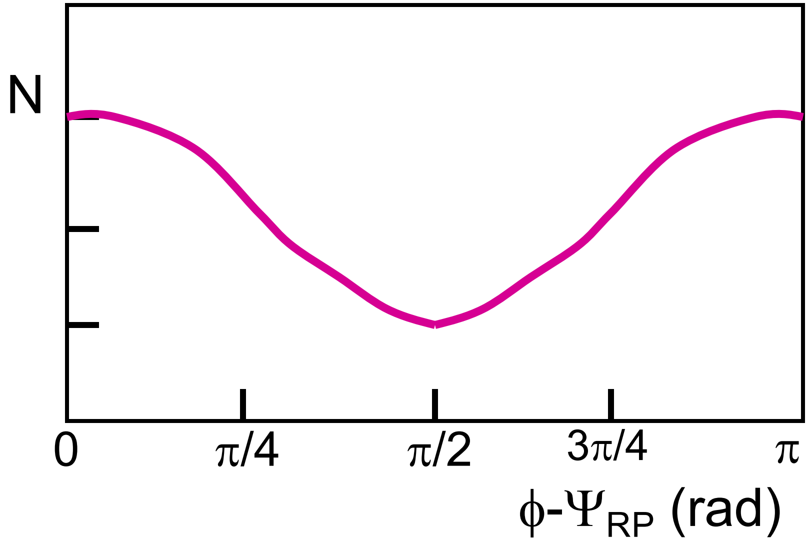
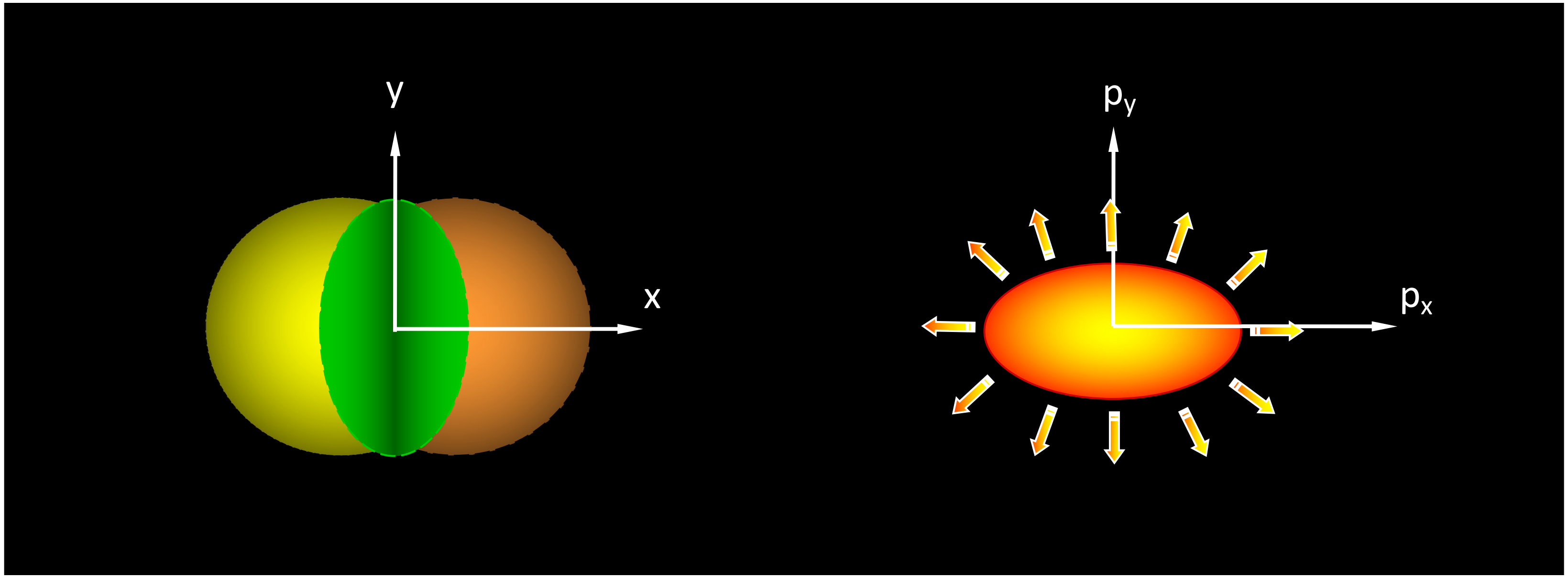


more, faster particles
seen in-plane



Anisotropy parameter v_2

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



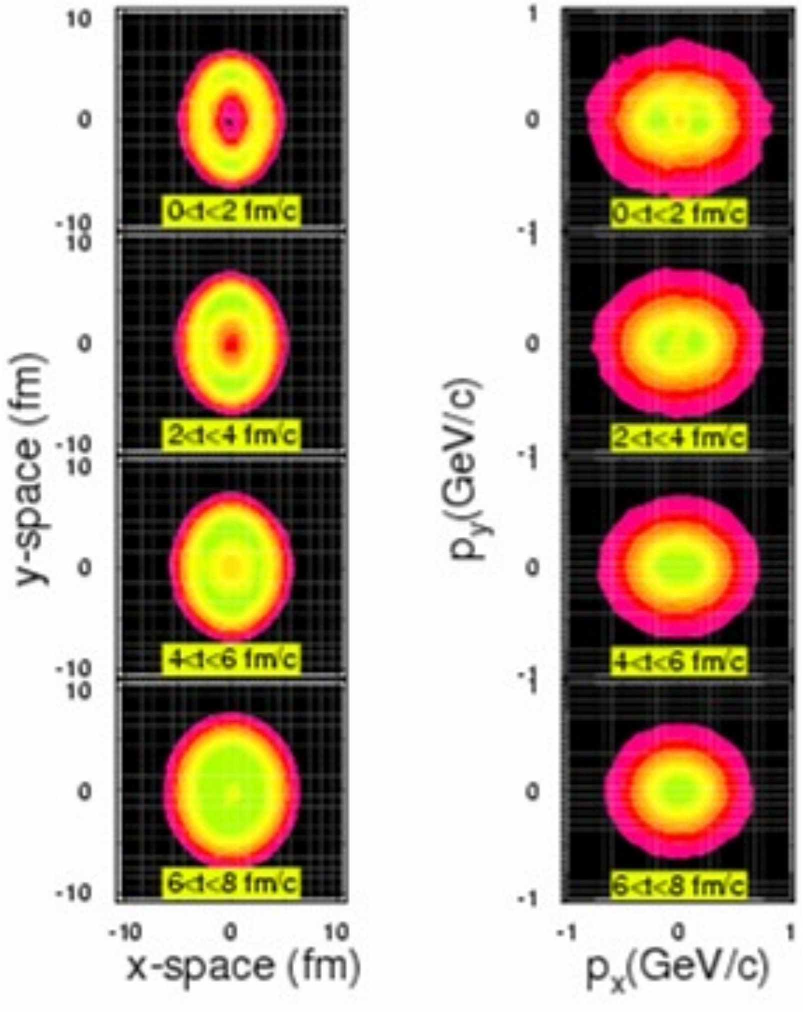
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

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

Flow : represents the collective motion of particles.

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 function measurements

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

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.

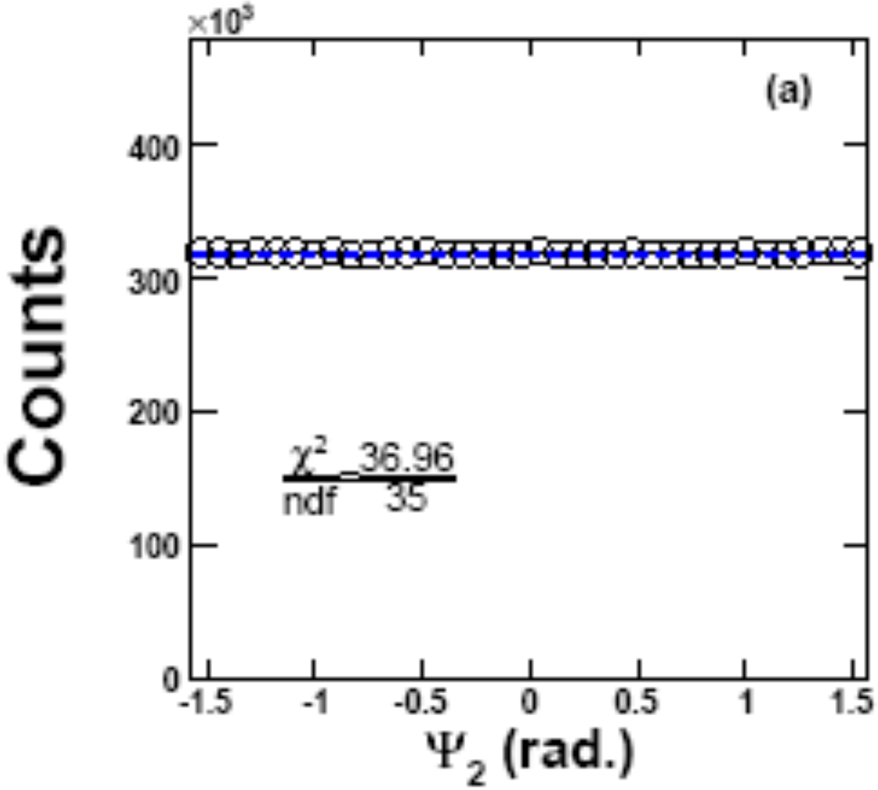
  - event plane angle

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

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

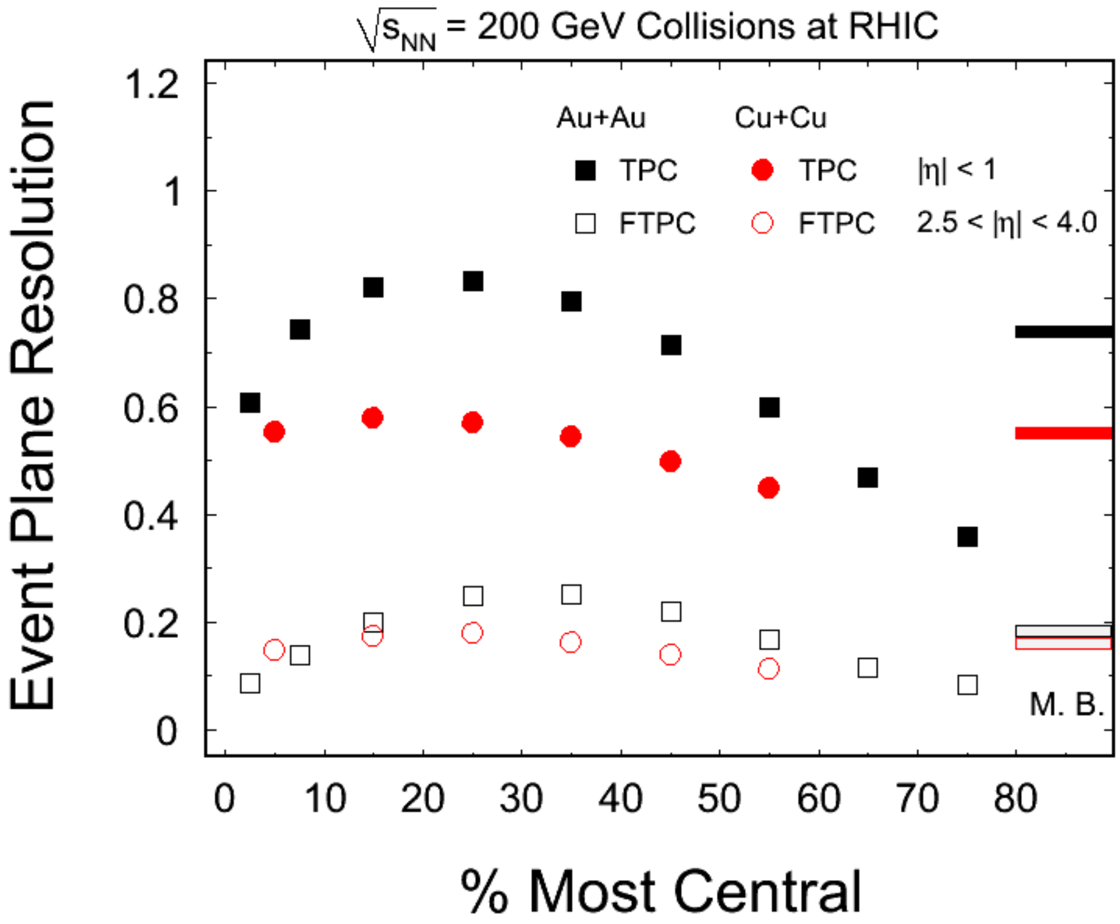
- v_2 calculation

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

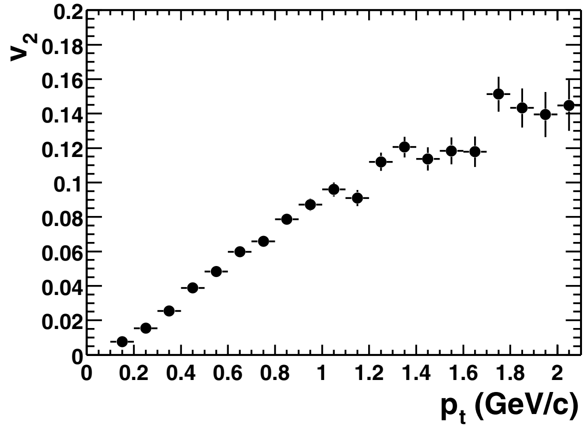


Flat distribution.

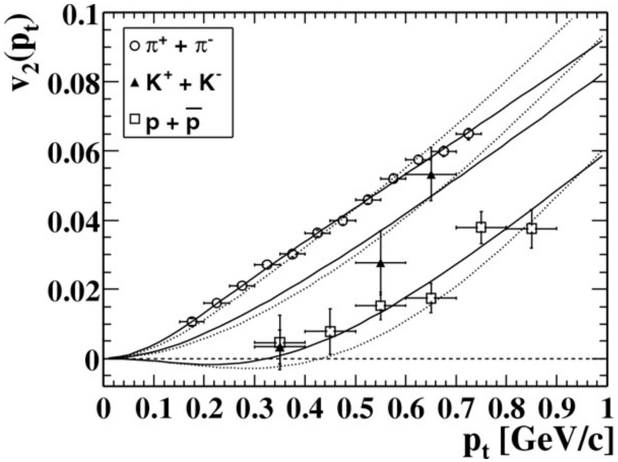
Event Plane Resolution

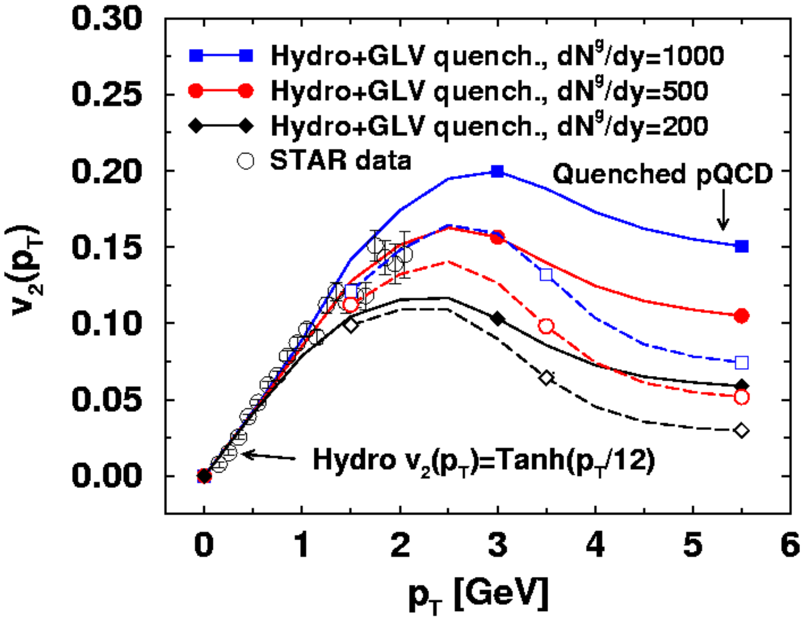


v_2 in Au Au Collisions at 130 GeV



STAR PRL 86,402(2001) 22k event





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

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

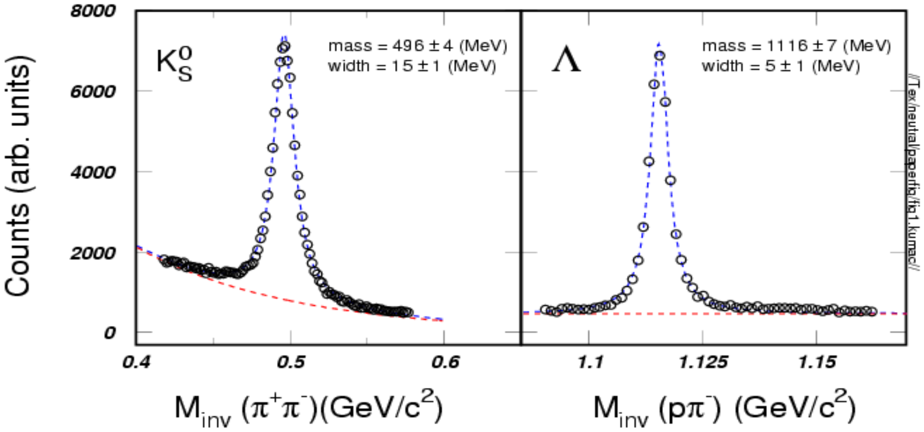
STAR: A. Tang PRL 87, 182301(2001) 120k events

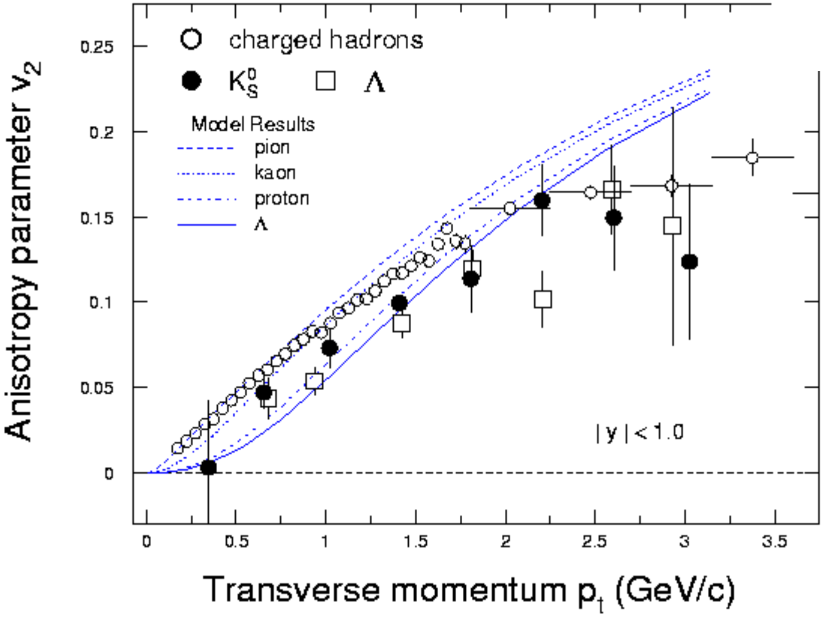
v_2 in Au Au Collisions at 130 GeV

V0 reconstruction

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

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

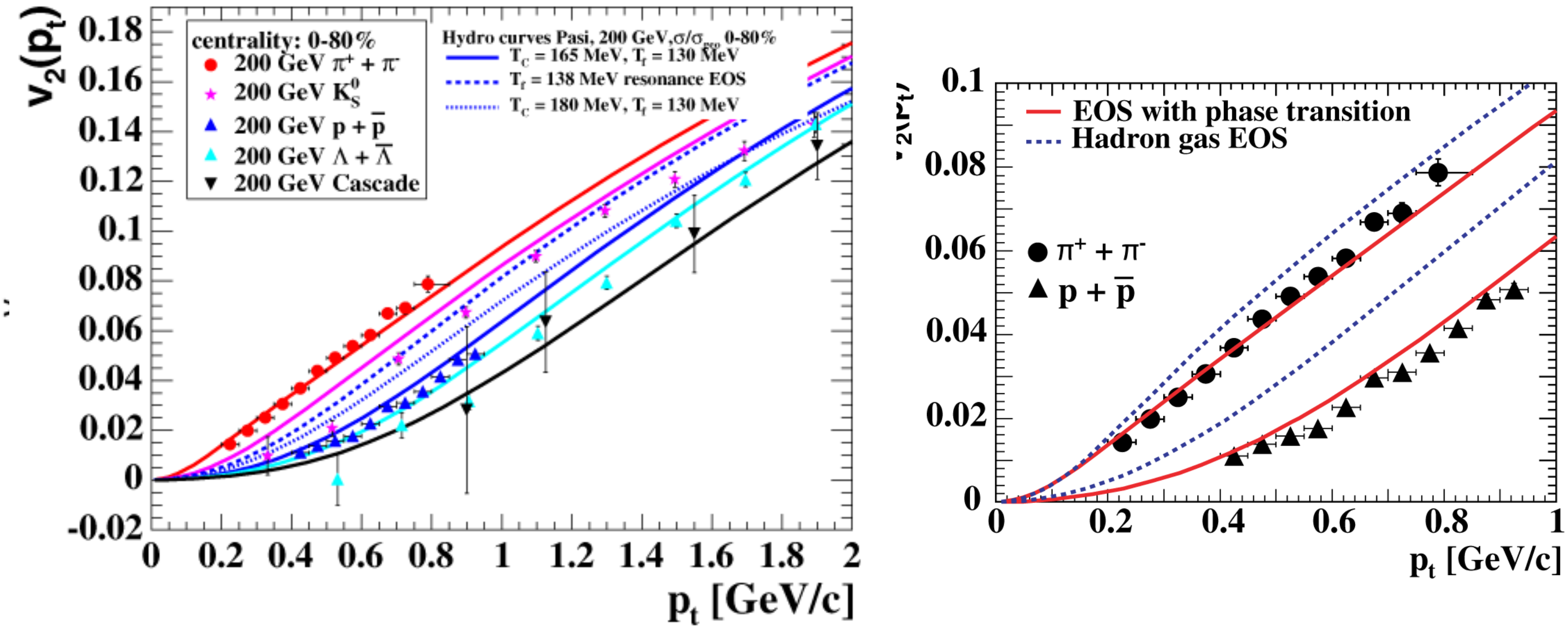




STAR(JH Fu) PRL 89, 132301(2002)
200k minibias, 180k central events

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

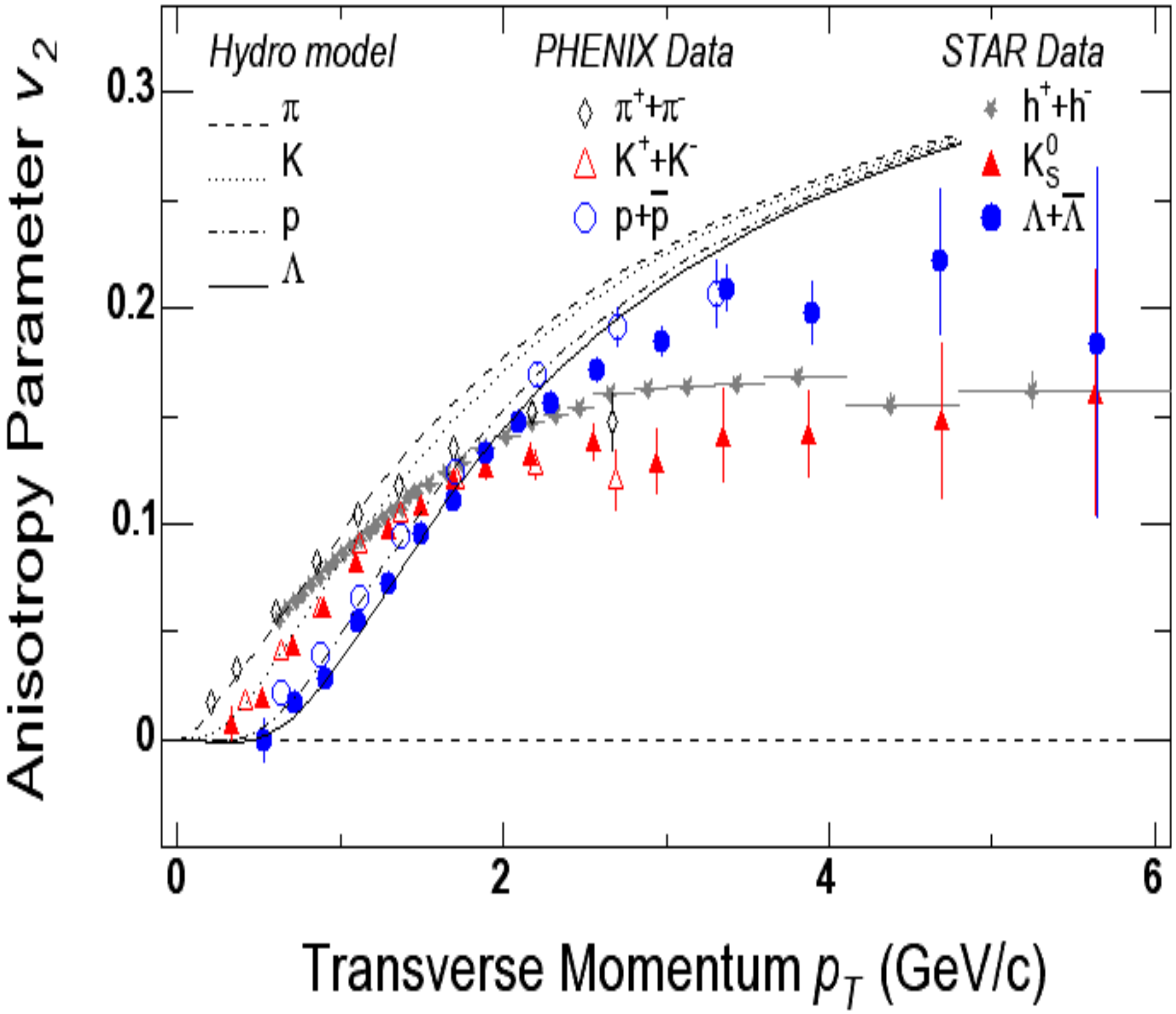
v_2 at Low p_T Region：Mass dependence



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

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?

Particle Identification

Rest are constructed: Invariant Mass + Decay Topology

V0 decay vertices

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

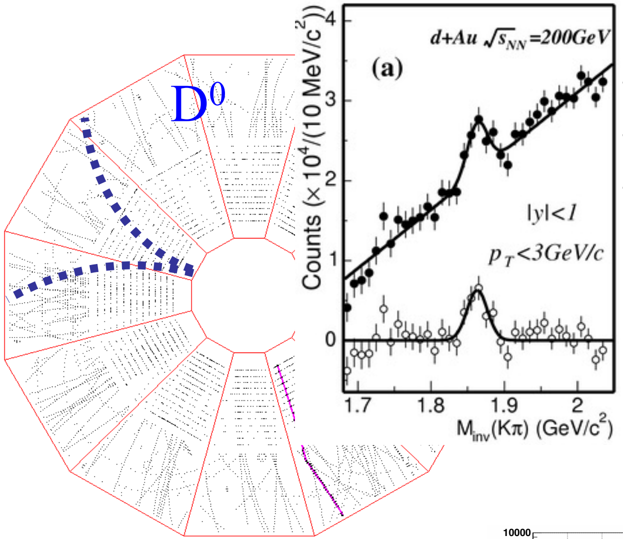
$\Lambda \rightarrow p + \pi^-$

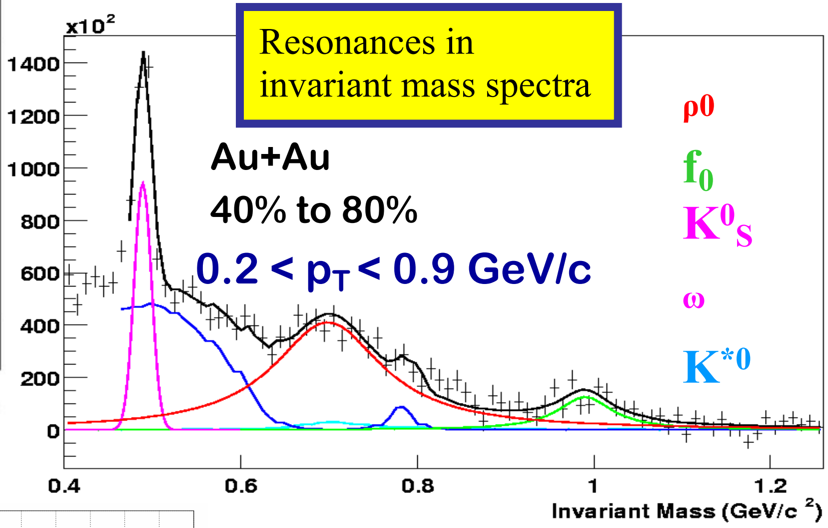
$\bar{\Lambda} \rightarrow \bar{p} + \pi^+$

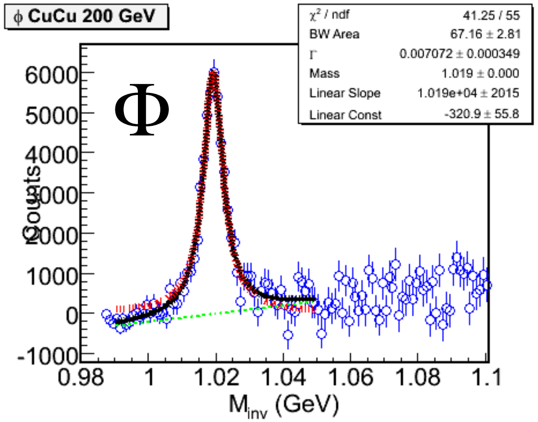
$\Xi^- \rightarrow \Lambda + \pi^-$

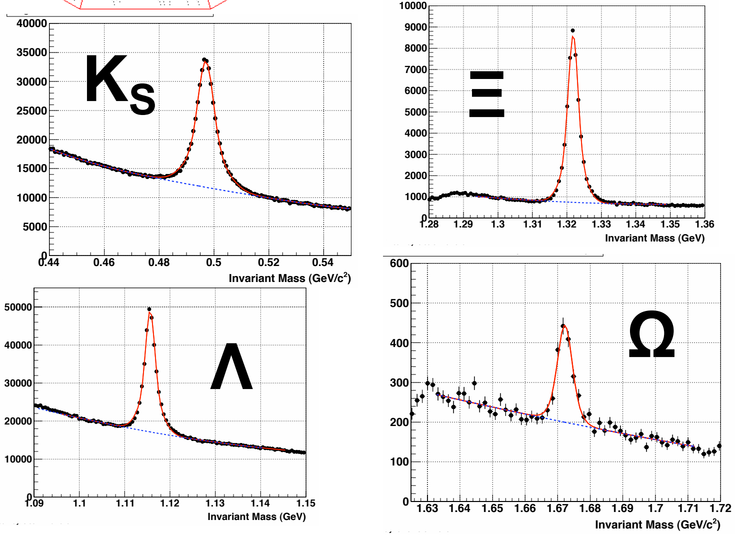
$\Xi^+ \rightarrow \bar{\Lambda} + \pi^+$

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

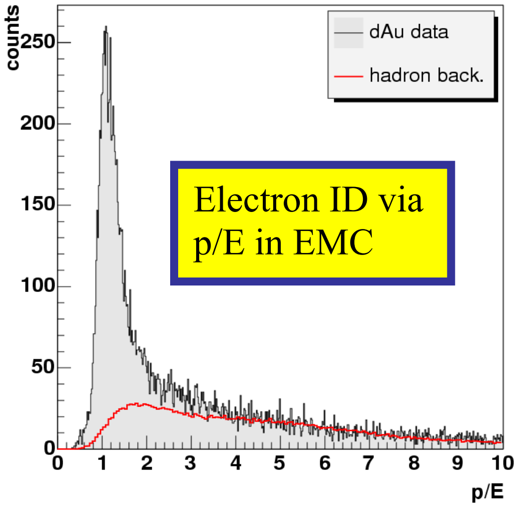



Resonances in invariant mass spectra



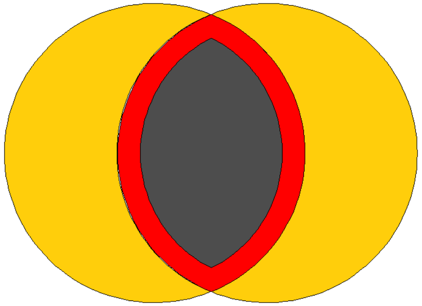


$$M^2 = E^2 - p^2$$


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



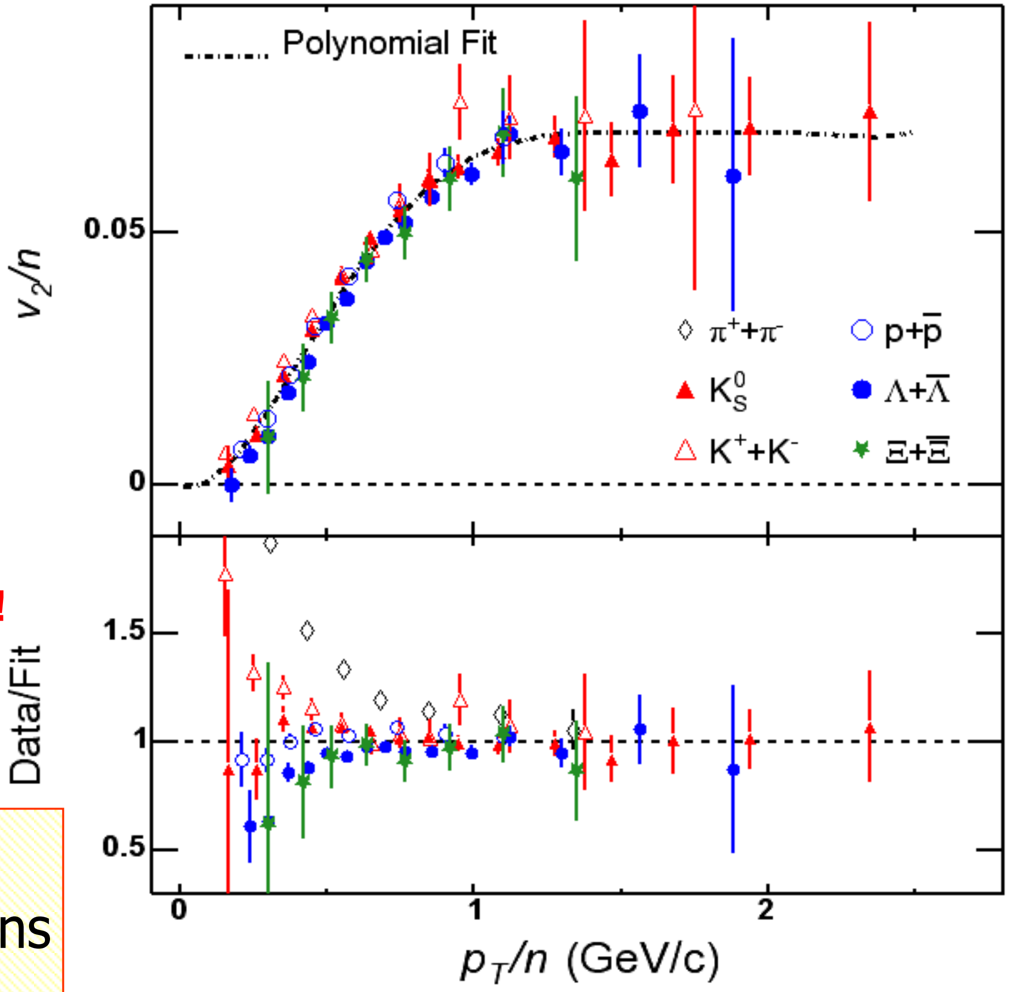
Hadronization Scheme for Bulk Partonic Matter:

K_S – two quark coalescence

Λ– three quark coalescence

from the partonic matter surface?!

Particle v_2 may be related to quark matter anisotropy !!

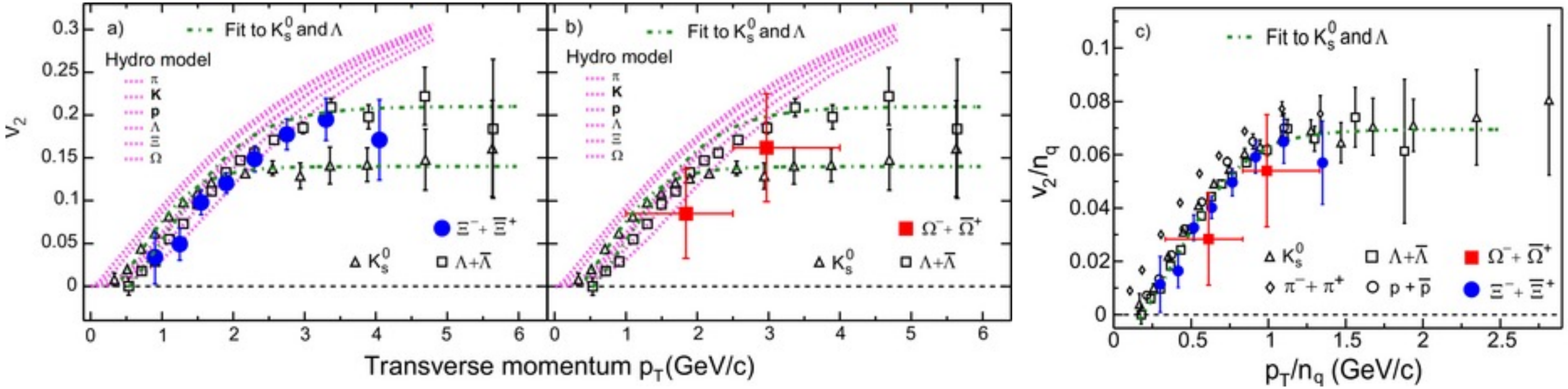


For hadron formation by coalescence of co-moving partons

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

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

NQ Scaling for Identified Particles

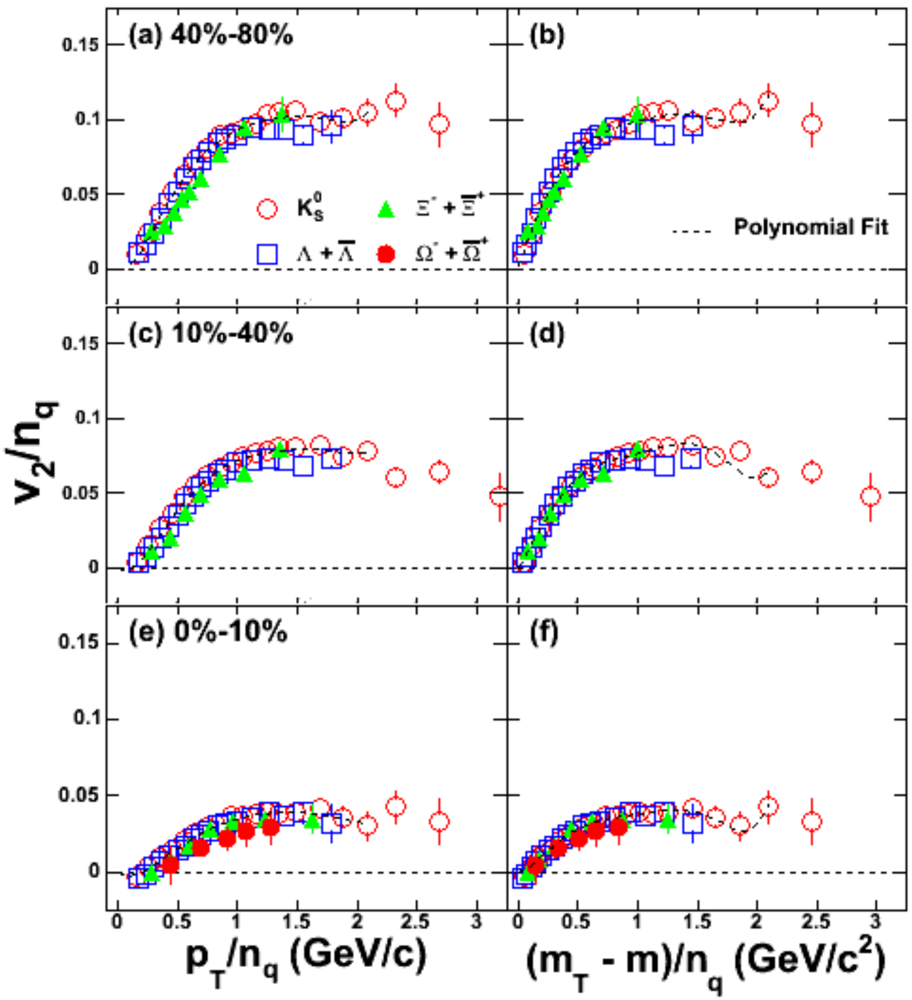


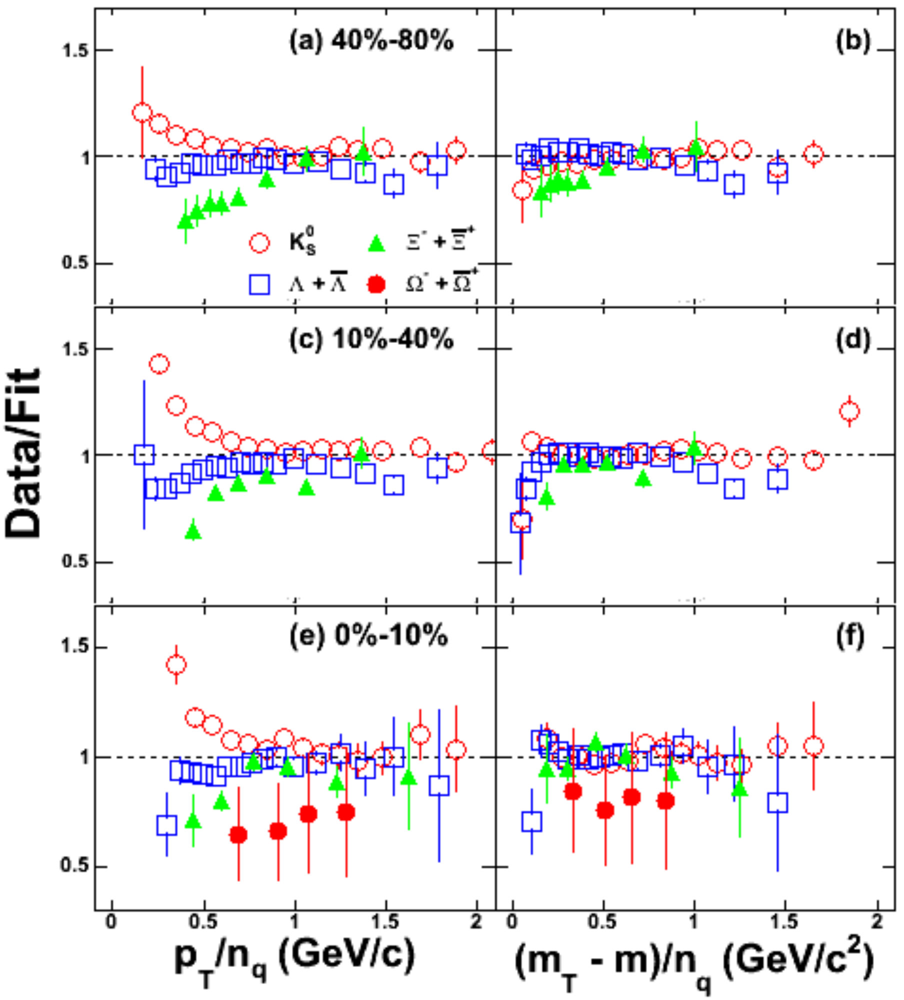
STAR： Nucl. Phys. A 757, 102, (2005);（H. Long, JH Fu, H. Huang, N. Xu) PRL 92,052302 (2004) ;
J. Phys. G 30, S1207, (2004); PHENIX: PRL 91,182301, (2003) .
Fit: X. Dong, S. Esumi, P. Sorensen, N. Xu, Z. Xu, PLB 597, 328 (2004) .

- 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.

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

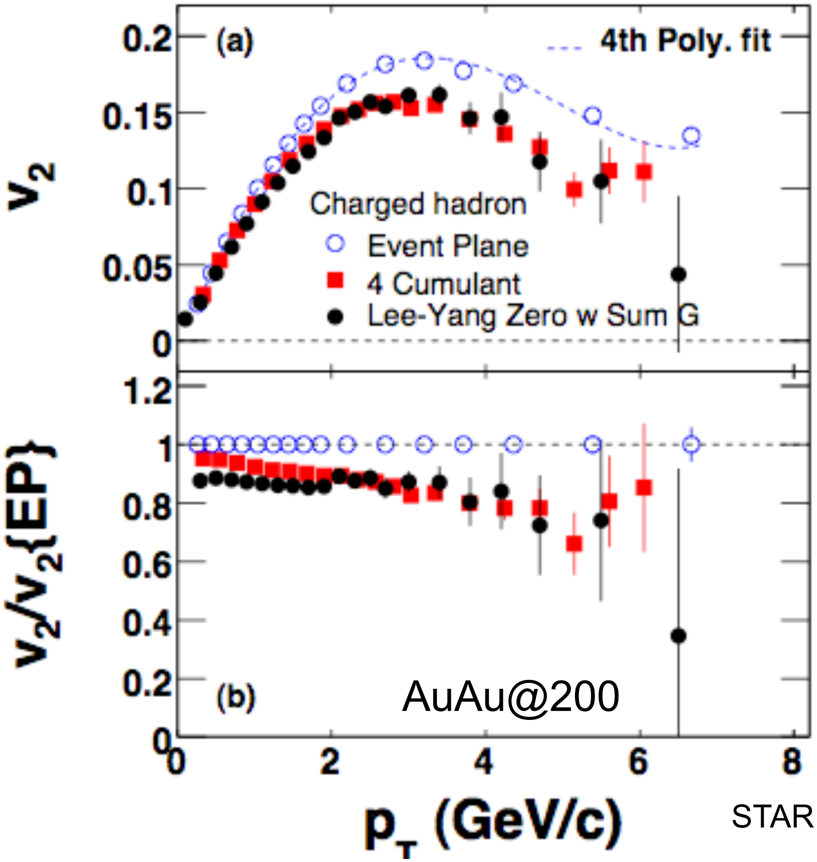
- Many-particles:
- $v_2\{4\}$: 4-particle - 2 * (2-particle)^2
- $v_2\{LYZ\}$: Lee-Yang Zeros multi-particle correlation

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

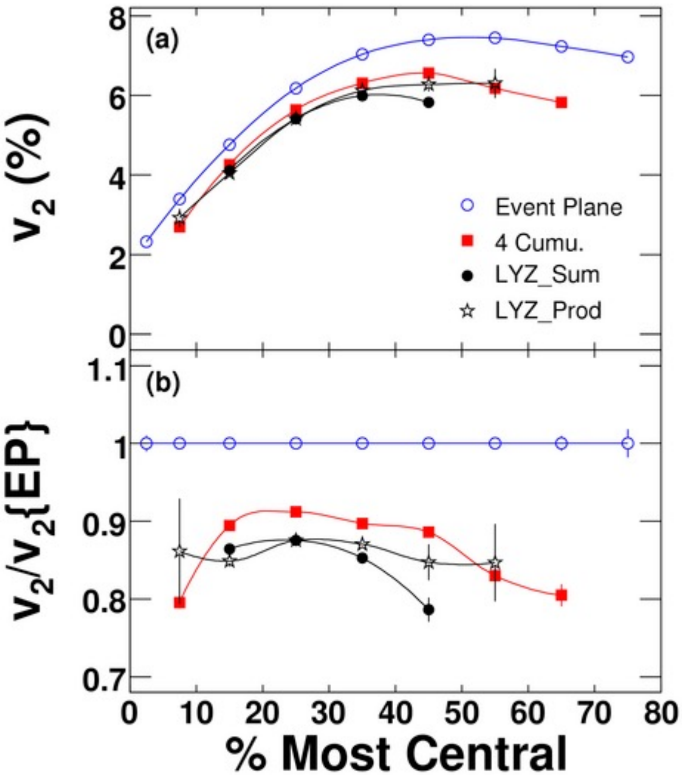
correlations from resonance decay, jets

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

Systematic Study of v_2



AuAu@200

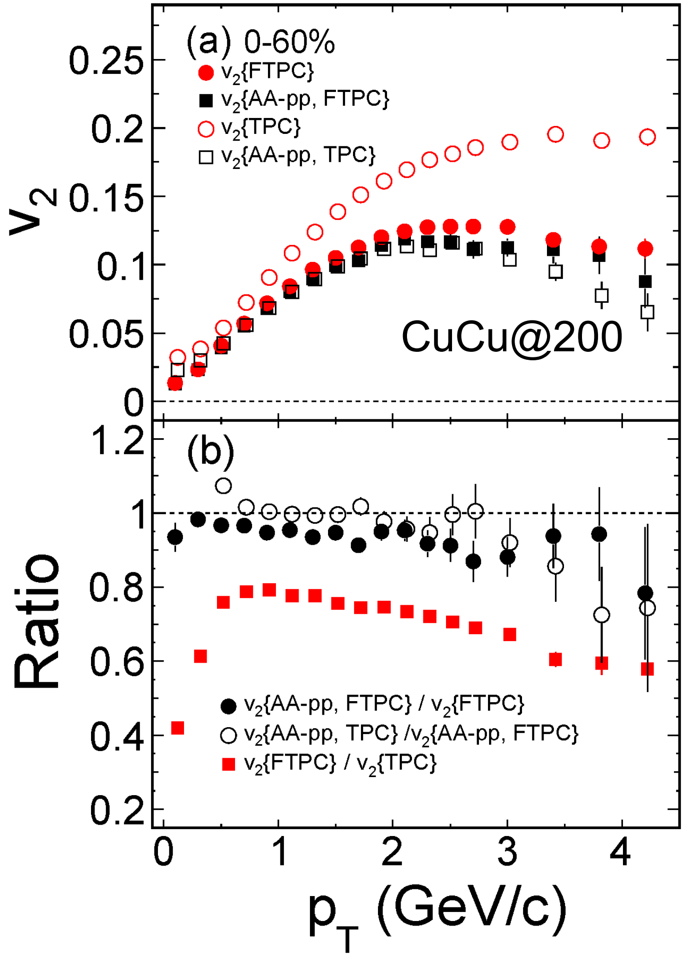


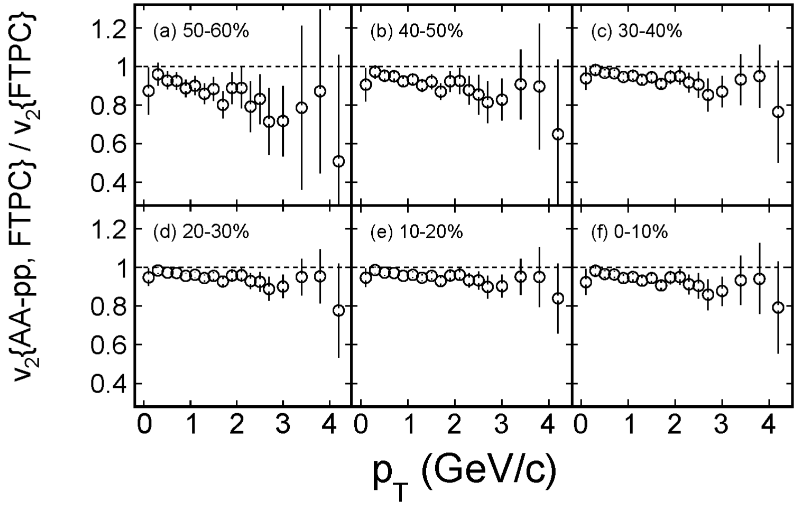
STAR: Y. Bai, Y. Lv, A. Tang, N. Xu ,PRC **77**,54901 (2008) . 25M

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

Non-flow in Cu+Cu Collisions

STAR: F. Liu, Y. Lu, S.S. Shi, X.H. Shi, A. Tang, PRC 81, 044902 (2010) 200GeV 24 M

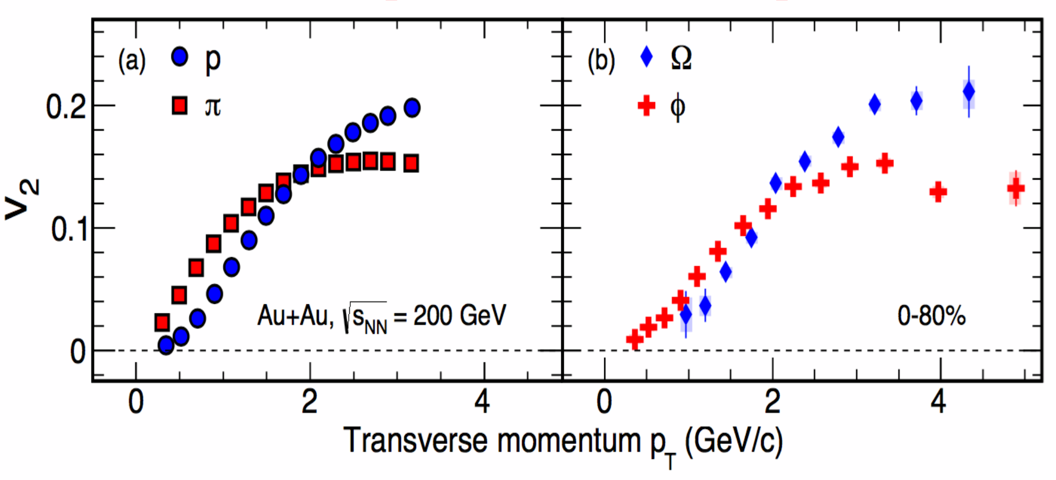




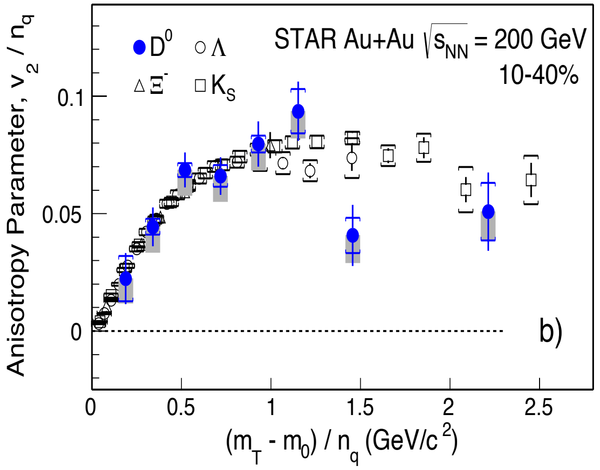
- ➢The eta gap between FTPCs and TPC can reduces most of the non-flow
- ➢v_2{AA-pp}: subtract non-flow based on azimuthal correlations in p+p collisions
- ➢nonflow effects increase with pT
- ➢larger nonflow contributions in peripheral collisions

Partonic Collectivity at RHIC

u- and d-quarks s-quarks



c-quarks



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;

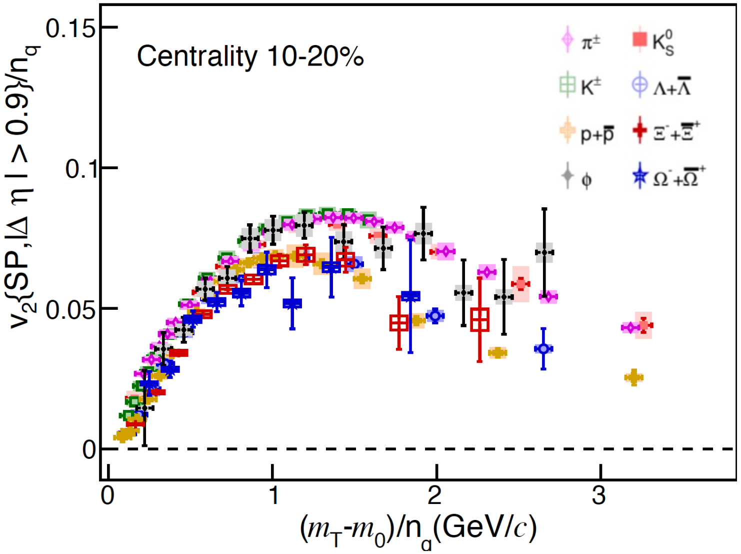
➔ ***Partonic Collectivity, necessary for QGP!***

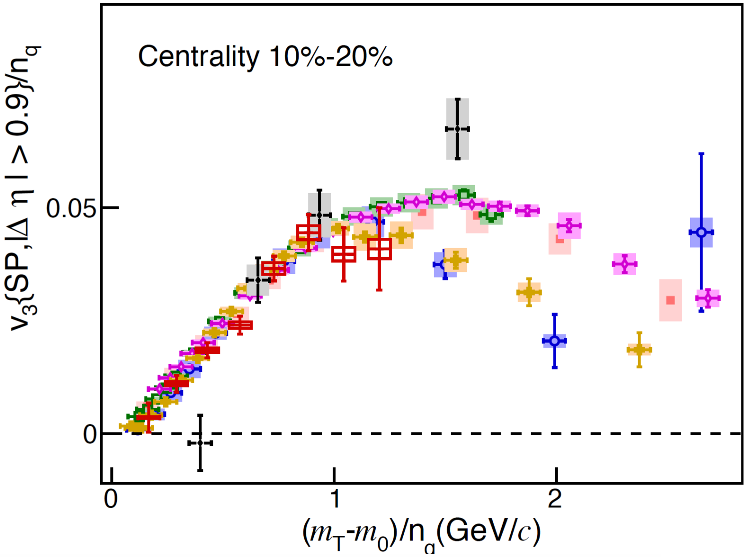
➔ ***De-confinement in Au+Au collisions at RHIC!***

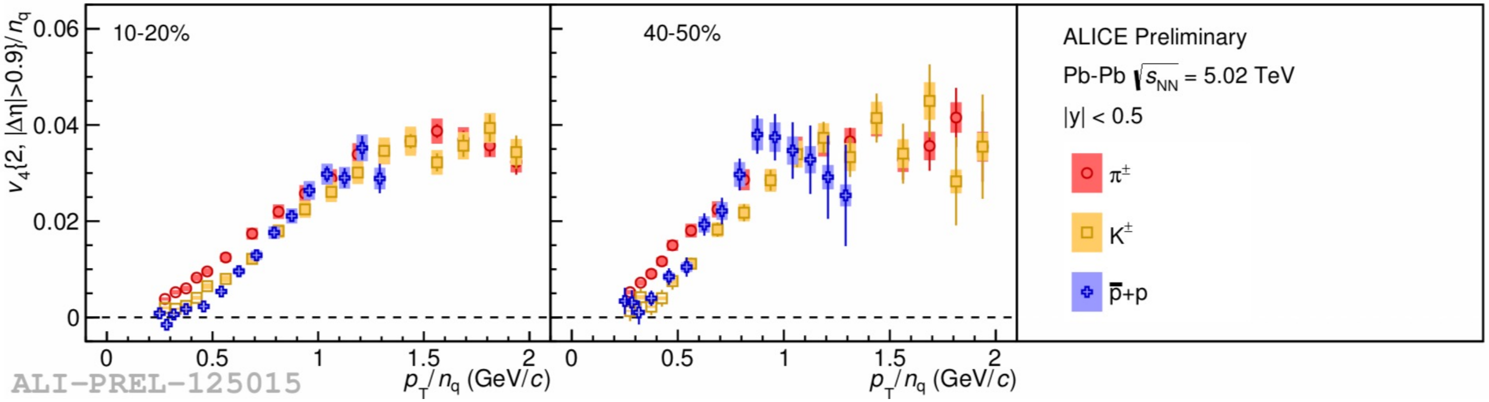
Elliptic Flow at LHC

•Pb + Pb 5.02 TeV

•**ALICE:** ICHEP 2018, ATHIC 2018





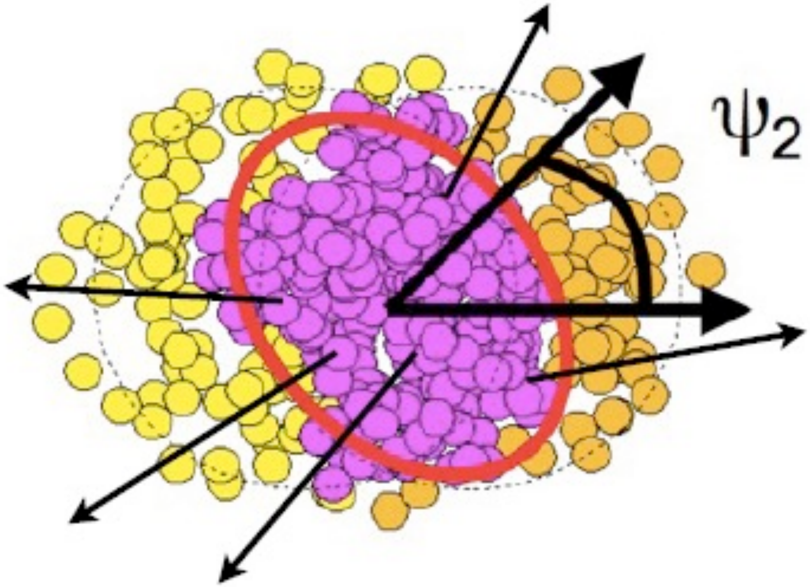


ALICE QM2017

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

Participant eccentricity

Event plane may be different from the reaction plane.



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

$$\boxed{v_2 \propto \epsilon}$$

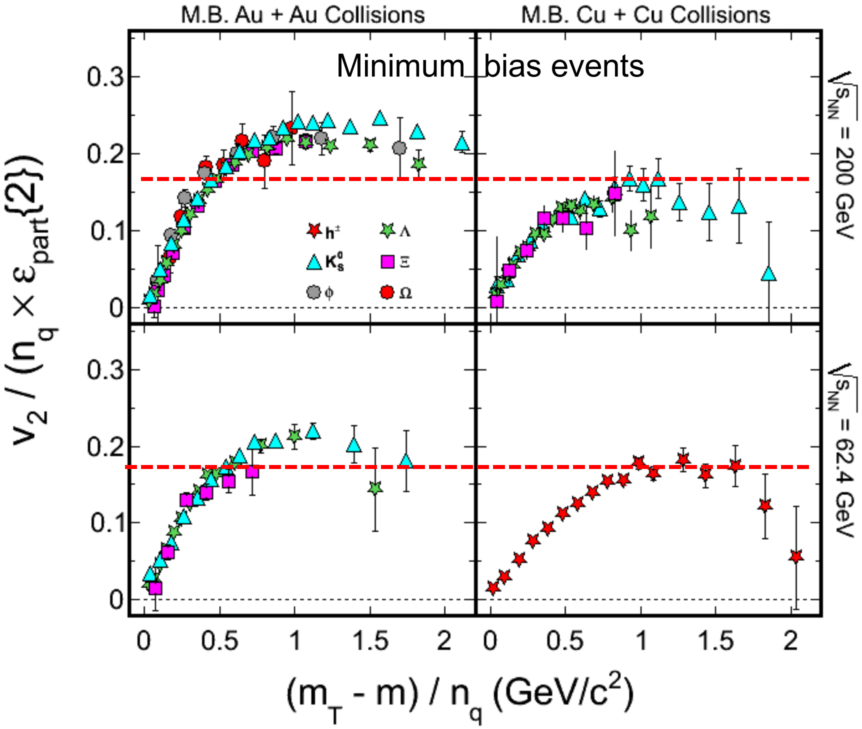
Can be nonzero even at vanishing impact parameter due to fluctuations.

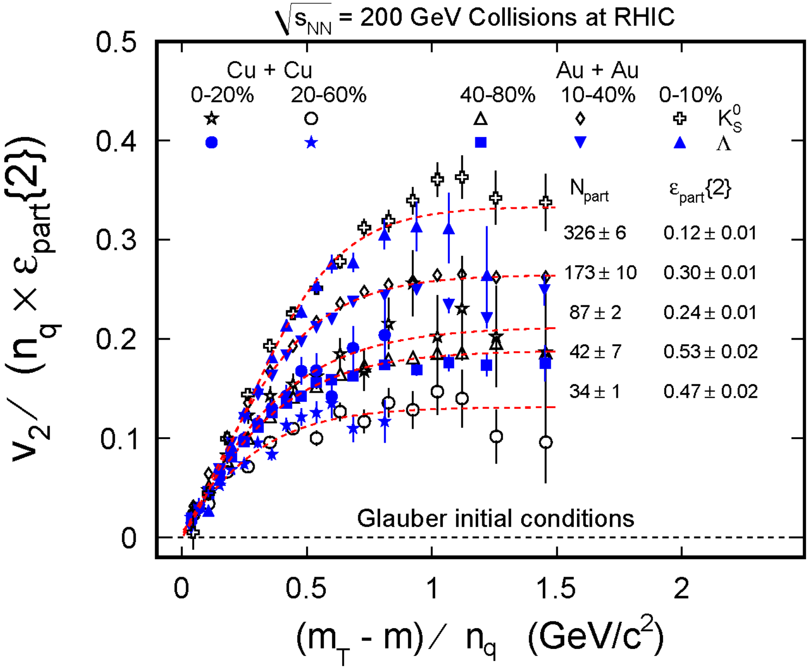
Important because high-multiplicity events mostly come from central collisions.

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

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)





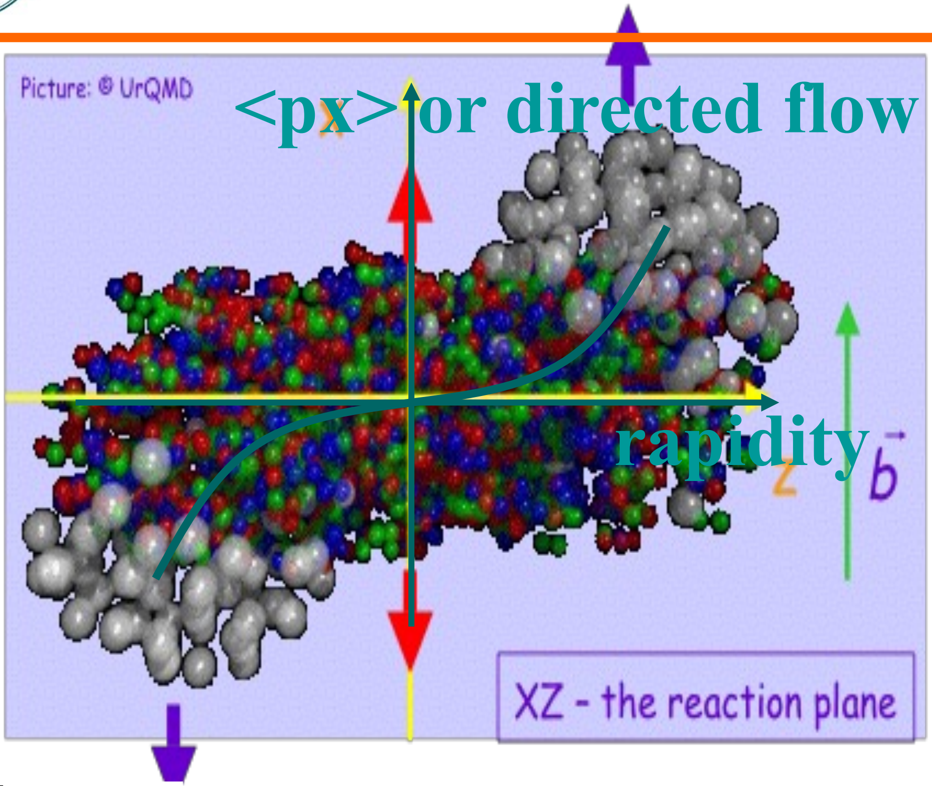
Au+Au and Cu+Cu at 200 GeV **Scaled by eccentricity** remove the initial geometry

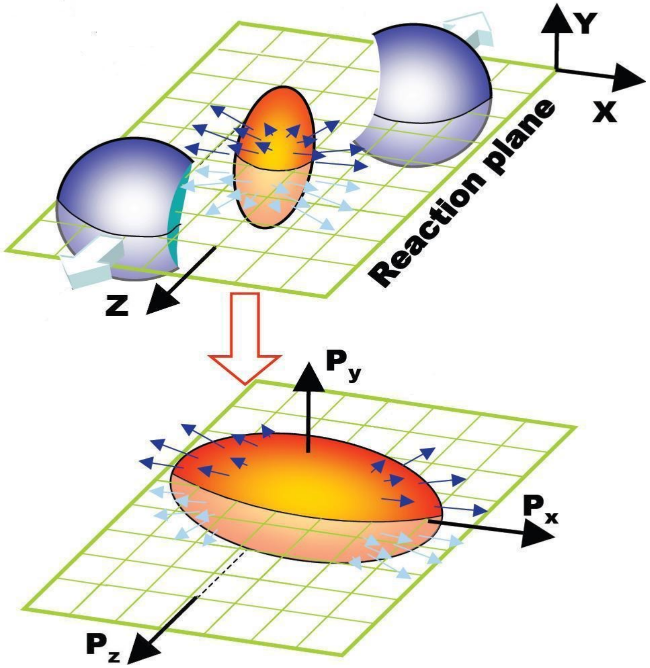
➢NQ scaling for each centrality bin

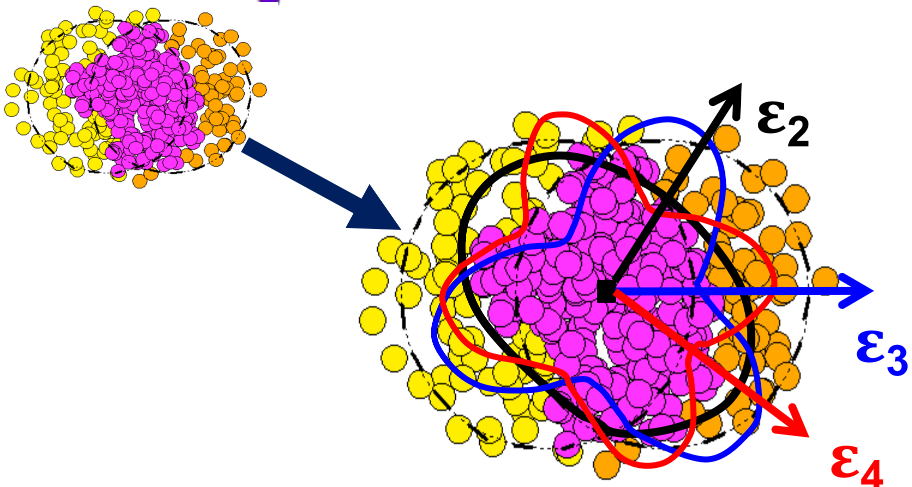
➢Collective flow: depends on the number of participants

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

Harmonics in hydro-picture





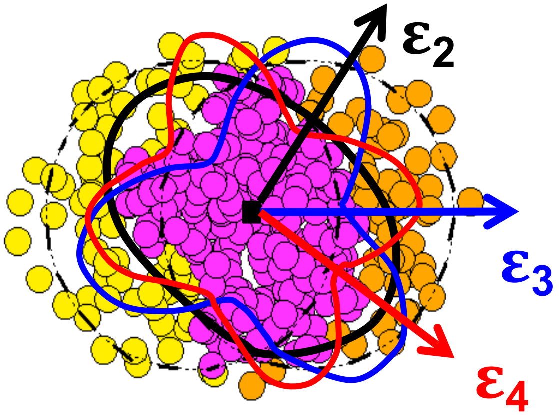


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

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

Harmonics in hydro-picture

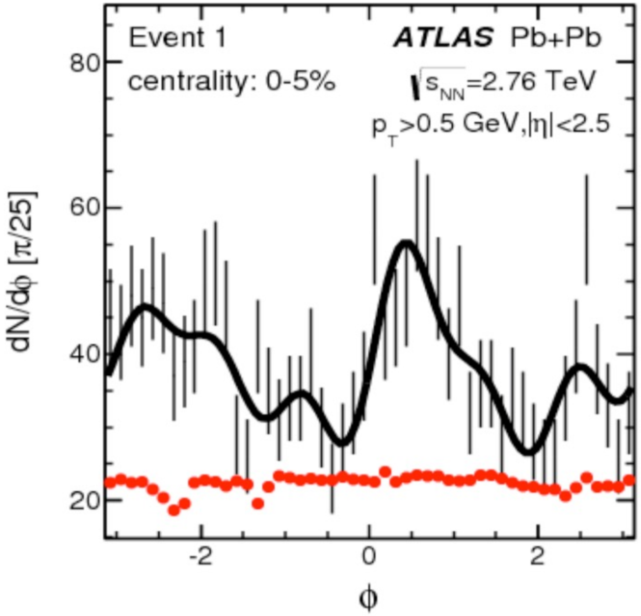
Initial state



Hydro-response

Space-time dynamics

Particle flow

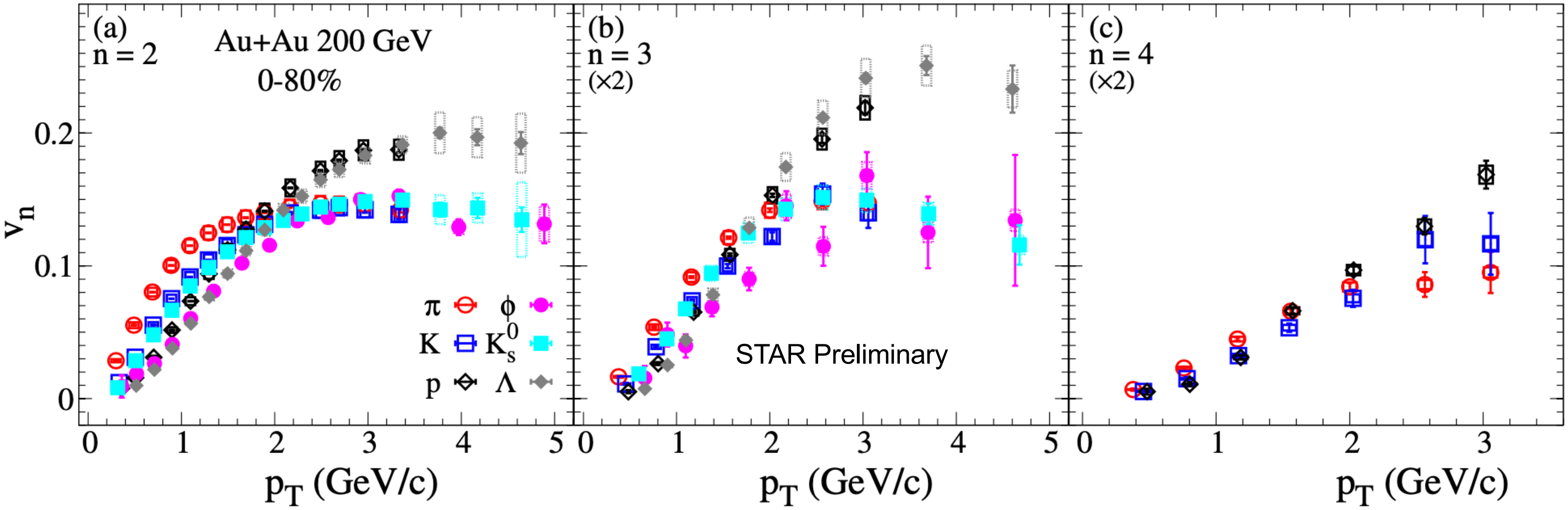


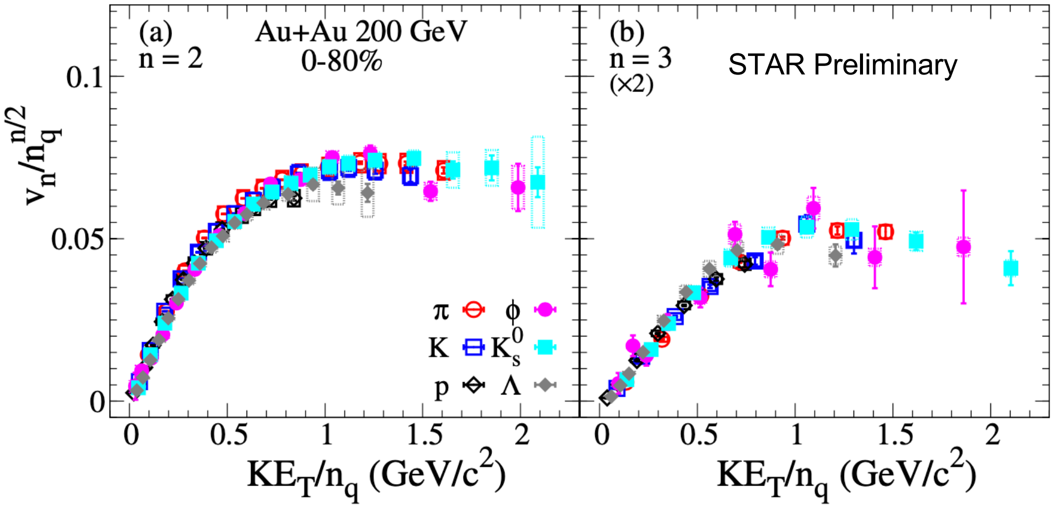
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

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

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

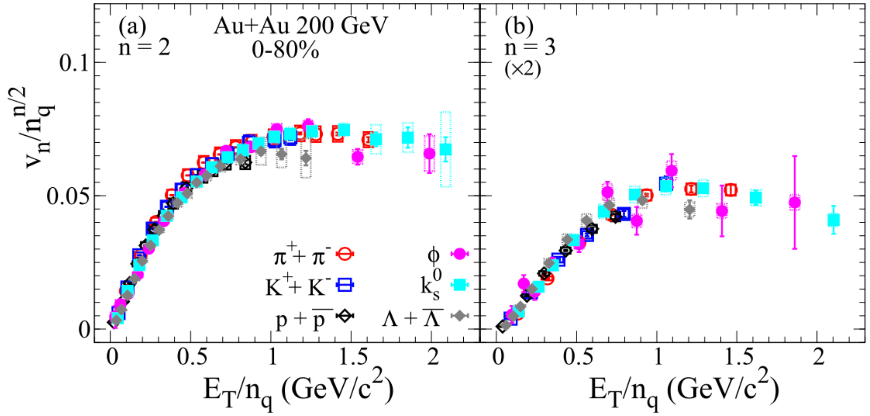
高阶流：200 GeV

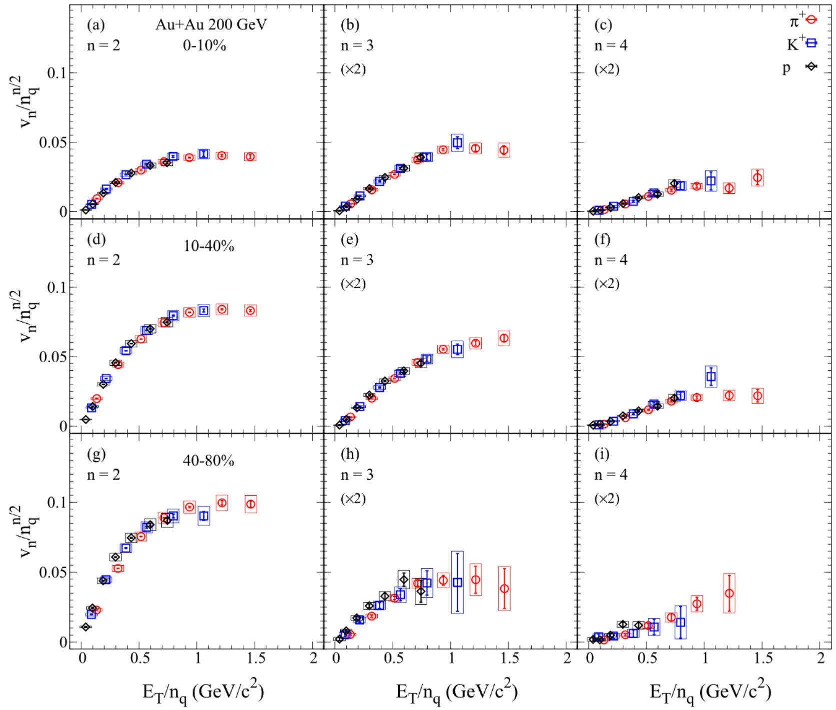




- ➢ 高阶流（v_3和v_4）同样符合部分子态集体运动的物理图像

Higher-order Flow in 200 GeV





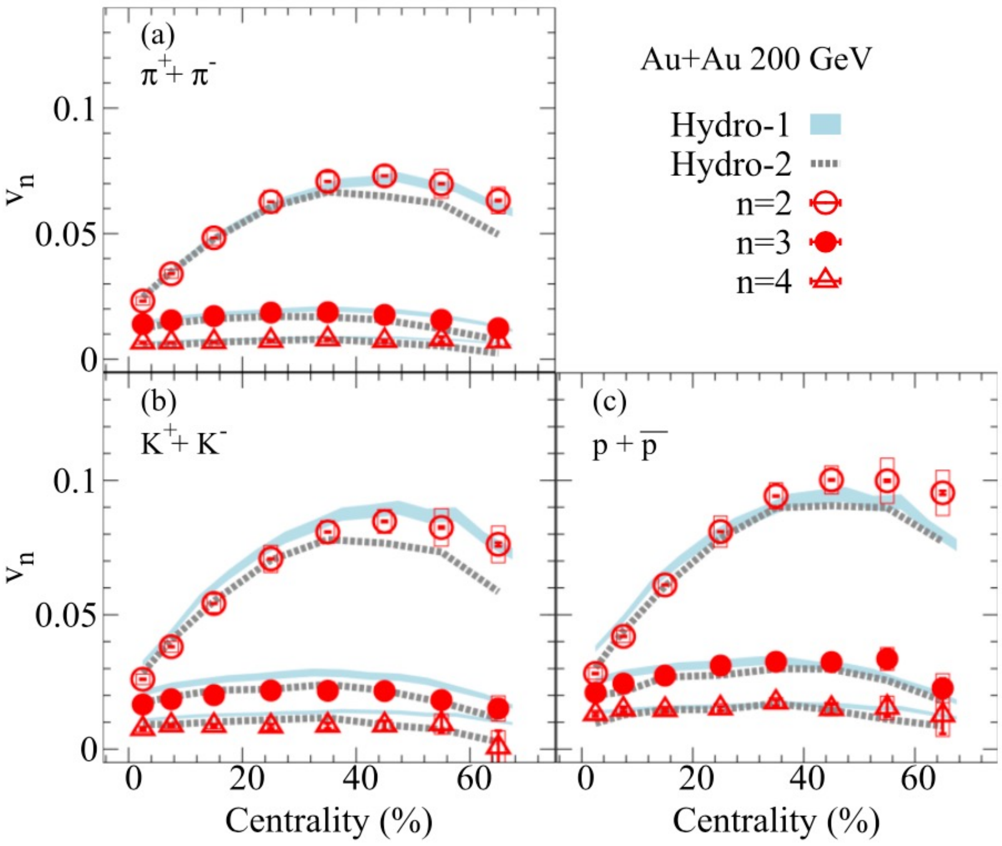
RHIC top energy

- 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



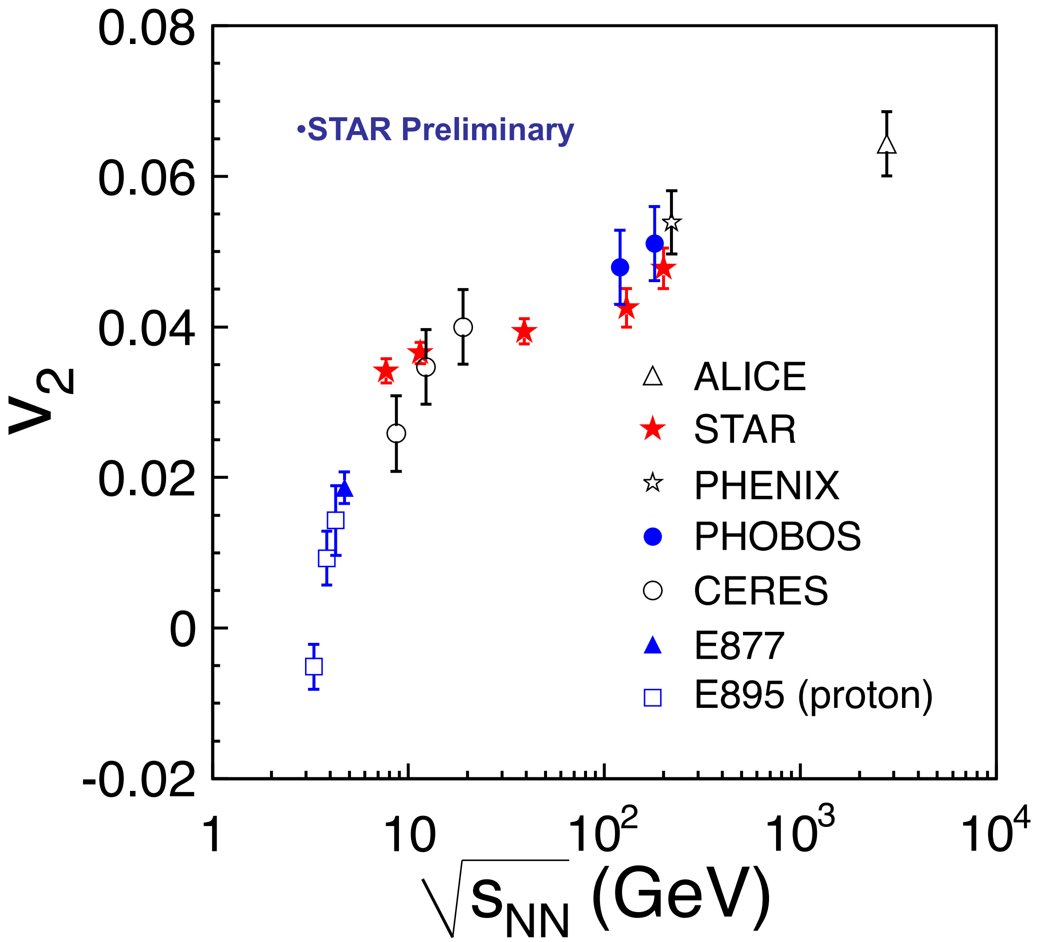
the v_n values decrease with increasing harmonic order. reflects the increase of viscous effects with increasing harmonic order

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

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

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

Energy Dependence



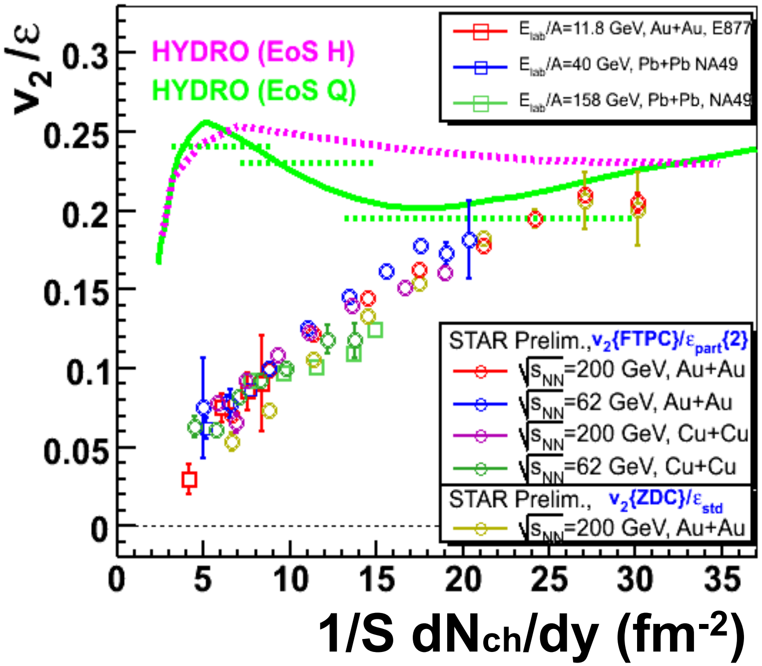
- ➢ STAR, ALICE:
  $v_2\{4\}$ results
  Centrality: 20-30%

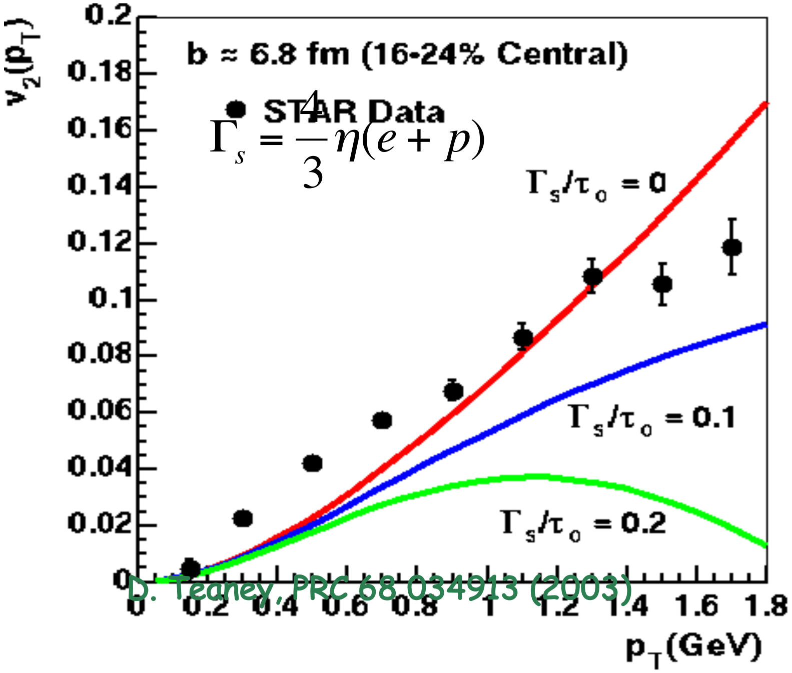
- ➢ An increasing trend is observed for p_T integrated v_2 from AGS to LHC

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

How Perfect ?

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





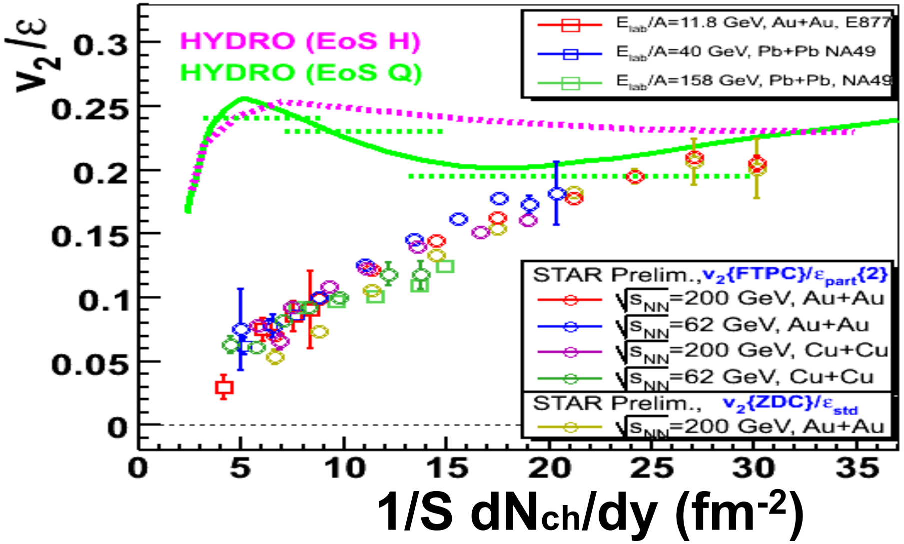
$$\Gamma_s = \frac{4}{3}\eta(e+p)$$

D. Teaney, PRC 68 034913 (2003)

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 !

Perfect Liquid at RHIC

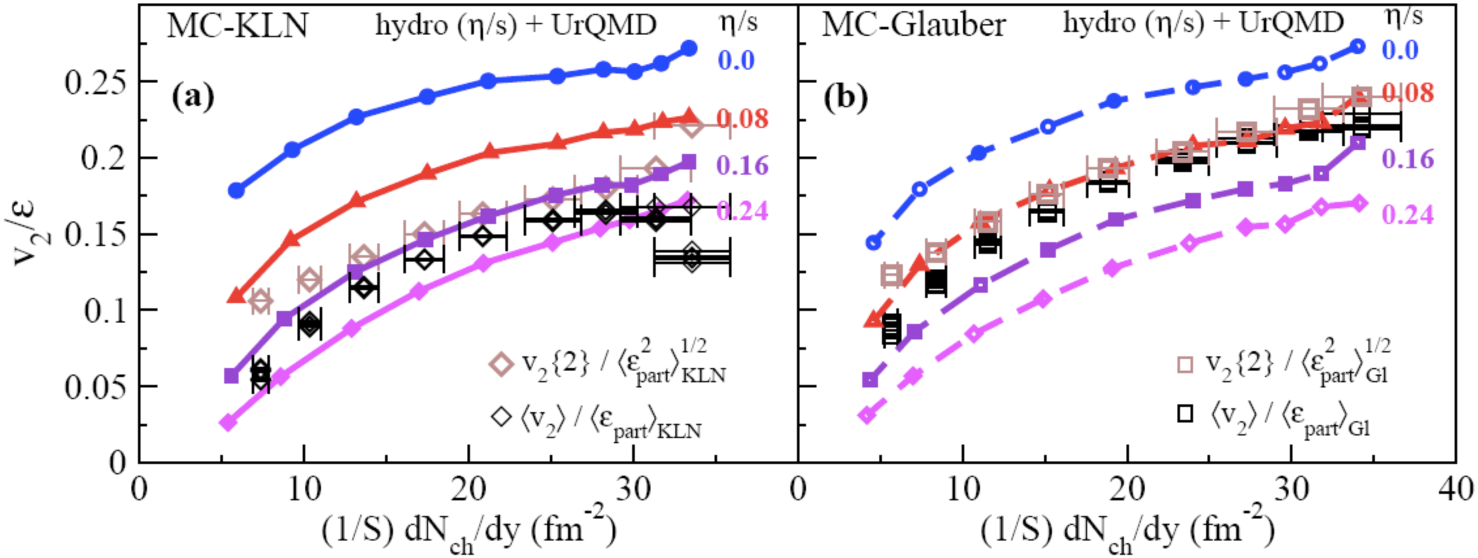


v_2/ε approaches the limit of ideal hydrodynamics

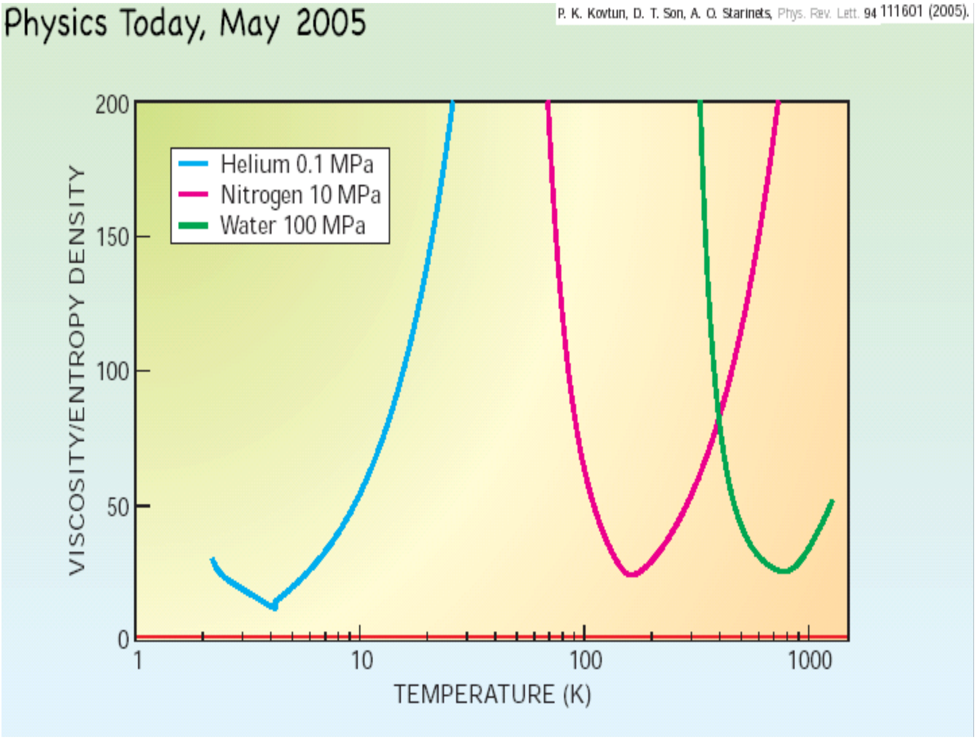
Small value of specific viscosity over entropy ***η/s***

Model uncertainty dominated by initial eccentricity ε

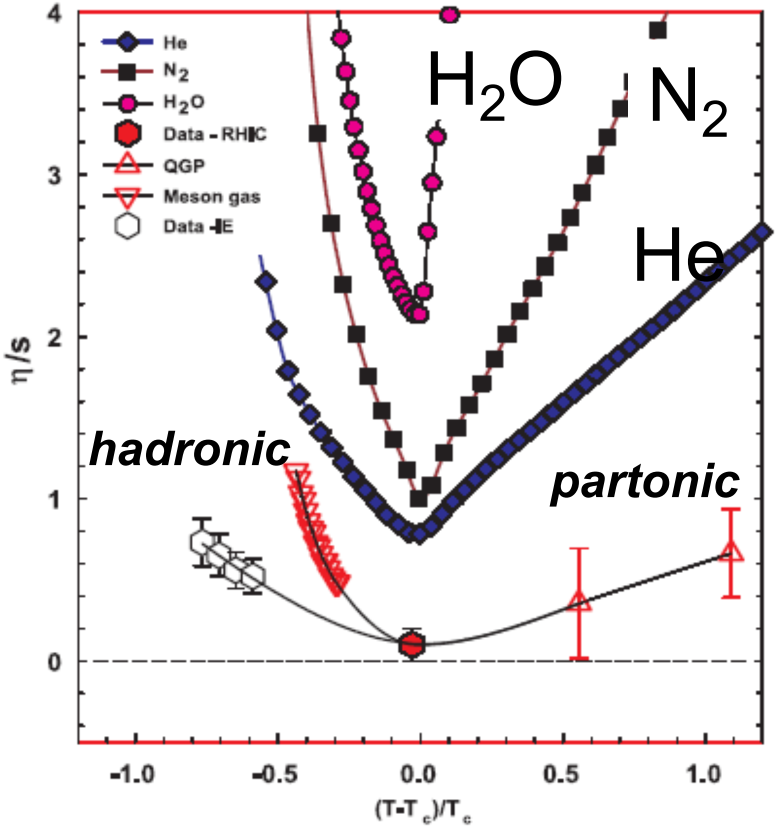
Model: Song *et al. arXiv:1011.2783*



Viscosity and the Perfect Fluid


Physics Today, May 2005

P. K. Kovtun, D. T. Son, A. O. Starinets, Phys. Rev. Lett. 94 111601 (2005).



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

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

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

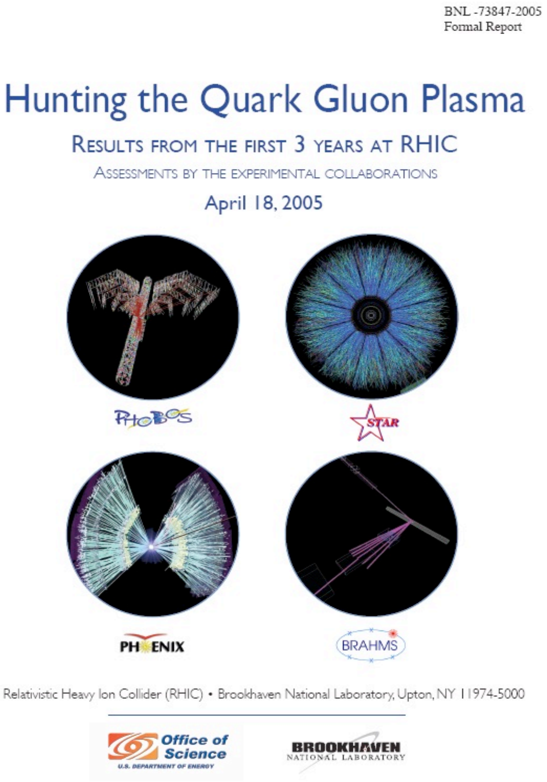
2) ***η/s***(QCD matter) < ***η/s***(QED matter)

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

PHOBOS

STAR

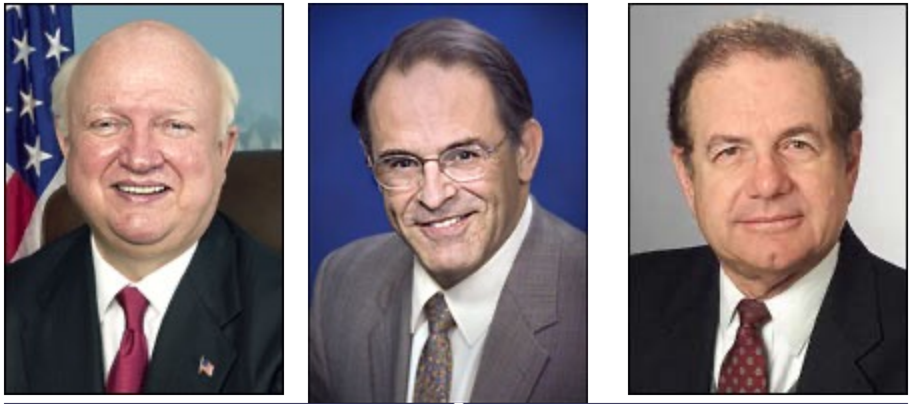
PHENIX

BRAHMS

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

Office of Science U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY



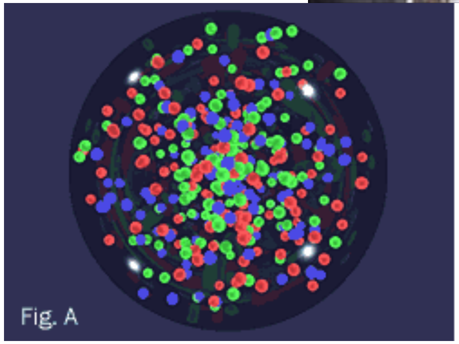


Fig. A

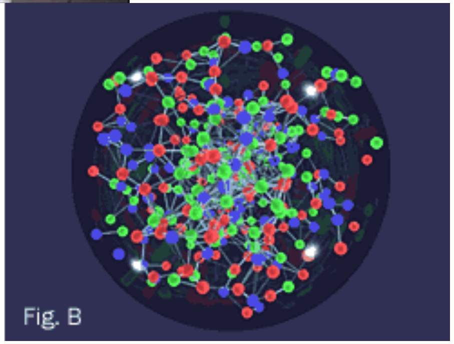
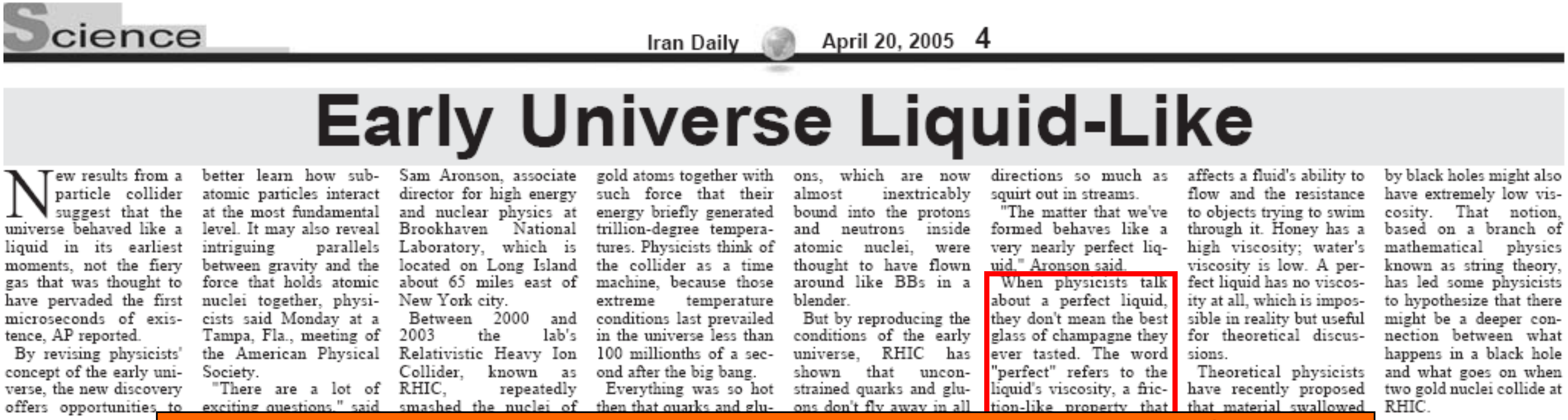


Fig. B

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.

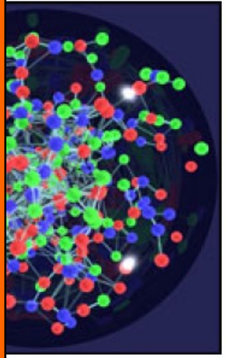
When physicist talk about a perfect liquid, they don't mean the best glass of champagne they ever tasted. The word "perfect" refers to the liquid's viscosity

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 Rel
(RHIC). All of the
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."



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.

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})

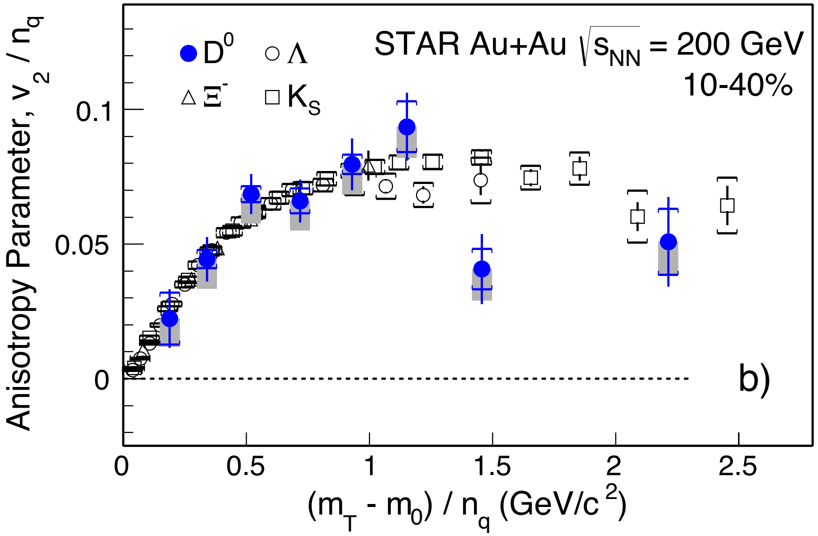
3) The matter behavior like a ***quantum liquid*** with small ***η/s***

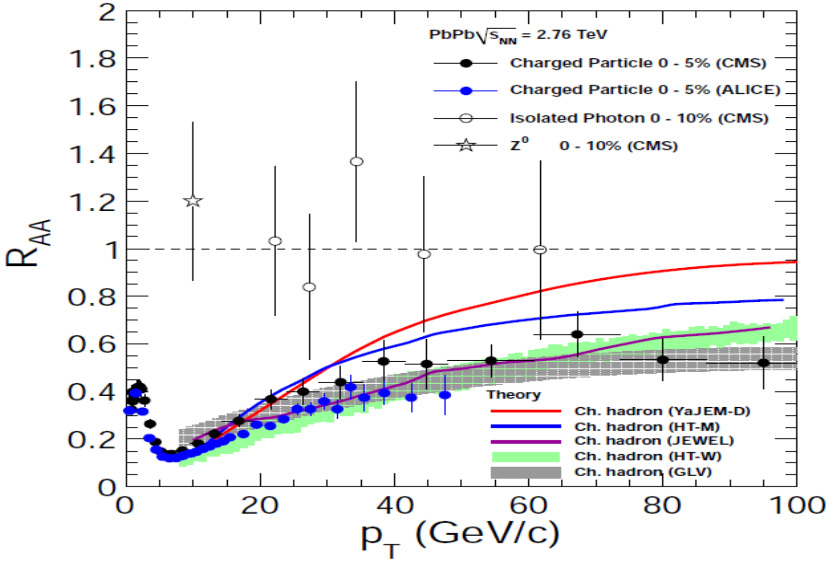
Search for QCD cretical point and phase boundary

Outline

- Introduction
- Collectivity
- 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。

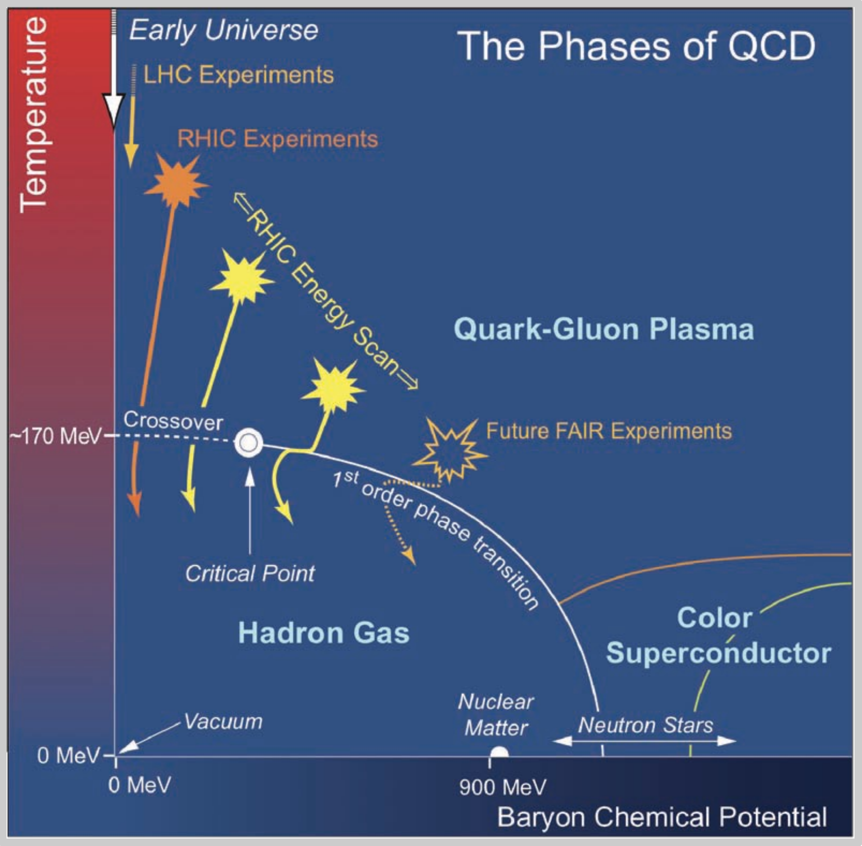
在μ_B＝0附近的相变是平滑过渡

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相变 临界点的寻找



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

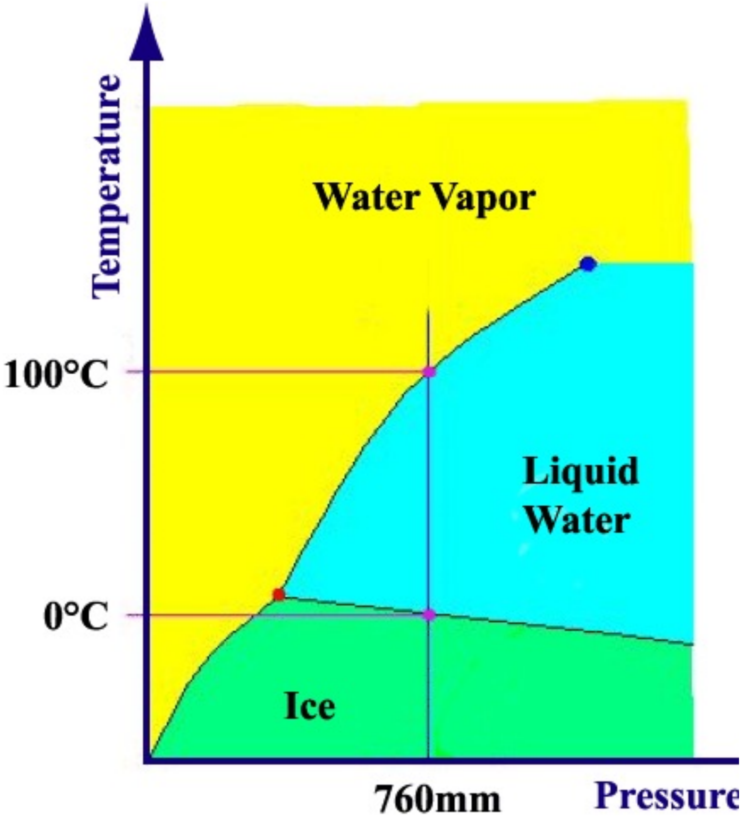
(6) Fluctuations

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

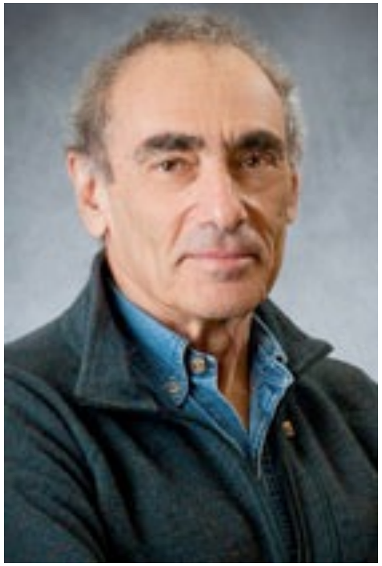
固态	T < 0度	冰
液态	0<T<100	水
气态	T> 100	气态

等离子体态：

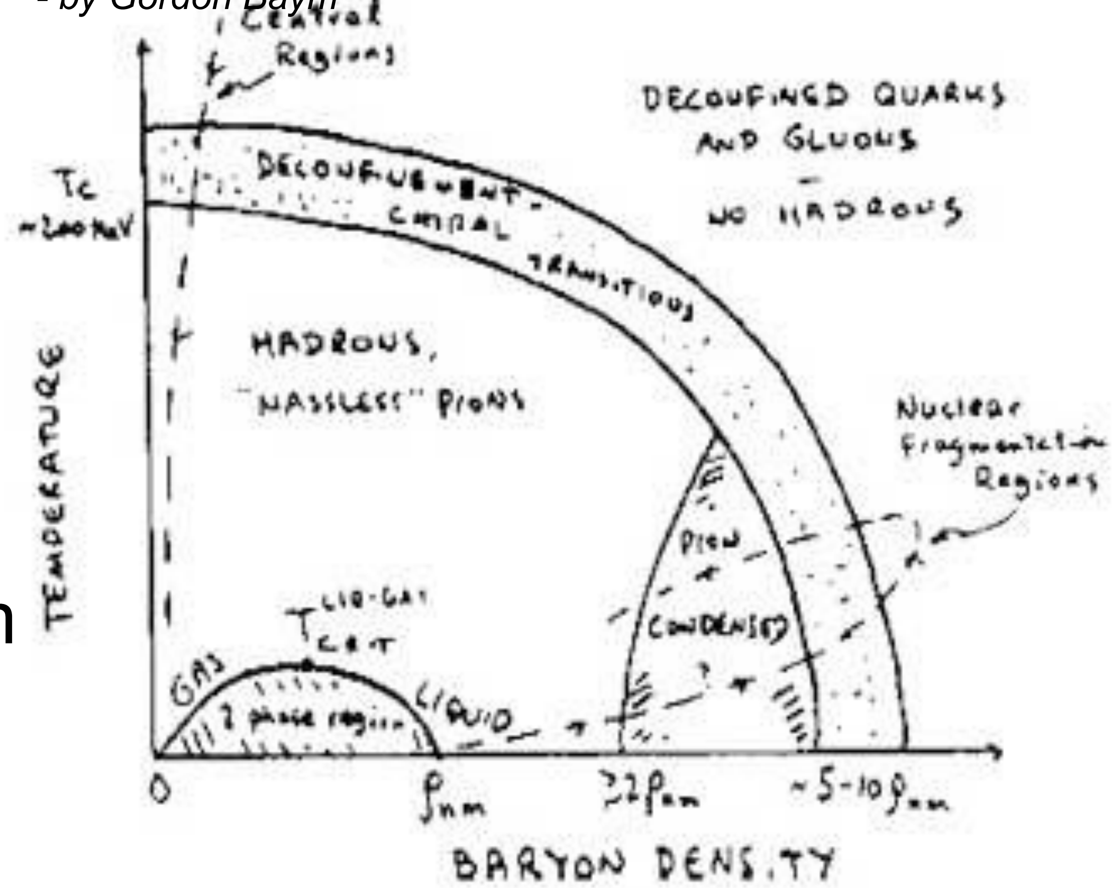
QCD Phase Diagram (1983)

1983 US Long Range Plan

- by Gordon Baym



Gordon Baym

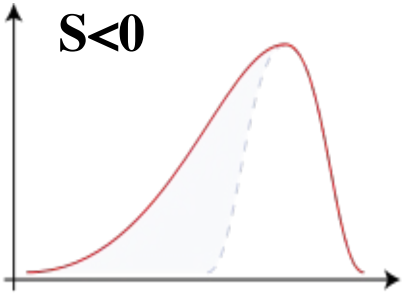


Higher Moments : Sensitive to the Correlation Length

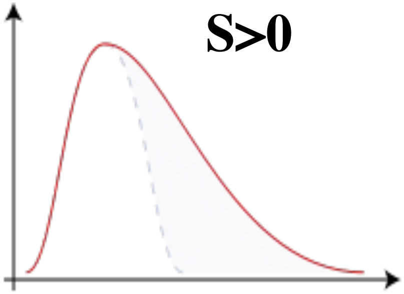
Skewness:

C_n: nth order cumulants

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



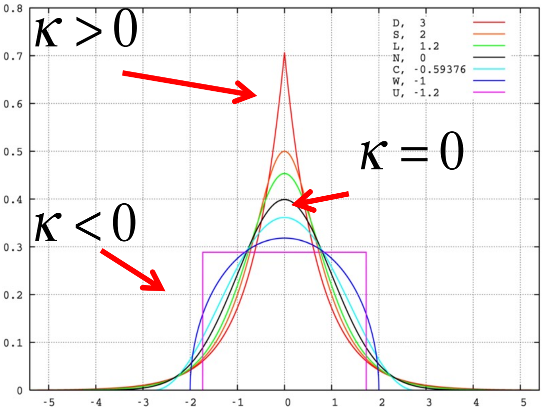
Negative Skew



Positive Skew

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)**

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

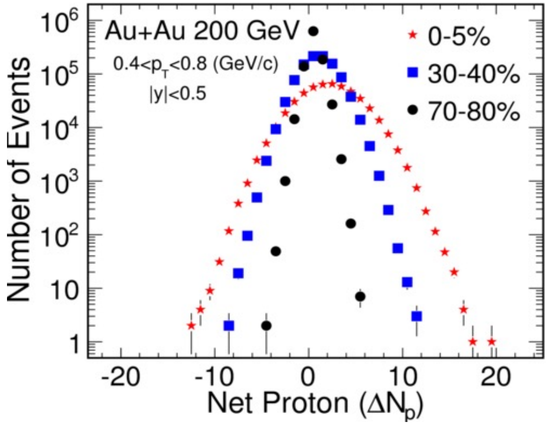
$$\chi_q^{(3)} = \frac{1}{VT^3}\langle(\delta N_q)^3\rangle$$

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

A. Bazavov et al . PRL109, 192302 (2012)
B. 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**

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

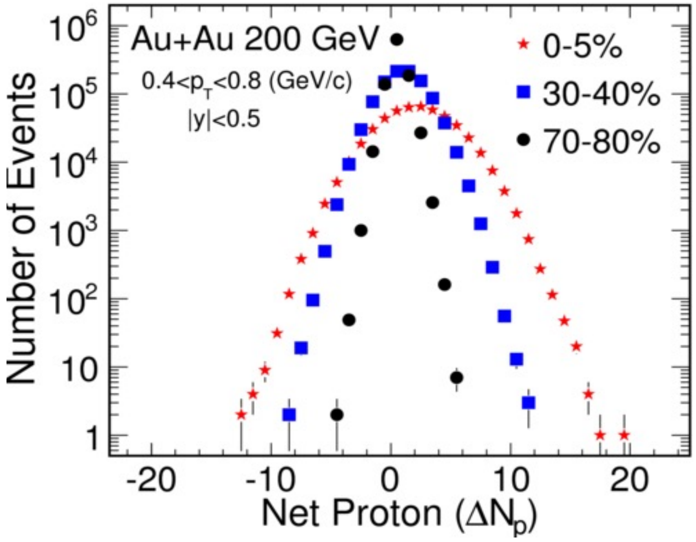
- Study Phase Transition and Bulk properties of QCD matter.

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).*

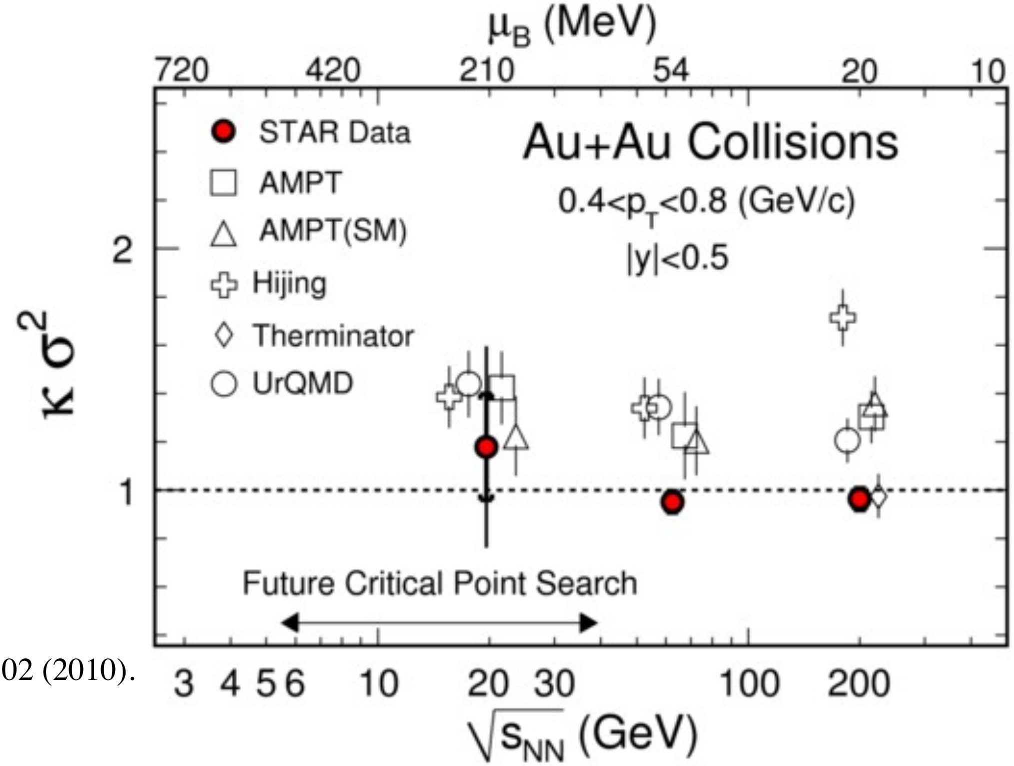
Observable: Higher Moments of Net-proton Distributions

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).

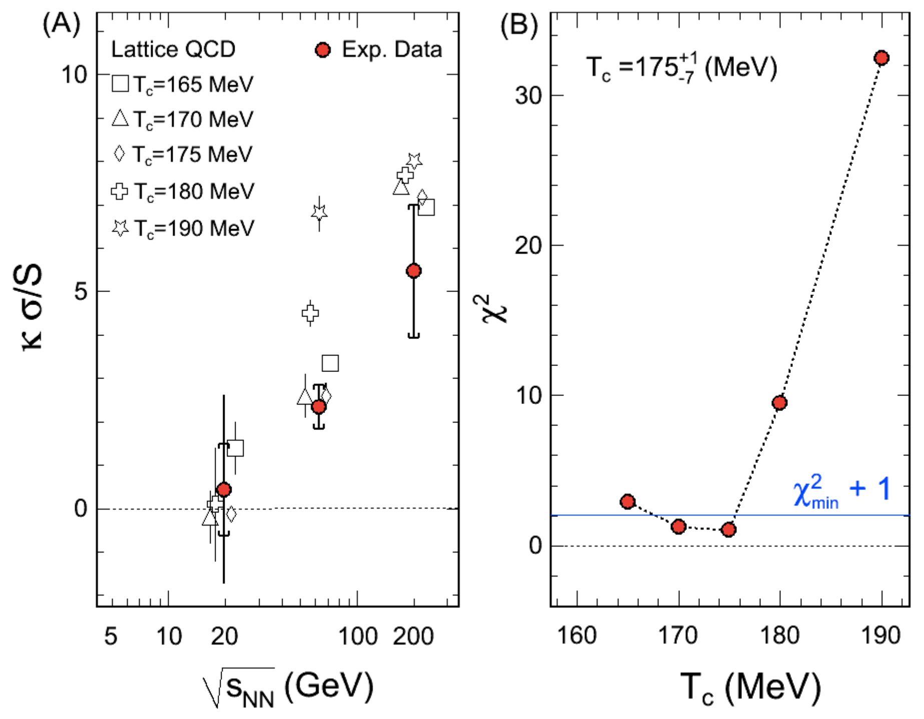


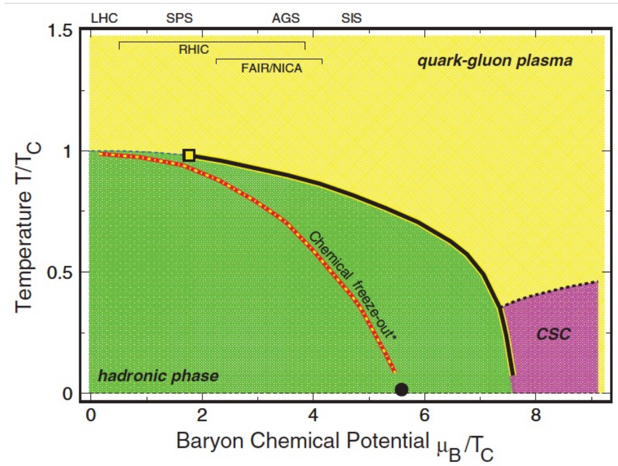
STAR: Physical Review Letters 105, 022302 (2010).



- ➢ 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

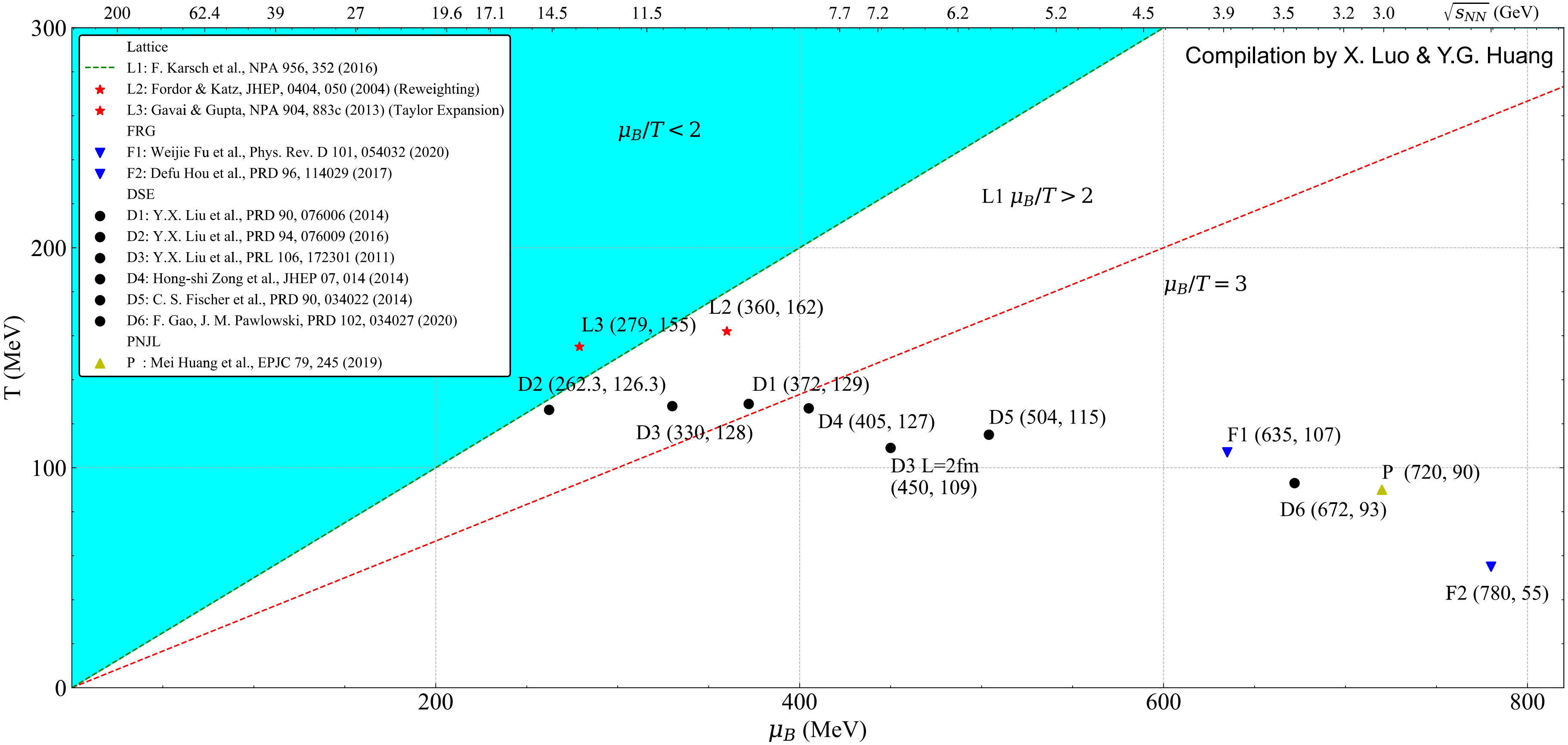
1) Central collisions at RHIC, the high moments measurements are consistent with thermal equilibrium assumption

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

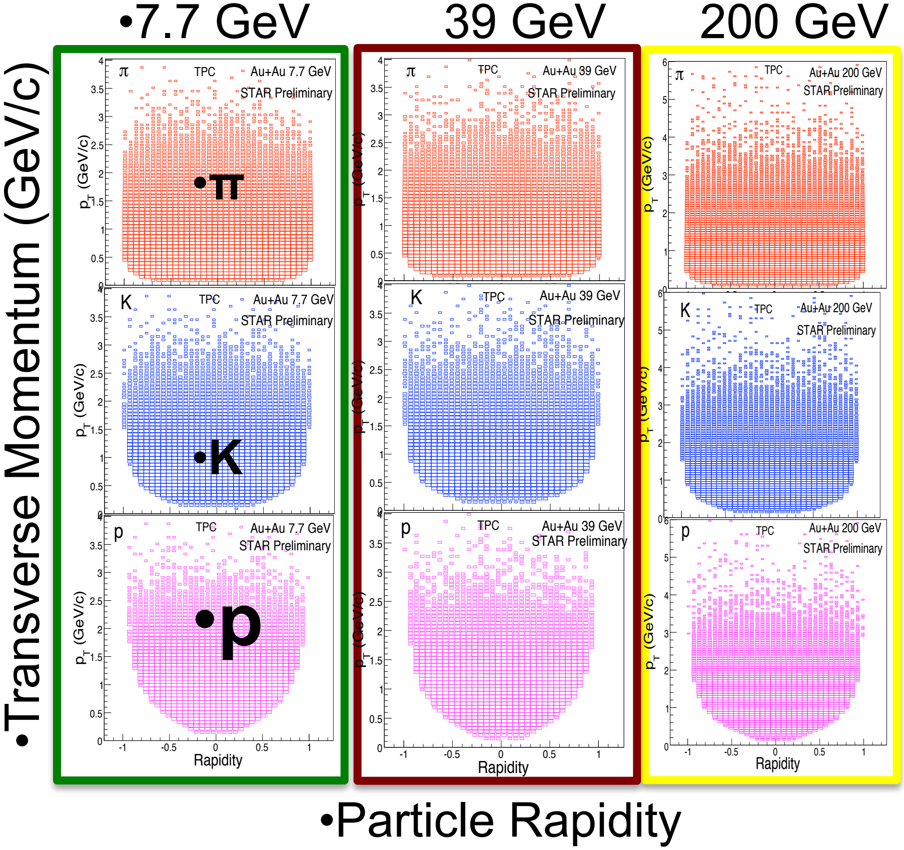
Preliminary collection from Lattice, DSE, FRG and PNJL (2004-2020)



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

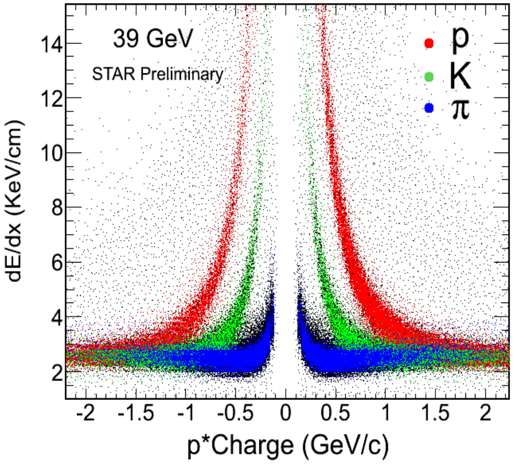
- 为开展临界点的寻找和状态方程的研究提供了可能

Data Analysis

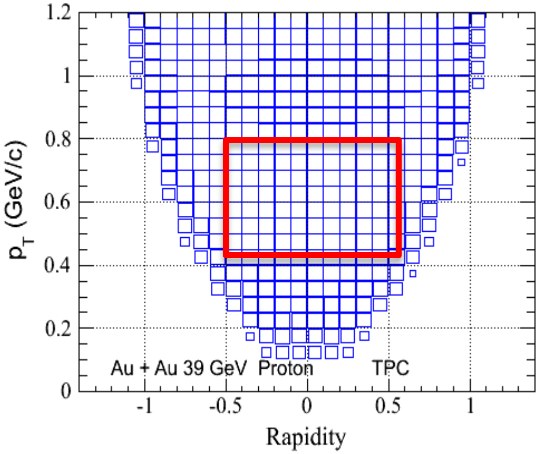
Energy (GeV)	7.7	11.5	19.6	27	39	62.4	200
Statistics (Million)	~3	~6.6	~15	~30	~87	~47	~242
Year	2010	2010	2011	2011	2010	2010	2010

➢ 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 $|y|<0.5$.

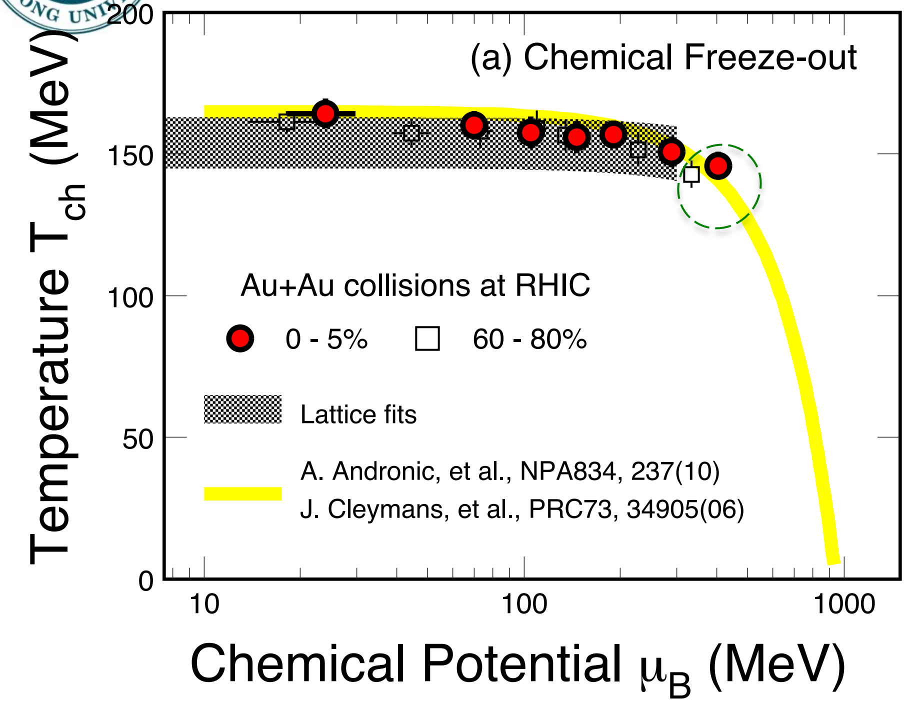
STAR TPC dE/dx PID

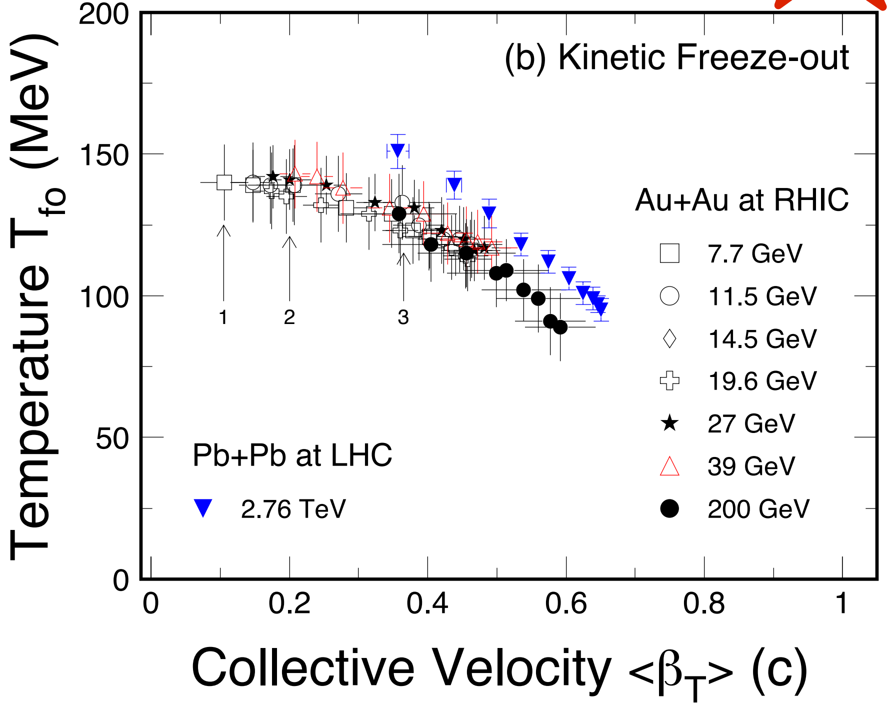


Proton Phase Space



Bulk Properties at Freeze-outs





Chemical Freeze-out: (GCE)

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

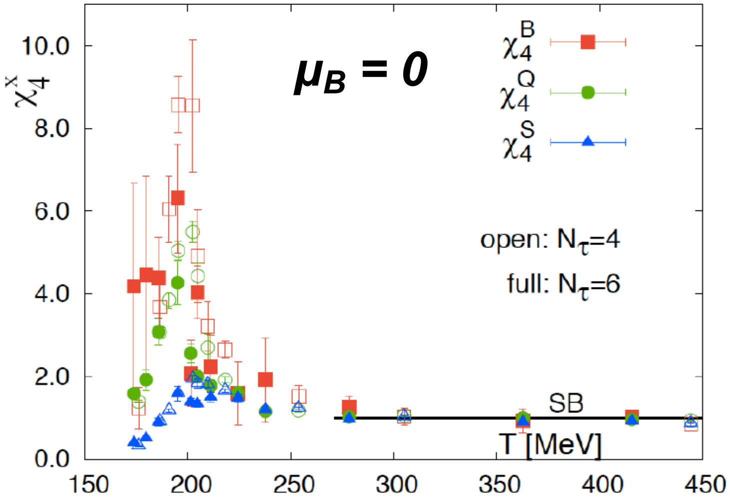
Kinetic Freeze-out:

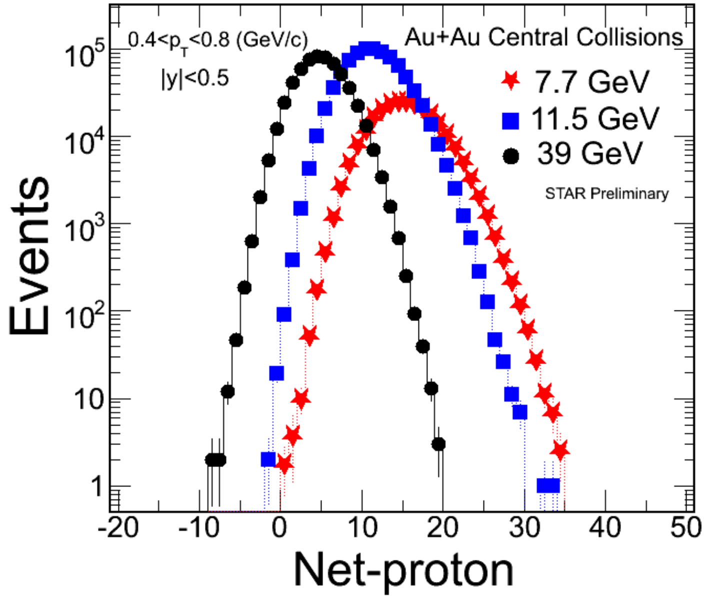
- Central collisions => lower value of T_{fo} and larger collectivity β_T

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

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

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:

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

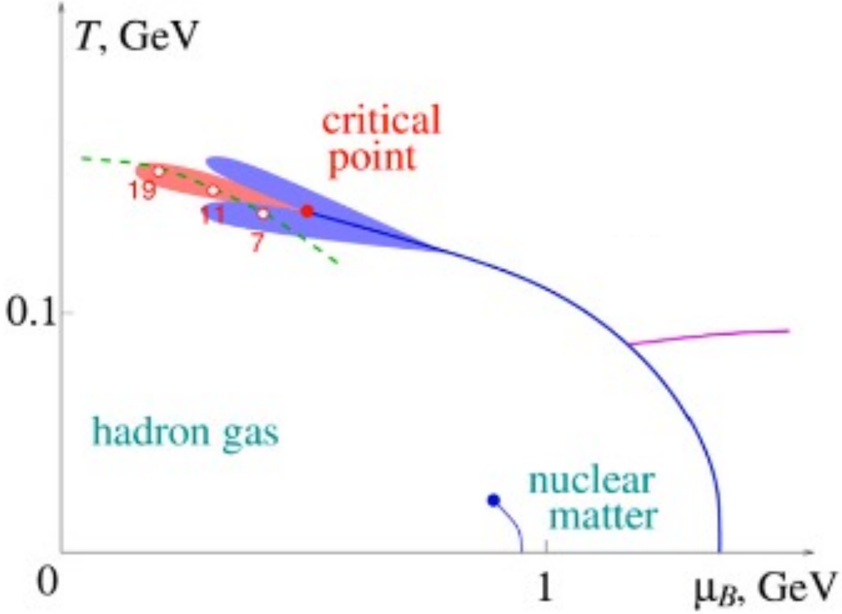
4) **Extract susceptibilities and freeze-out temperature**. An independent/important test of thermal equilibrium in heavy ion collisions.

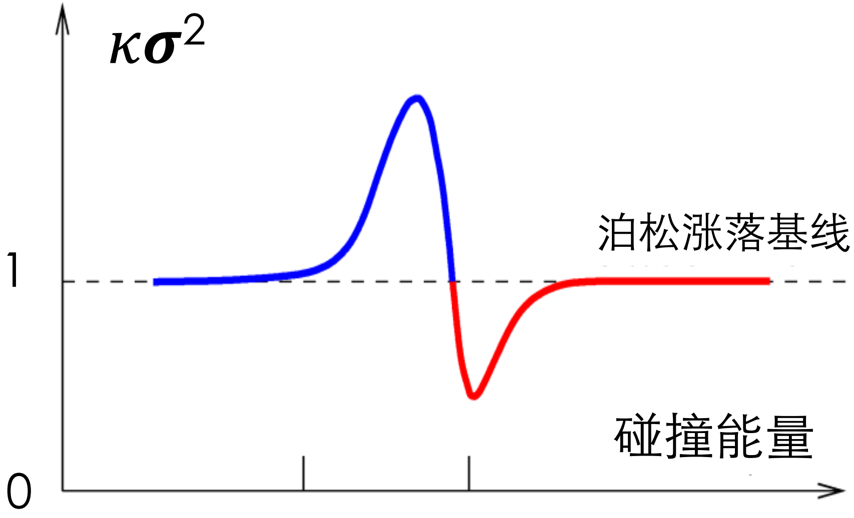
References:

- 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

模型预言：QCD临界点信号

假设：体积无穷大以及静态系统





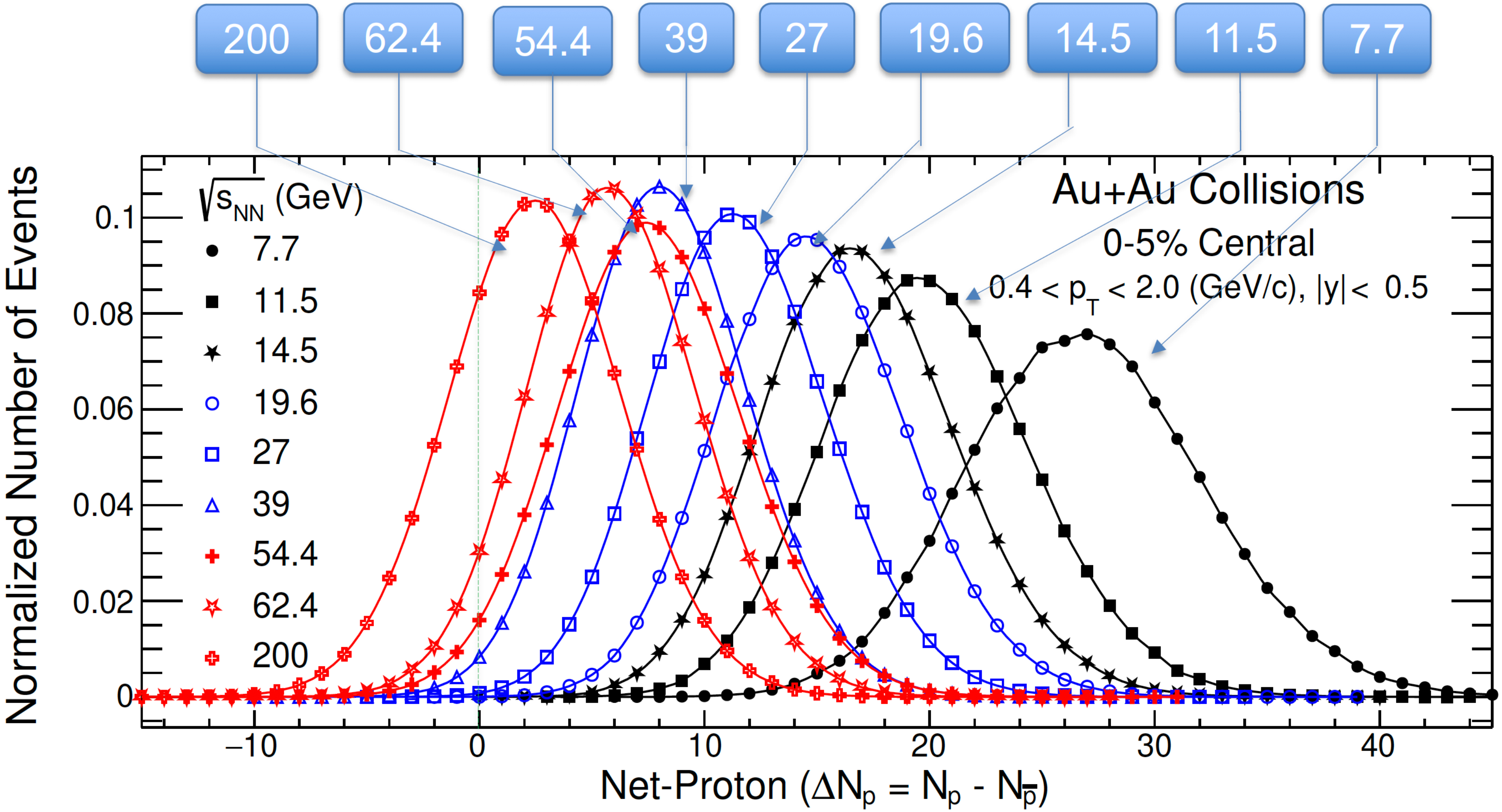
M. Stephanov, PRL107, 052301 (2011); J. Phys. G 38, 124147 (2011).
Schaefer et al., PRD 85, 034027 (2012); W. Fu et al., PRD 94, 116020 (2016).
J.W. Chen, J. Deng, et al., PRD 93, 034037 (2016). PRD 95,014038 (2017).
W. K. Fan, X. Luo, H.S. Zong, IJMPA 32, 1750061 (2017);
G. Shao et al., EPJC 78, 138 (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。

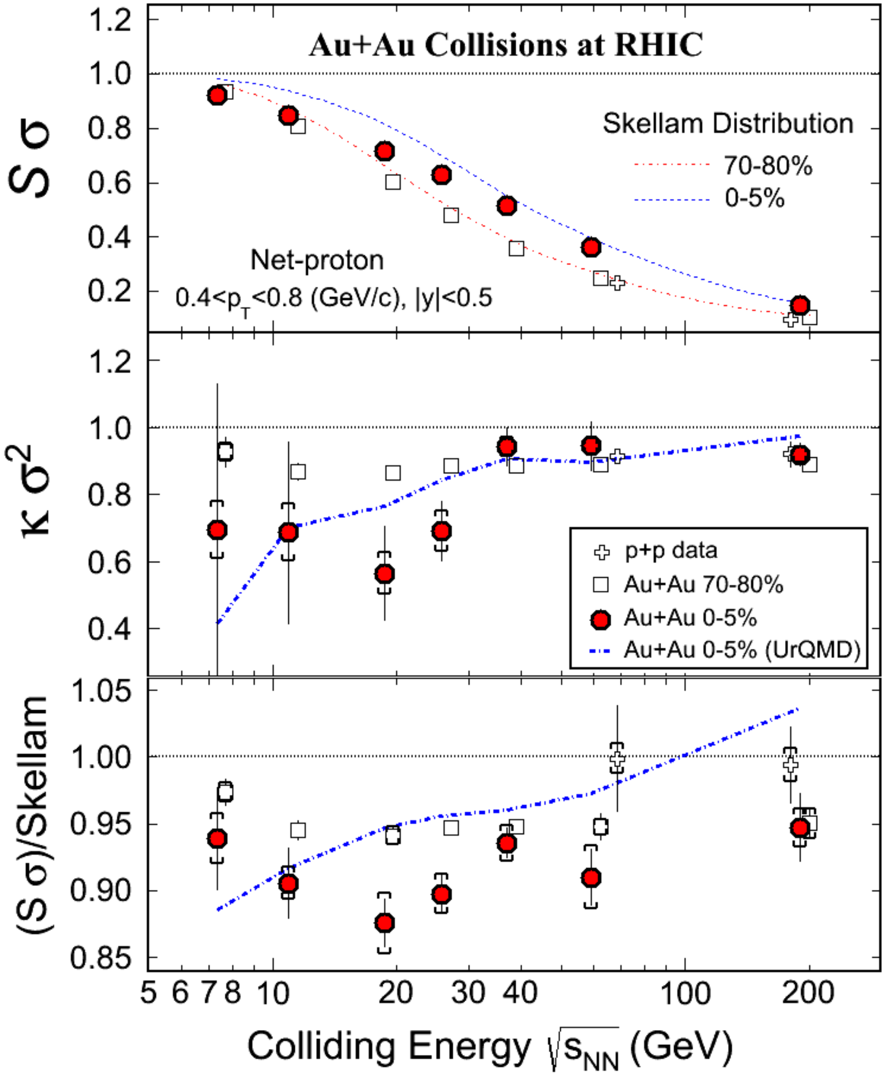
Raw Event-by-Event Net-Proton Distributions



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 asbaryon conservation, hadronic scattering effects, are implemented.
- ➢ Higher statistics are needed in order to draw physics conclusion at lower beam energies.

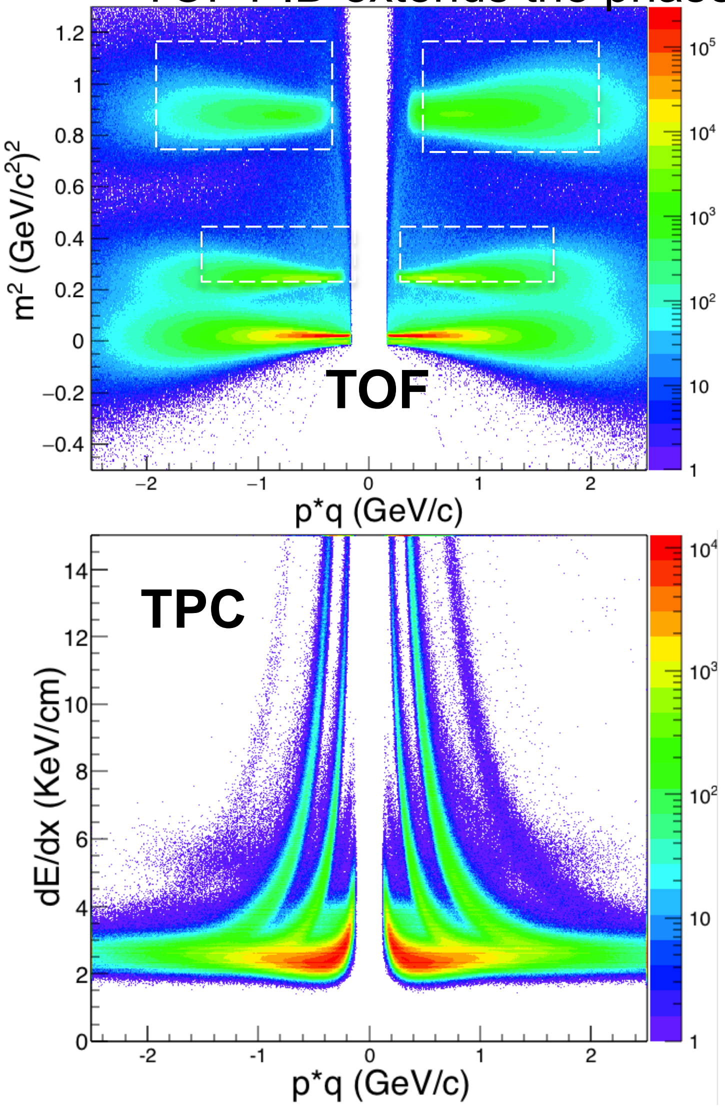
Significance of Deviations from Skellam:

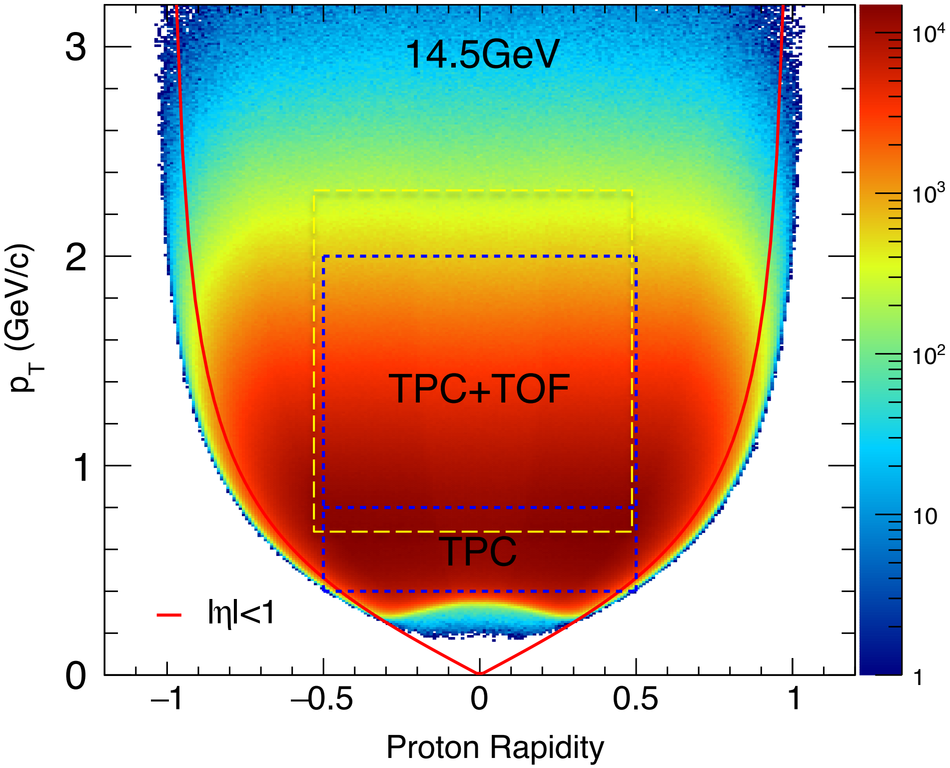
$$|Data - Skellam| / \sqrt{err_{stat}^2 + err_{sys}^2}$$

Largest deviation for 19.6 and 27 GeV !

Proton Identification with TOF

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





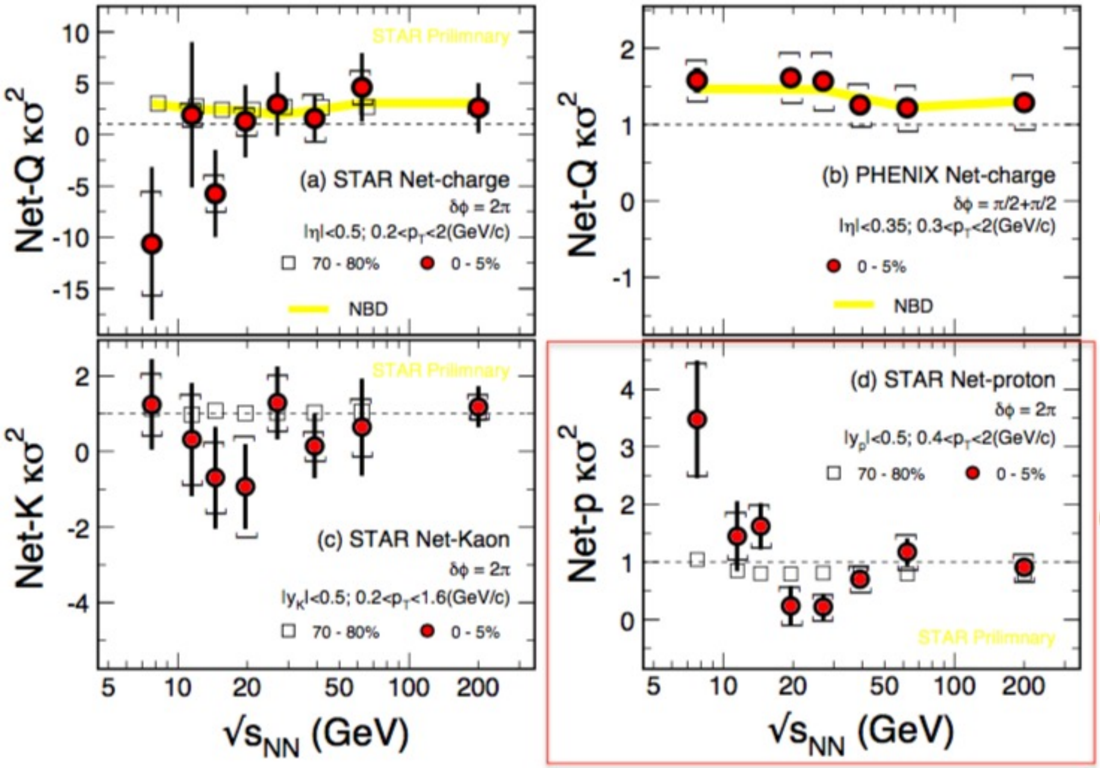
Acceptance: $|y| \leq 0.5$, $0.4 \leq p_T \leq 2$ GeV/c

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): **$\varepsilon_{TPC} * \varepsilon_{TOF} \sim 0.5$**

STAR实验测量:净质子和净K介子高阶矩



$$error(\kappa * \sigma^2) \propto \frac{1}{\sqrt{N}} \frac{\sigma^2}{\varepsilon^2}$$

In STAR:

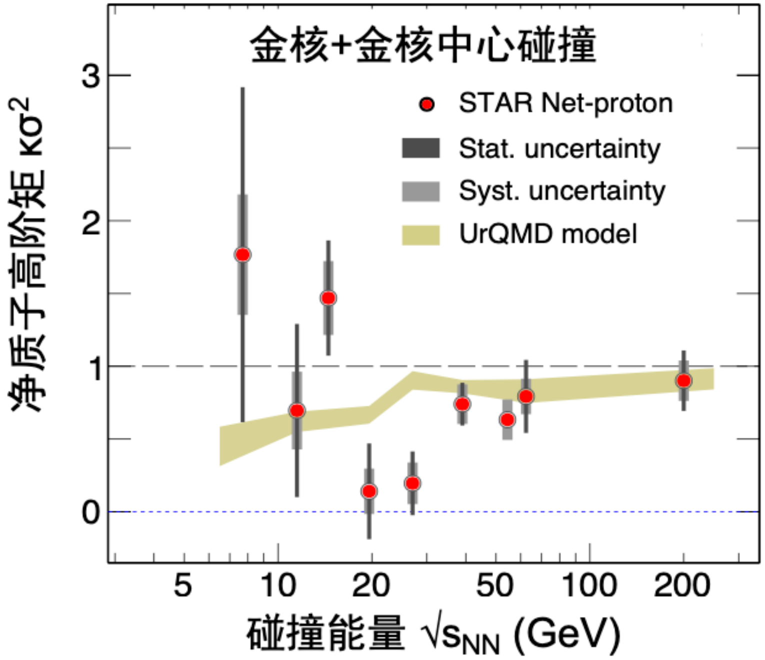
σ(Q) > σ(K) > σ(p)

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

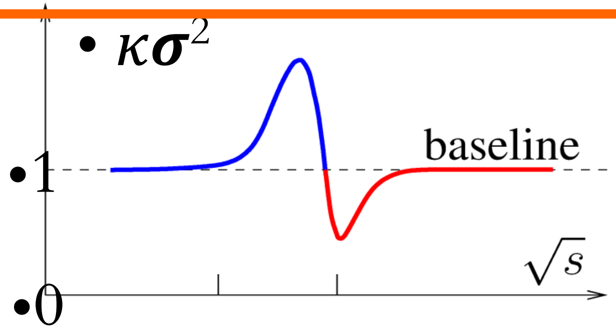
1) The results of net-Q and net-Kaon show flat energy dependence.
2) Net-p shows **non-monotonic energy dependence** in the most central Au+Au collisions starting at $\sqrt{s_{NN}}$ < 27 GeV!

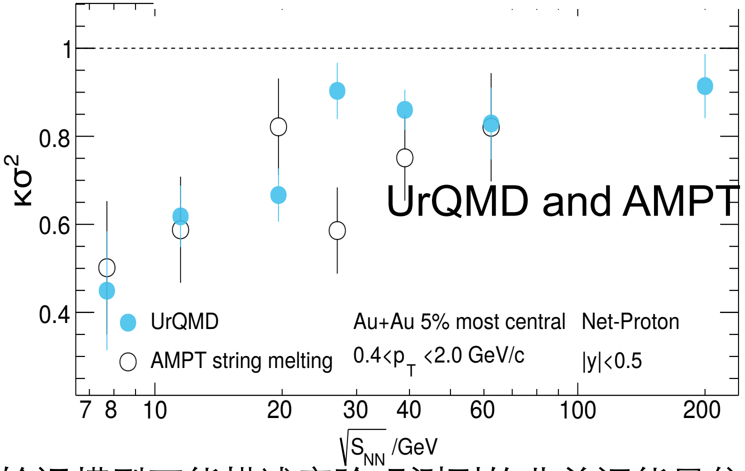
•能量扫描中净质子数分布的高阶矩子

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



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，暗示系统进入临界区。

•BESII：低能量点的精确测量

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

Collider mode

Au+Au Collisions

$\sqrt{s_{NN}}$ (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

FXT mode

$\sqrt{s_{NN}}$ (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

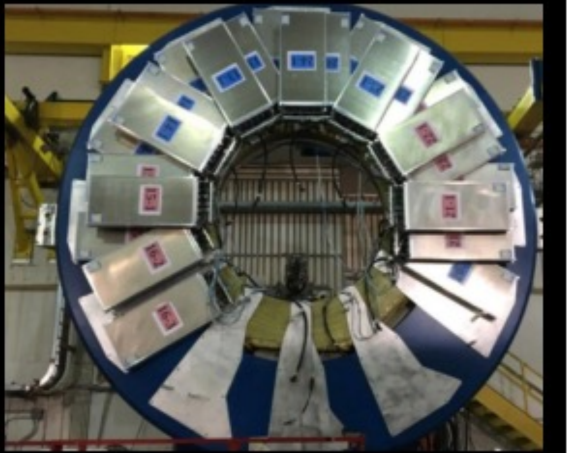
- Most precise data to map the QCD phase diagram :

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

Major Upgrades for BES-II

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

Very successful and important for BES-II



Full EPD has been installed

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

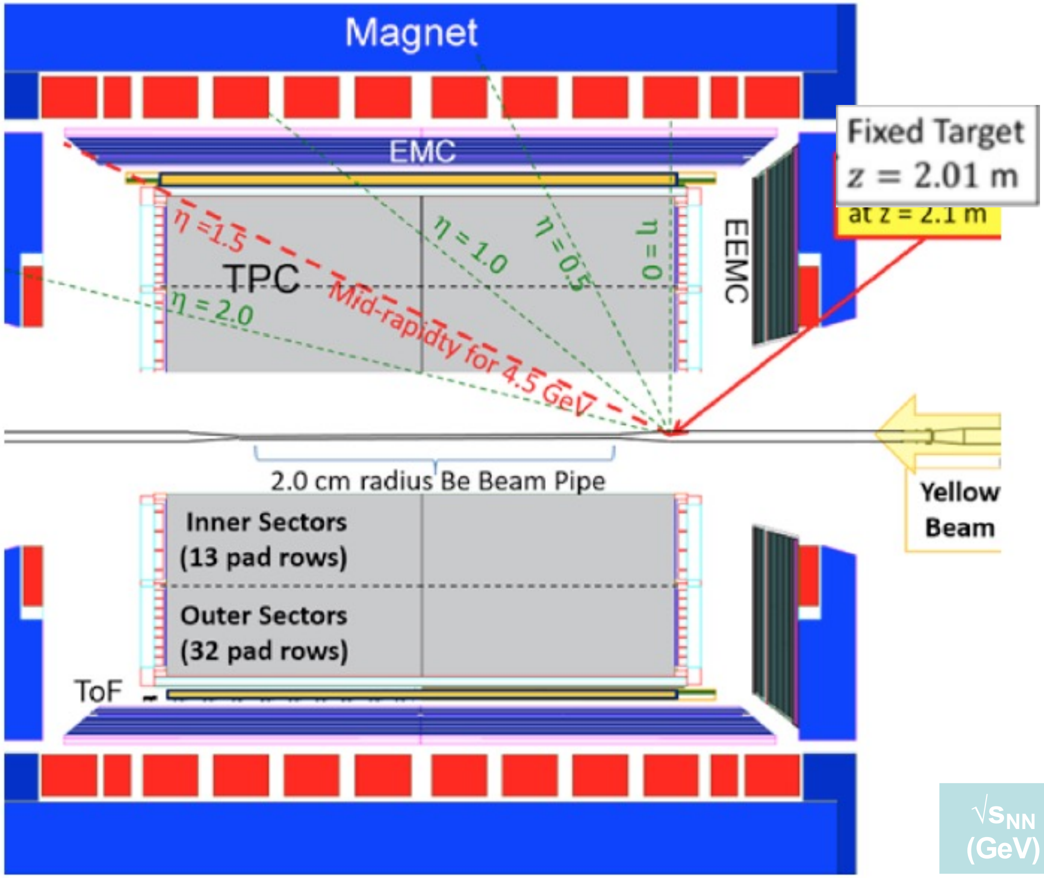
EPD:

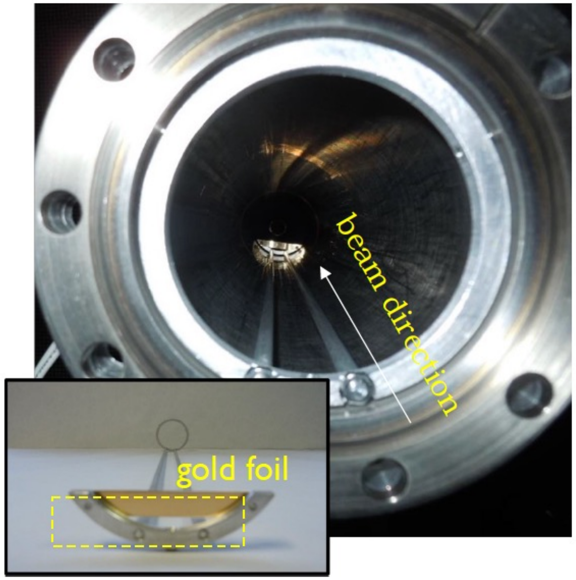
- Improves trigger
- Better centrality & event plane measurements
- Ready in 2018

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)

FXT Experiments at STAR (2018-2021)





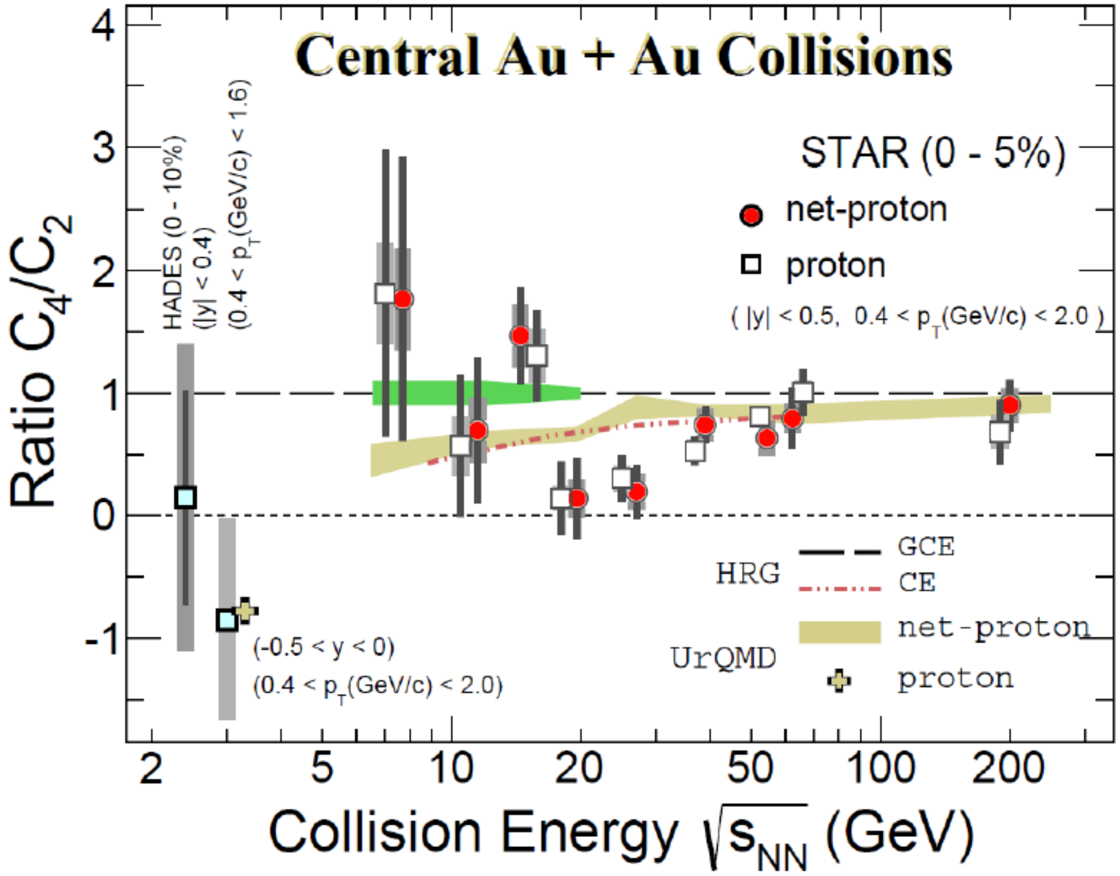
金箔靶： 厚度：250 微米，
安装在距离TPC中心：Z=201 cm

为了扫描更高重子密度的相图区域
STAR进行了固定靶实验

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	μ_B (MeV)	T_{CH} (MeV)
3.0	259	2018	750	80
3.0	2000	2021	750	80

3 GeV is the lowest energy of STAR fixed target experiment which extends the coverage of μ_B up to 750 MeV !

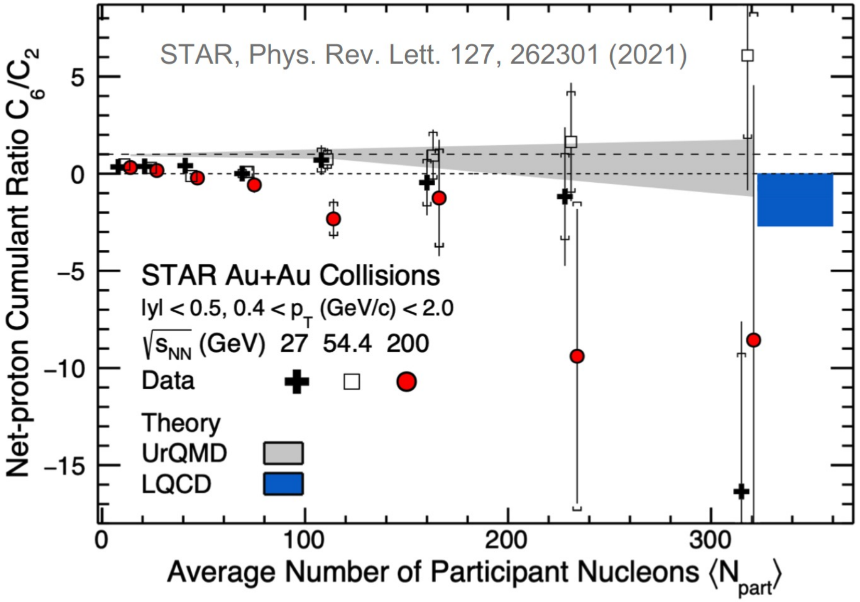
Energy Dependence of Fourth-order Fluctuations

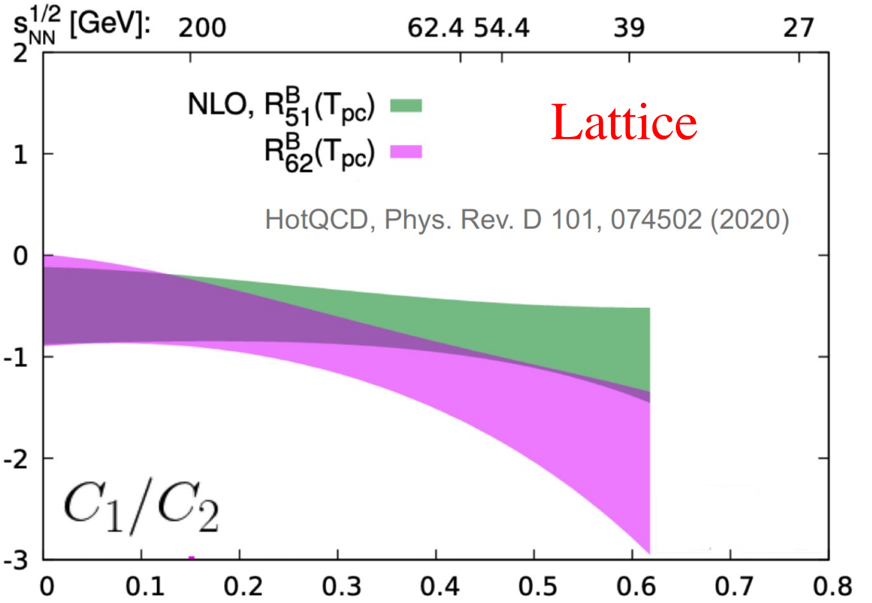


首次在金核金核中心碰撞中观测到净质子数分布四阶涨落的非单调能量依赖，与理论预言的QCD临界点信号一致，暗示QCD临界点的存在。

STAR: PRL 126 (2021) 092301, PRC 104 (2021) 024902 ,PRL 128(2022)202303

Higher-order baryon number fluctuations





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

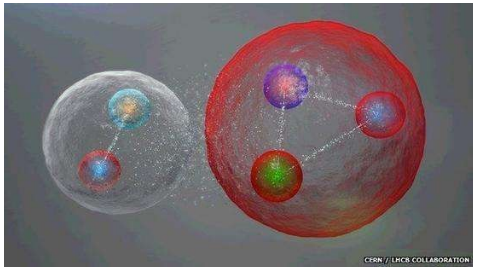
丁亨通(hotQCD)等, Phys. Rev. D 101, 074502 (2020);

- 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.

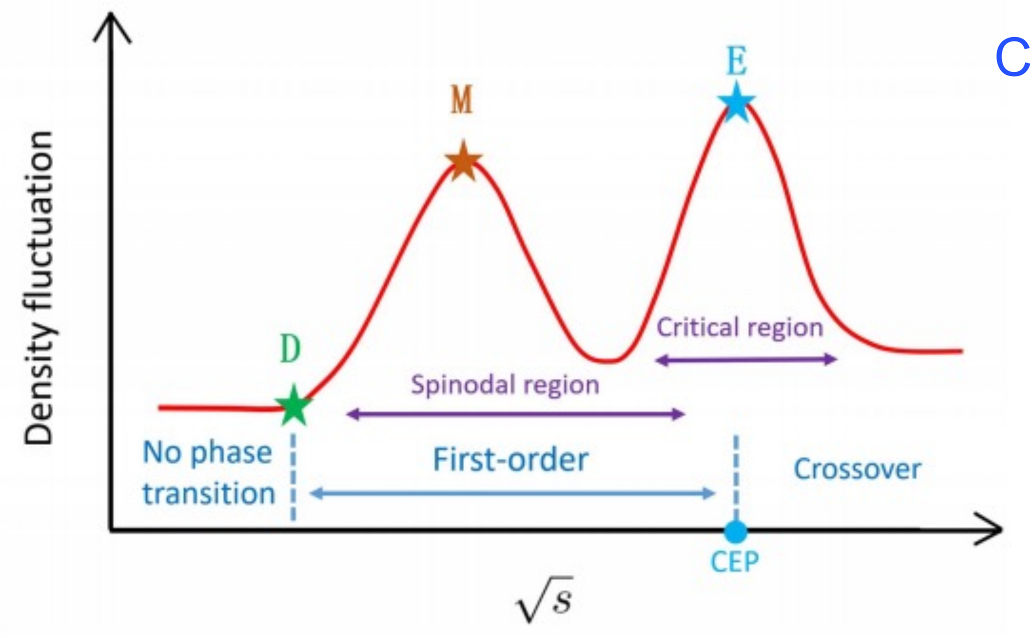
New Observable for CP: Light Nuclei Production

Near CP or 1st order phase transition, baryon


CERN / LHCB COLLABORATION

Light nuclei production

(Baryon Clustering)



Coalescence + nucleon density flu.

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

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

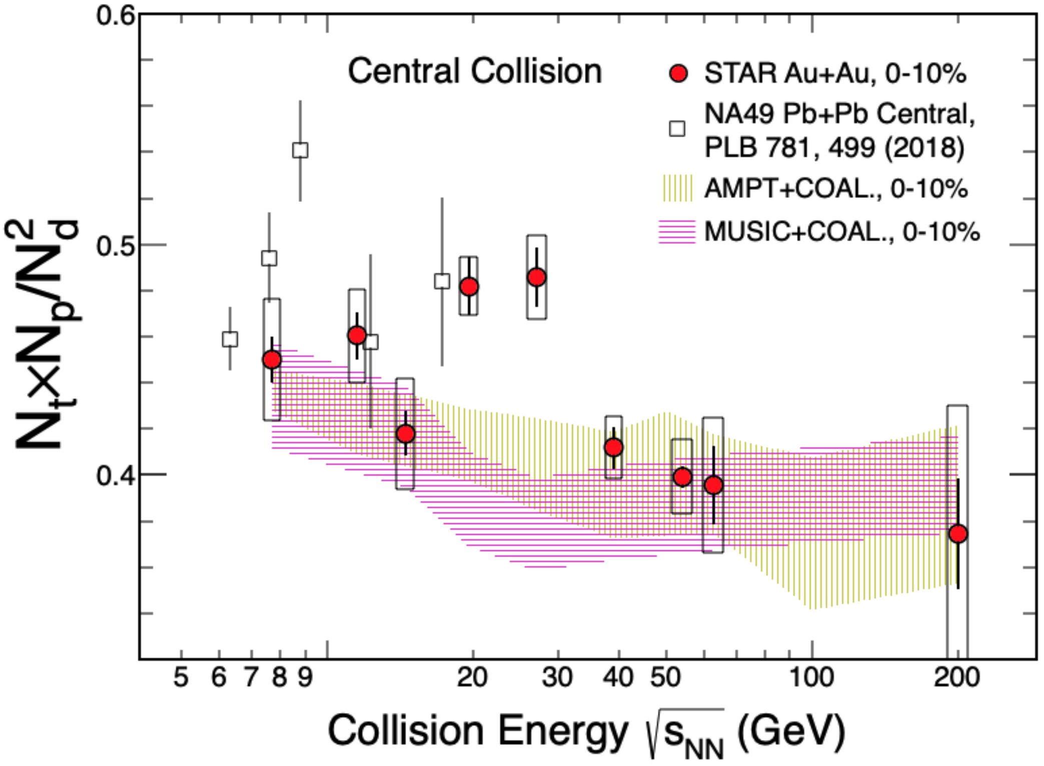
$$N_t \cdot N_p / N_d^2 \approx g(1+\Delta n)$$

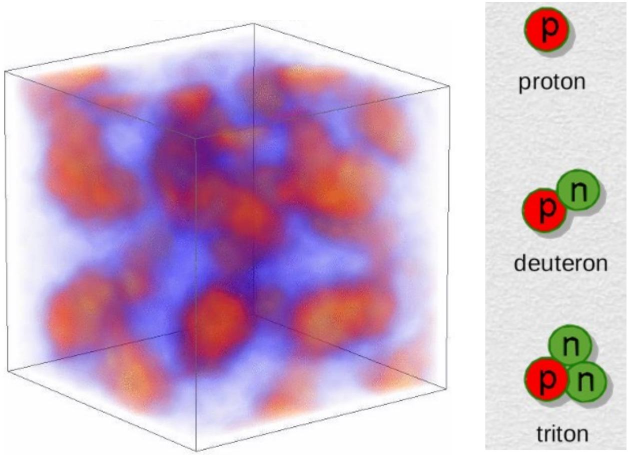
Neutron density fluctuations:

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

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





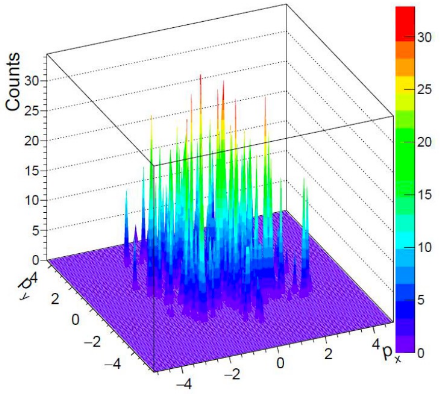
$$N_t \cdot N_p / N_d^2 \approx g(1 + \Delta n)$$

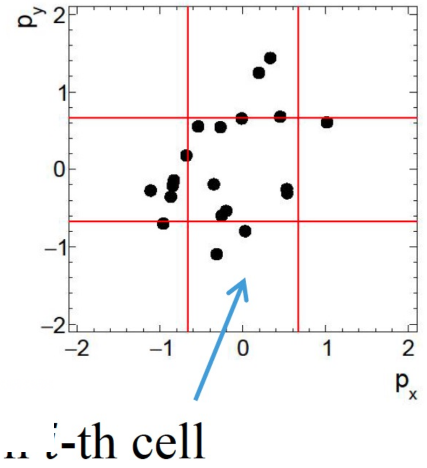
中子密度涨落：$\Delta n = \langle(\delta n)^2\rangle / \langle n\rangle^2$

g=0.29

- 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





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

⬇

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

⬇

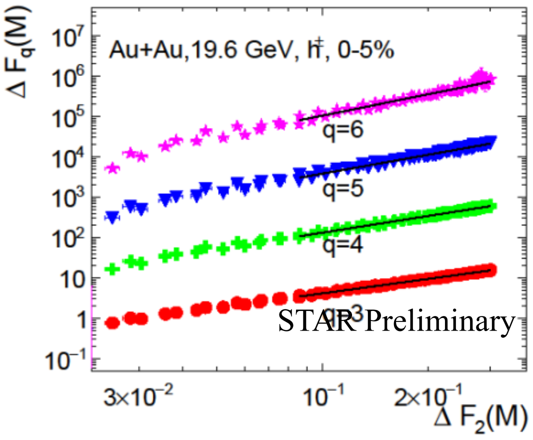
$$\Delta F_q(M) \propto \Delta F_2(M)^{\beta_q}$$

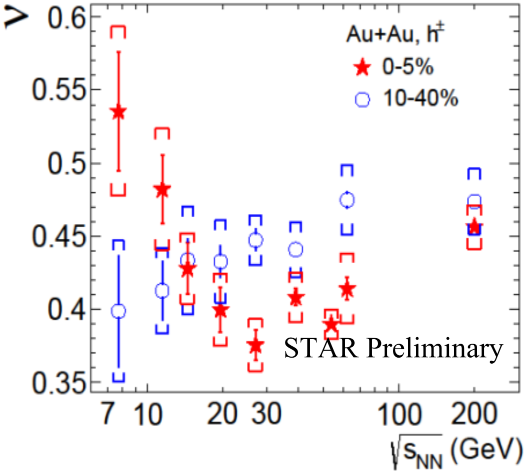
⬇

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

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

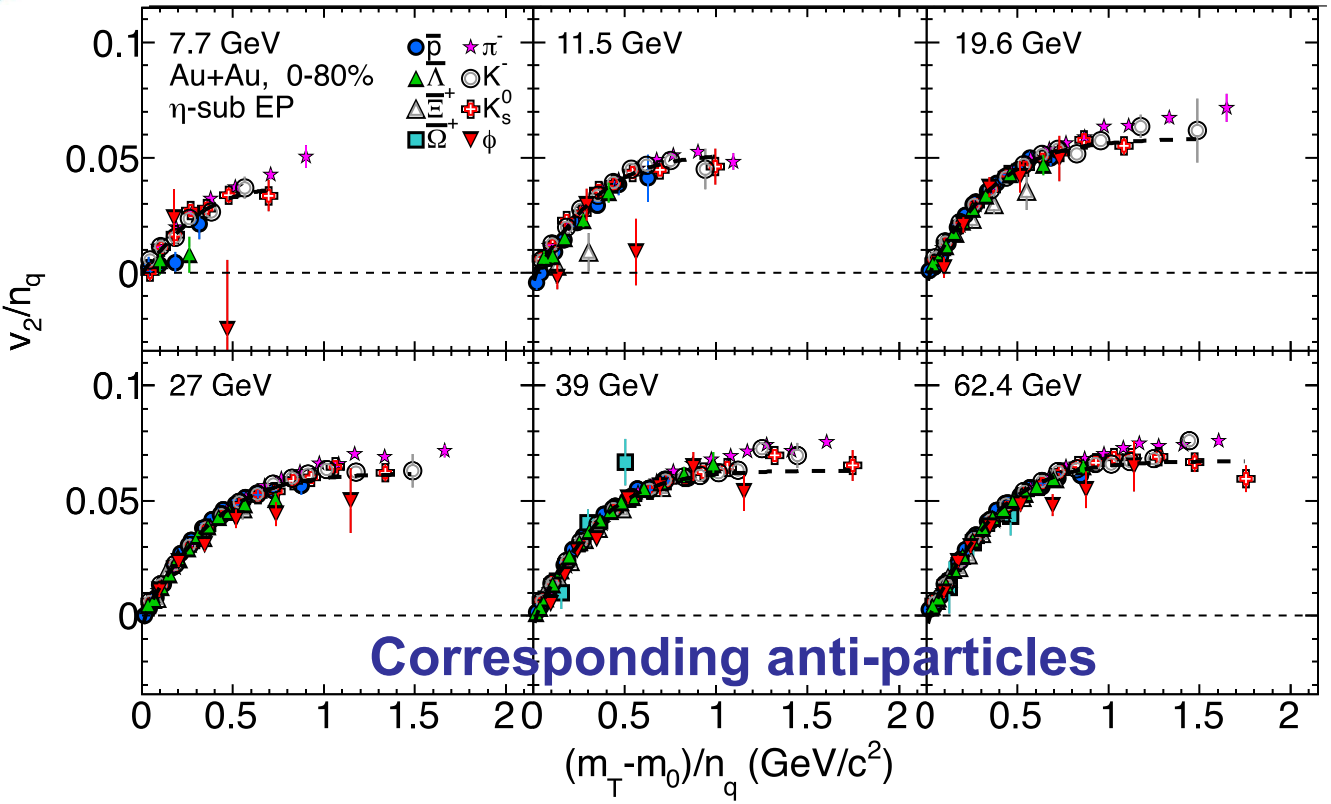
主要完成人：吴锦、林裕富、李治明、罗晓峰
Jin Wu (for STAR), ISMD 2021





- STAR 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



Corresponding anti-particles

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

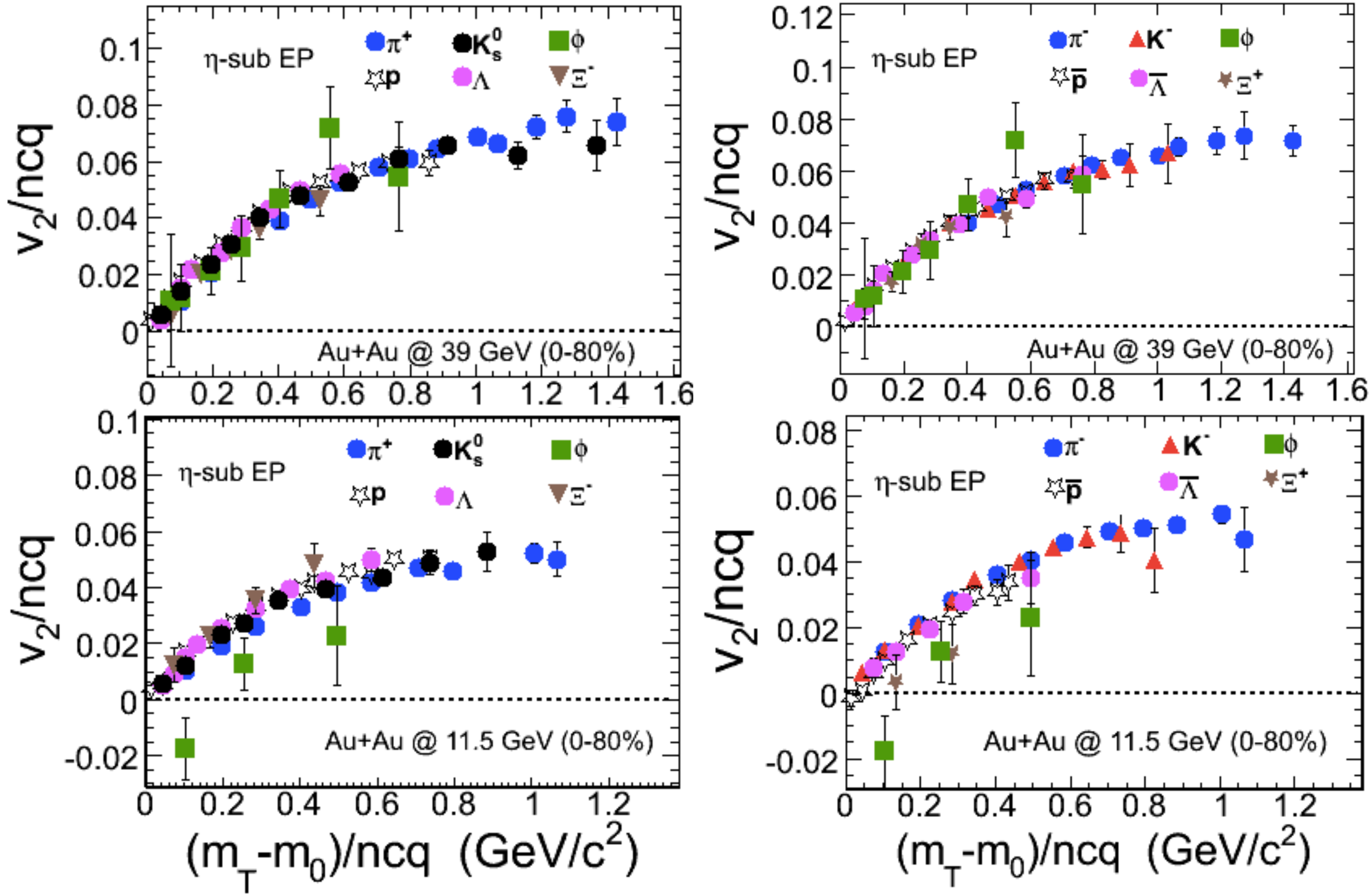
Hadronic interactions are more important at lower energies

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

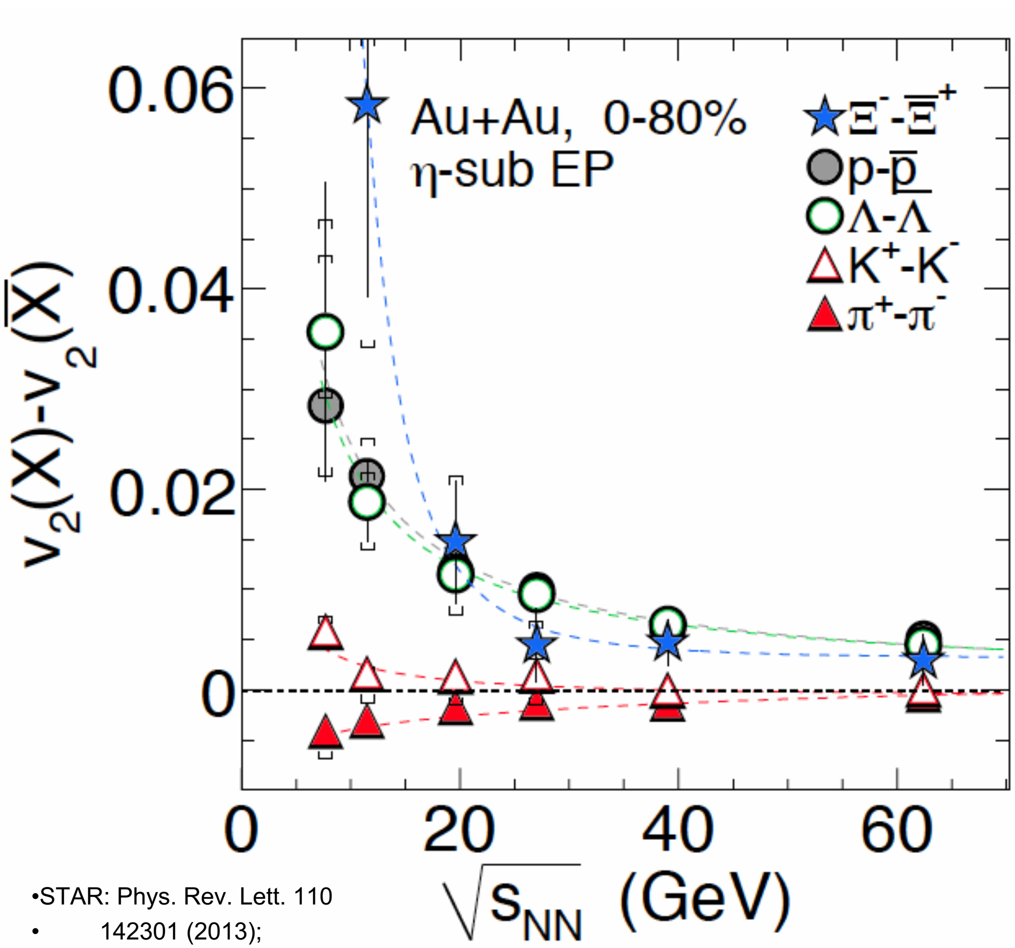
Ref: B. Mohanty and N. Xu: J. Phys. G 36, 064022(2009)

ϕ-meson v_2 vs. $\sqrt{s_{NN}}$



- The φ-meson v_2 falls off trend from other hadrons at 11.5 GeV
- An effect of 2.6σ

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?

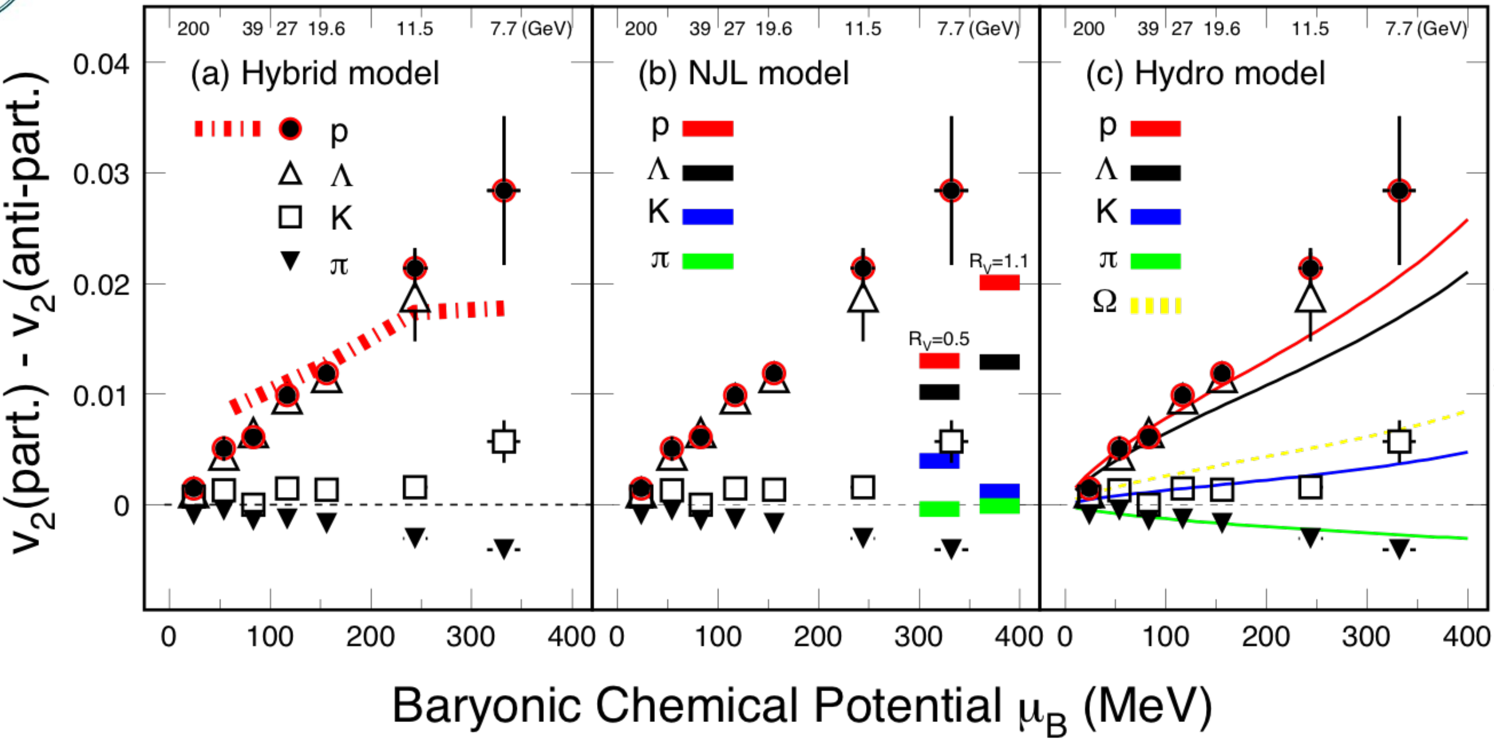
ref: J. Dunlop et al., PRC 84, 044914 (2011)

Hadronic potential?

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

The difference between particles and anti-particles is observed

Particle vs. Anti-particle v_2

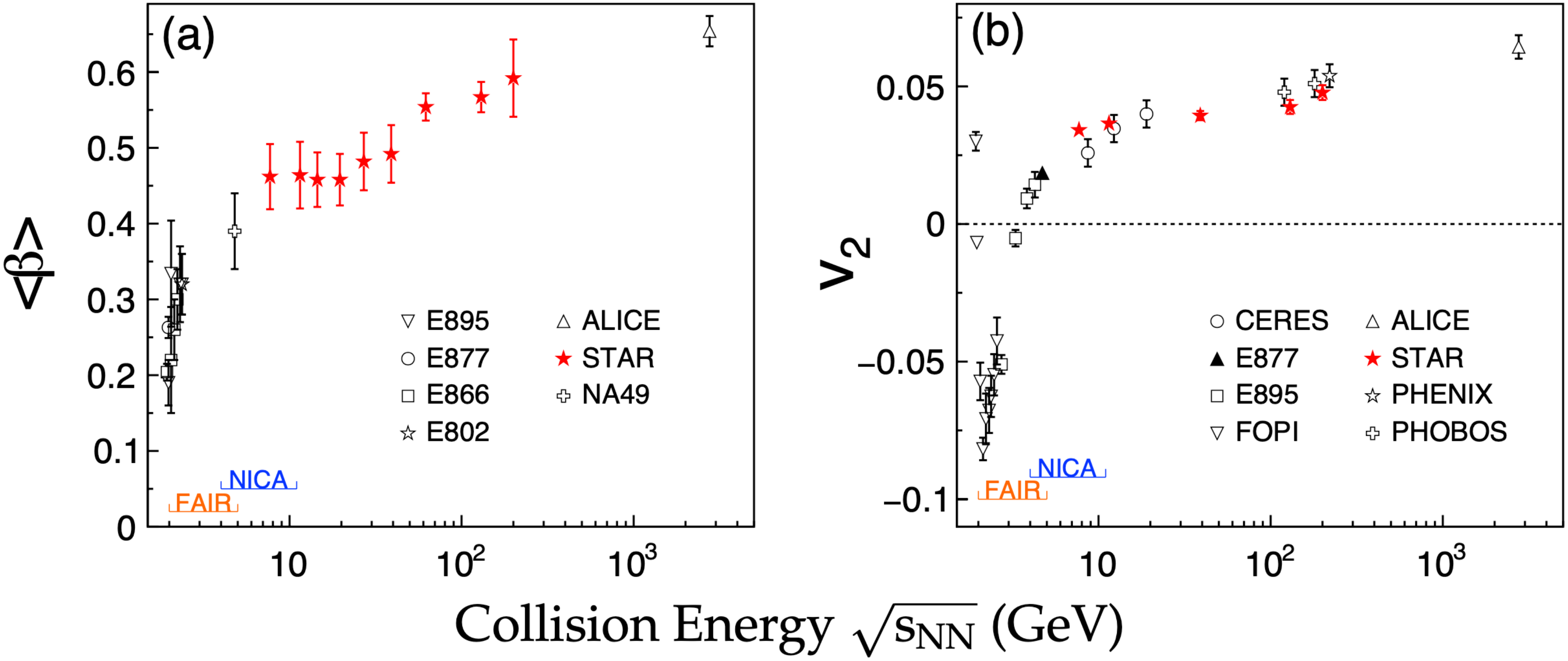


BESII : multi-strange hadrons

- **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)

v_0/v_2: Softest Point

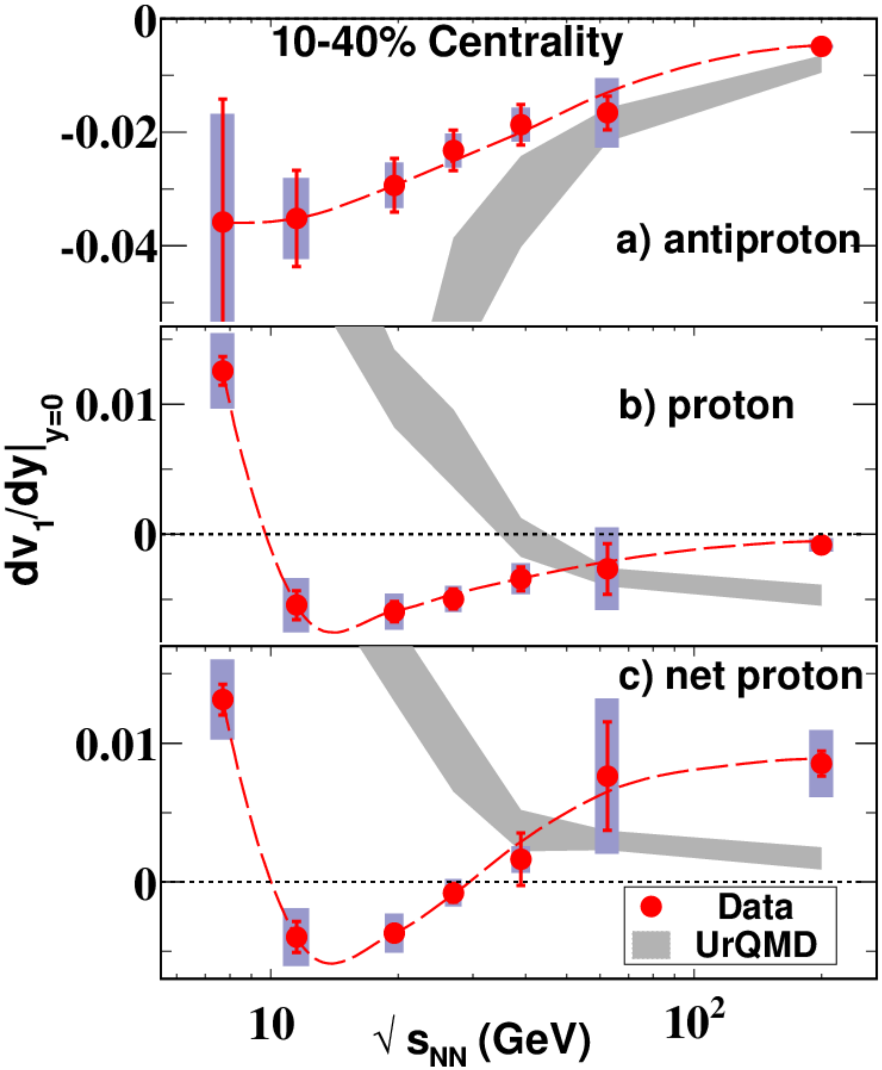


- A non-monotonic variation could be observed around the so-called "softest point of EOS"

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

Directed Flow v_1: Softest Point

BESII : centrality dependence



dv_1/dy：中心快度区直接流对快度的斜率

- 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

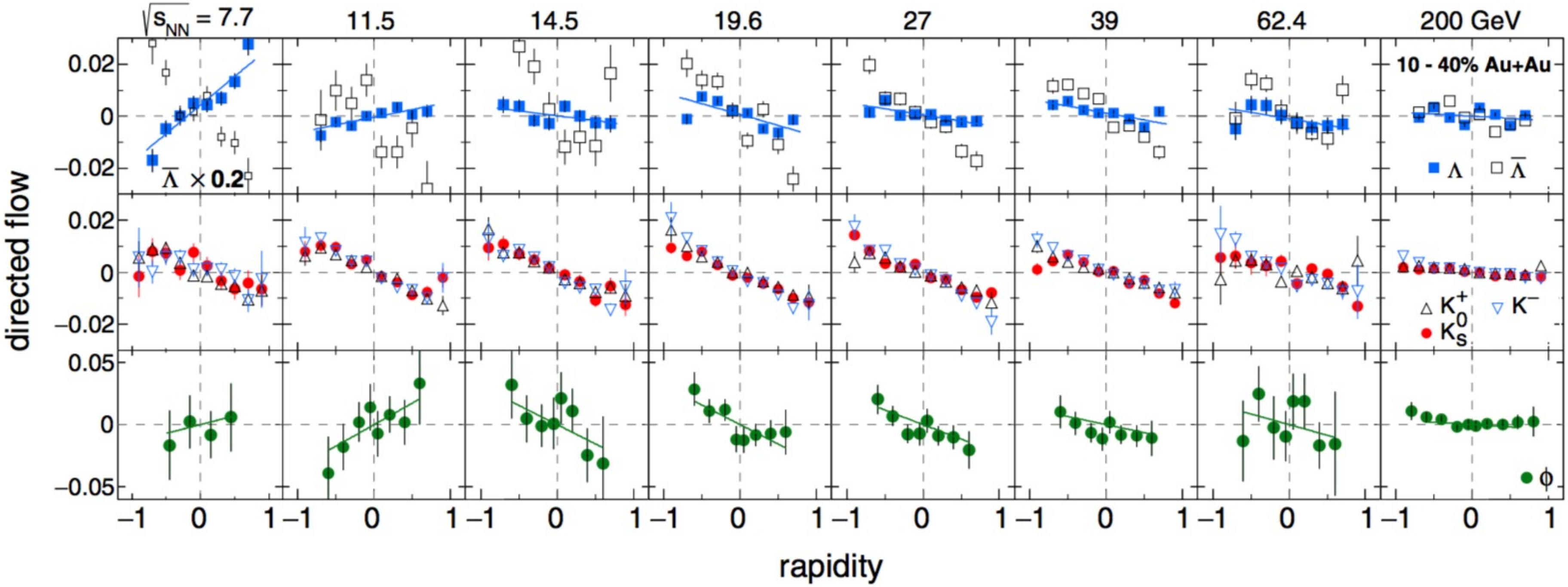
净质子的斜率为

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

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

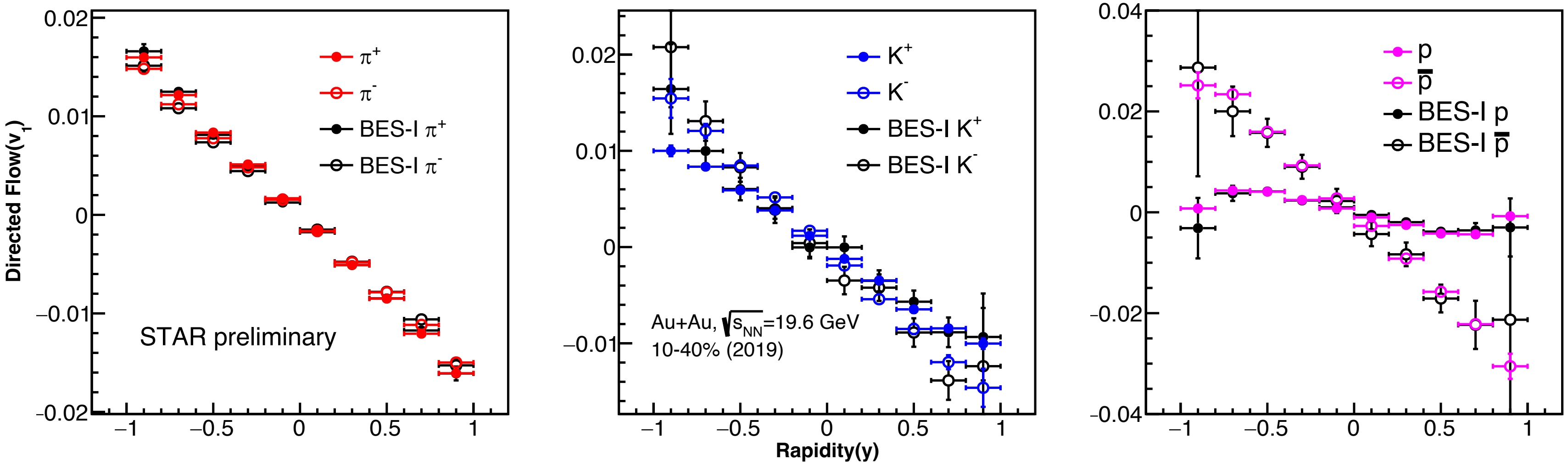


- ➢ Mesons and all produced baryons show negative slope except ϕ mesons when collisions energy < 14.5 GeV

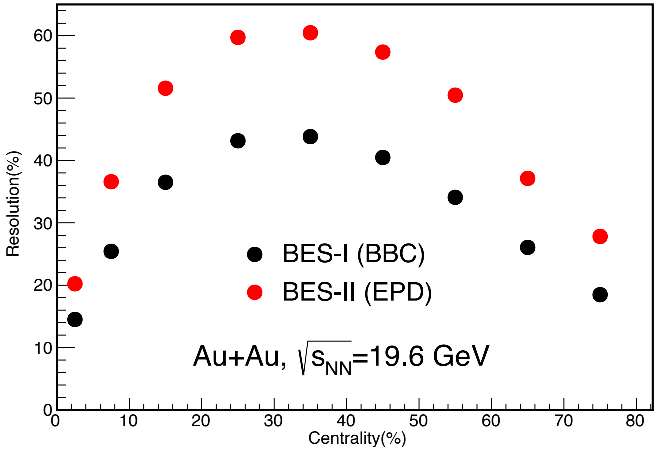
Change of medium property? High precision data needed: BESII

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

BESII v_1: 19.6 GeV

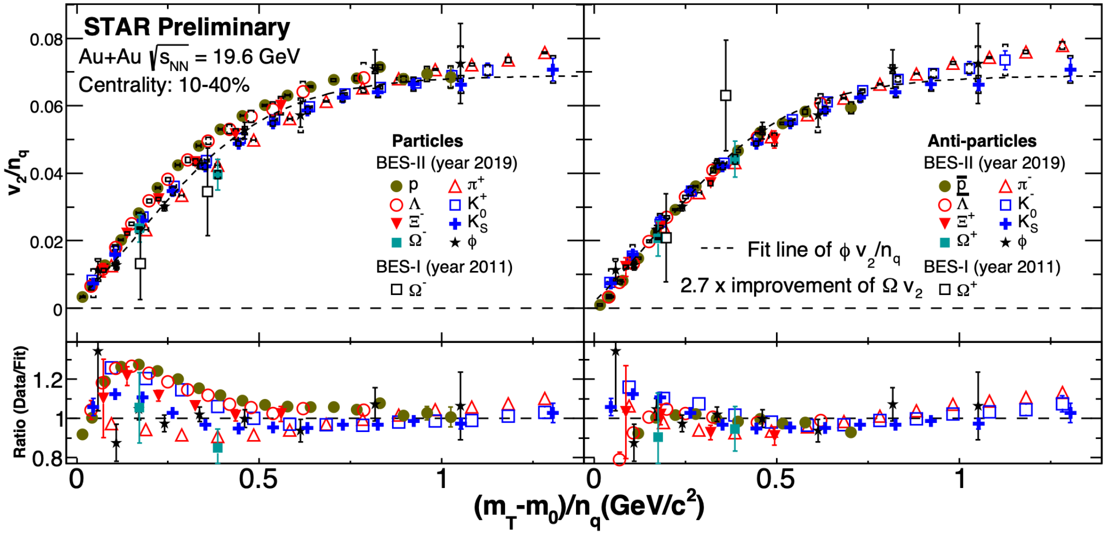


STAR 刘佐文: SQM2022, ISMD2022

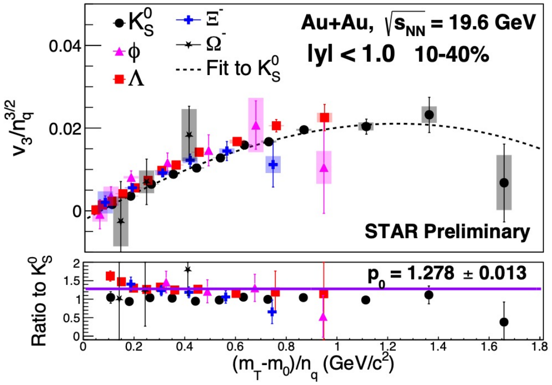


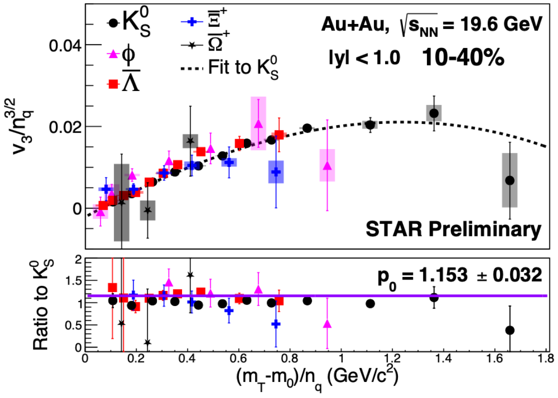
- Resolution improved about 50% comparing to BES-I
- The statistical uncertainties reduced by a factor 8 comparing to BES-I results.

BESII v_2: 19.6 GeV



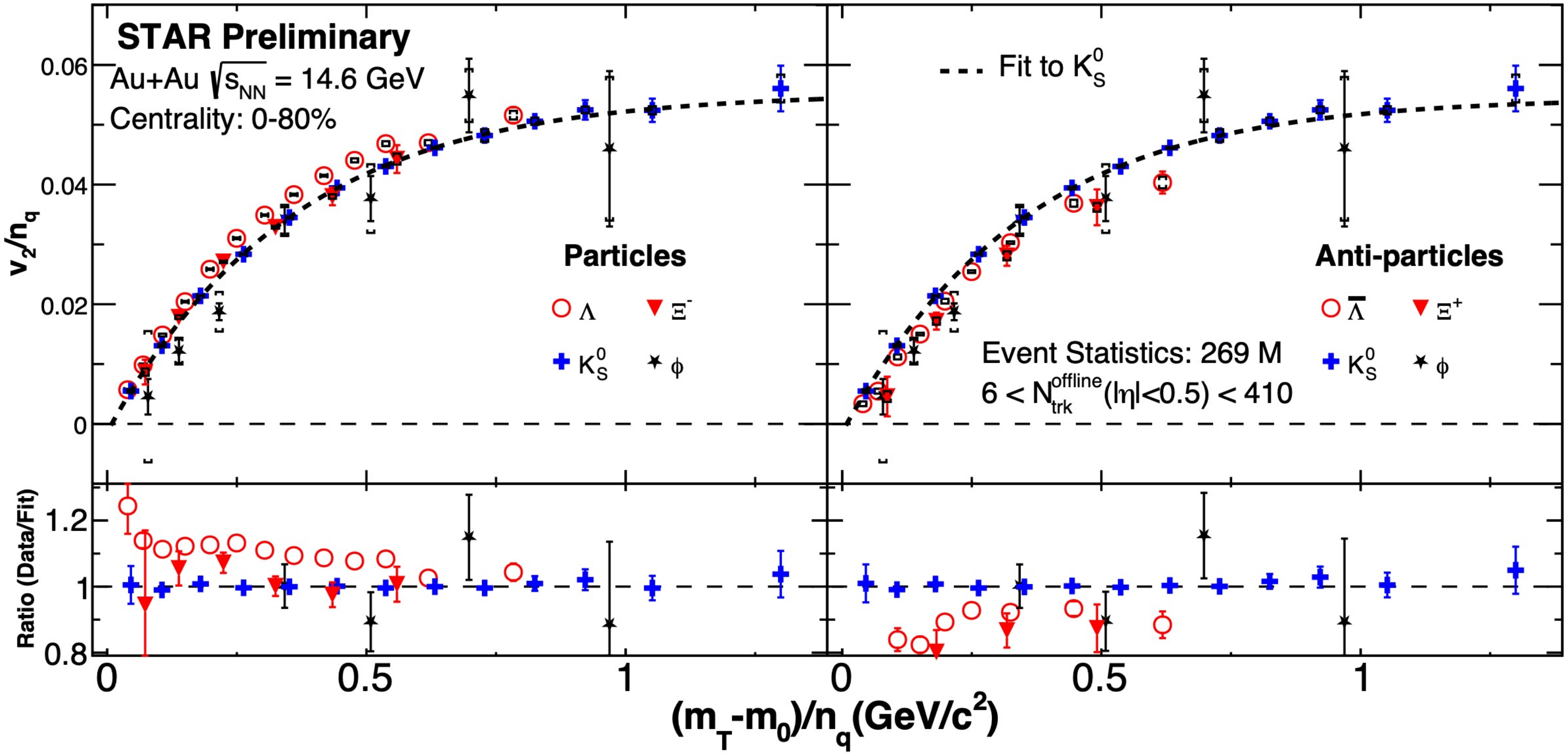
STAR 刘利珂: SQM2022





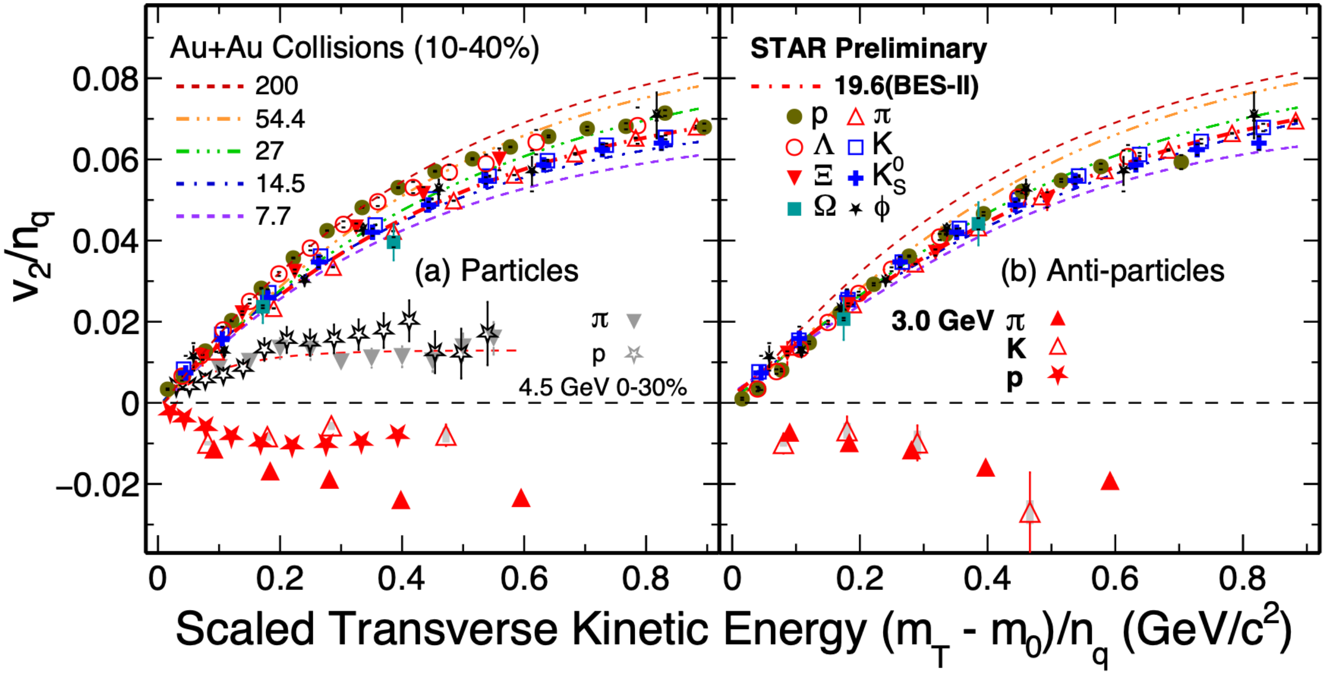
- ➢ The NCQ scaling holds within 20% for particles and within 10% for anti-particles
- ➢ The NCQ scaling of anti-particles better than particles: produced vs. transported quarks

BESII v_2: 14.6 GeV



- The NCQ scaling holds within at 20% level

NCQ Scaling at 3 GeV

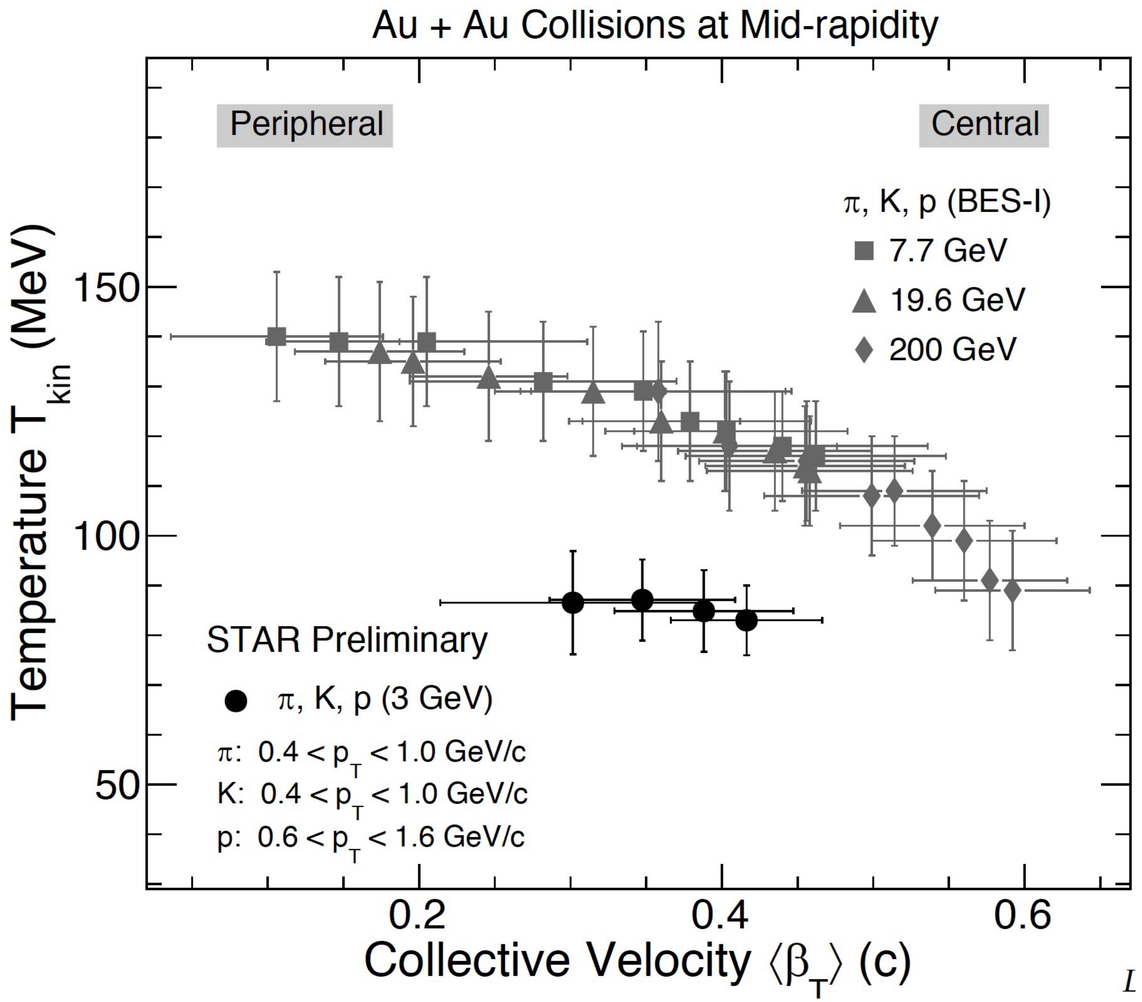


STAR: Phys. Lett. B 827 (2022) 137003 兰少位，施梳苏等

- 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

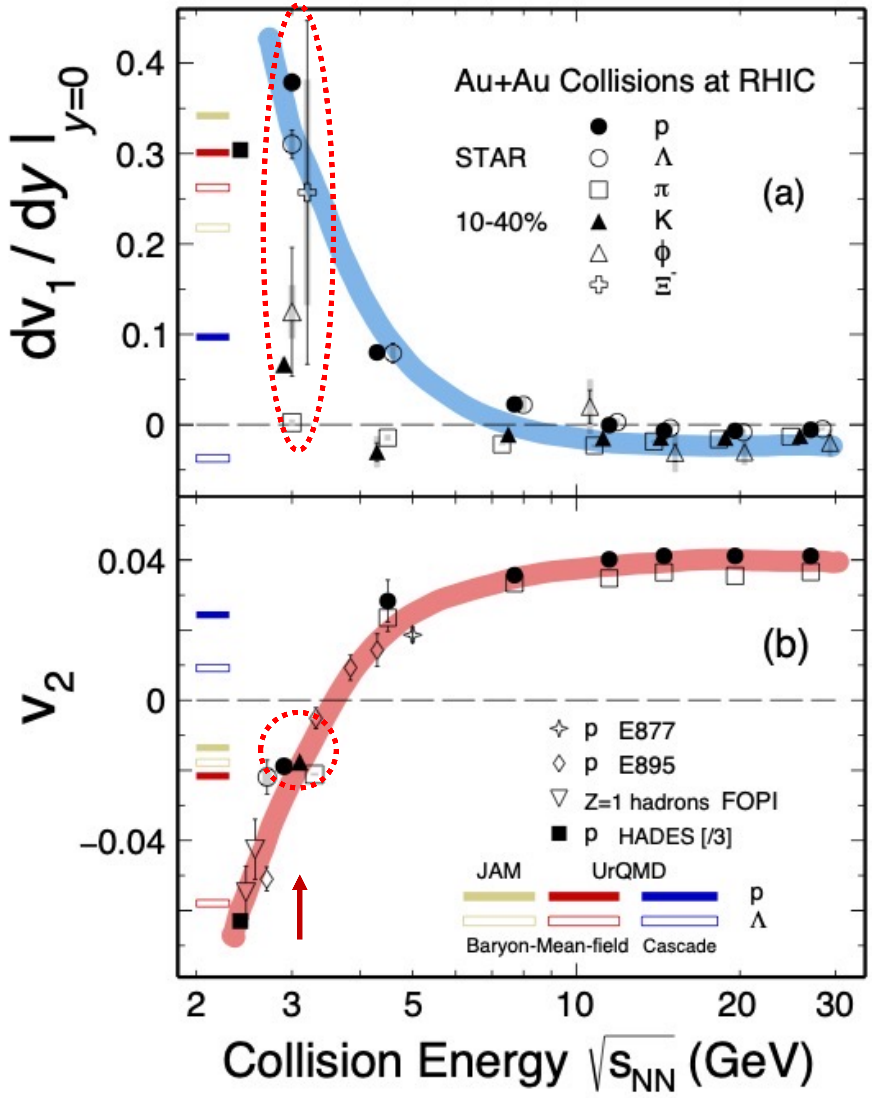
STAR: Phys. Rev. C 88 (2013) 14902; Phys. Lett. B 827 (2022) 137003
X. Dong et al. Phys. Lett. B 597 (2004) 328-332

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

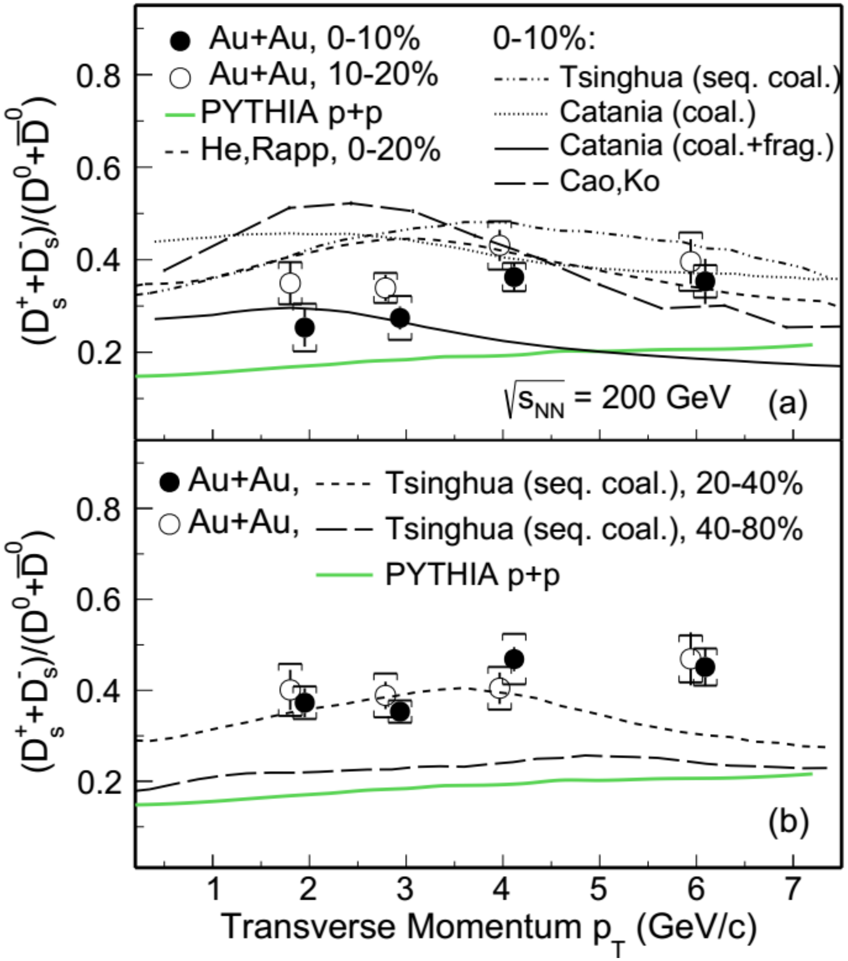
v_1 Slope and v_2 vs. Energy

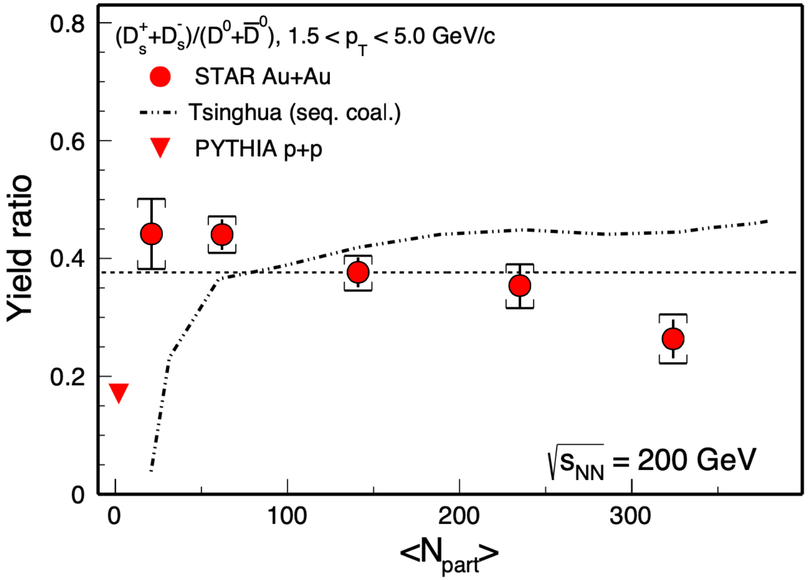


- ➢ The v_1 slopes ($dv_1/dy|_{y=0}$) of baryons at 3 GeV are positive and larger than those of mesons
- ➢ For the first time, kaon and ϕ v_1 slopes are found to be positive at 3 GeV
- ➢ Opposite collective behavior to high energy results
- ➢ The results from UrQMD with baryonic mean-field potential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

EoS dominated by the baryonic interactions at 3 GeV

高能重离子碰撞中D_s/D^0增强



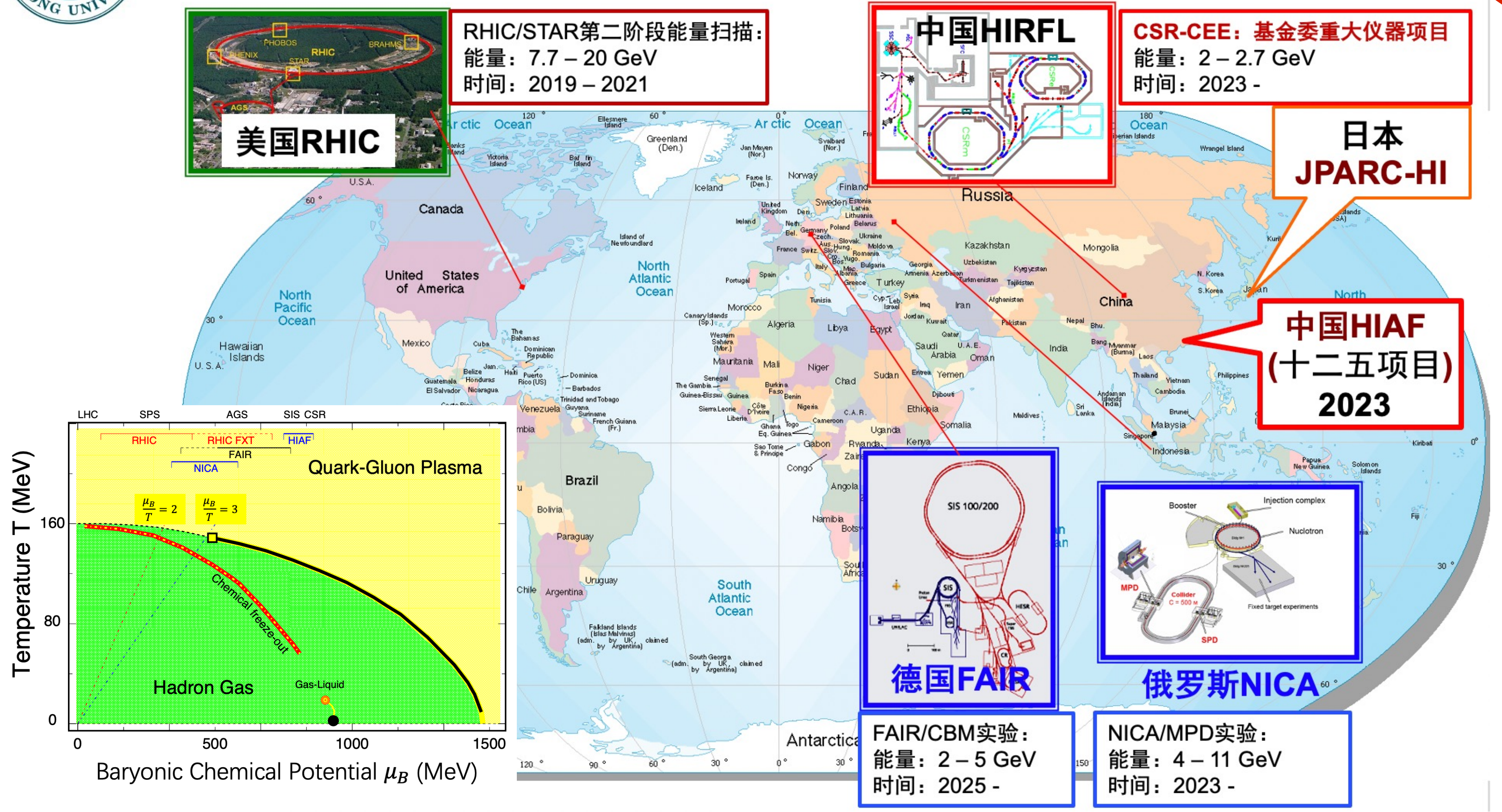


- 高能重离子碰撞中D_s/D^0显著增强

奇异性增强+夸克级联的强子化机制

STAR, PRL 127 092301 (2021)

未来高重子密度区重离子碰撞实验



美国RHIC

RHIC/STAR第二阶段能量扫描：
能量：7.7 – 20 GeV
时间：2019 – 2021

中国HIRFL

CSR-CEE：基金委重大仪器项目
能量：2 – 2.7 GeV
时间：2023 -

日本
JPARC-HI

中国HIAF
(十二五项目)
2023

德国FAIR

FAIR/CBM实验：
能量：2 – 5 GeV
时间：2025 -

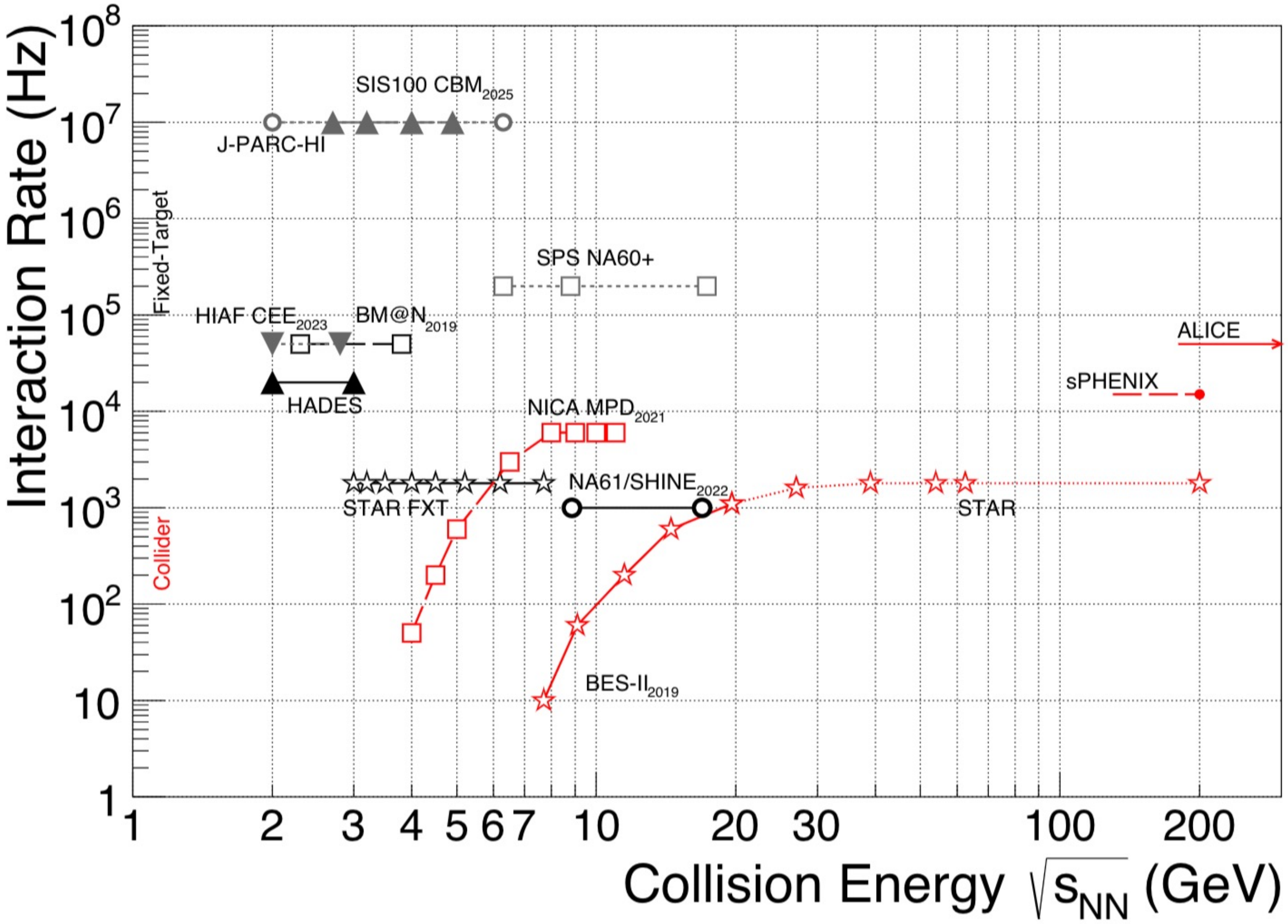
俄罗斯NICA

NICA/MPD实验：
能量：4 – 11 GeV
时间：2023 -

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2024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

3x10^{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

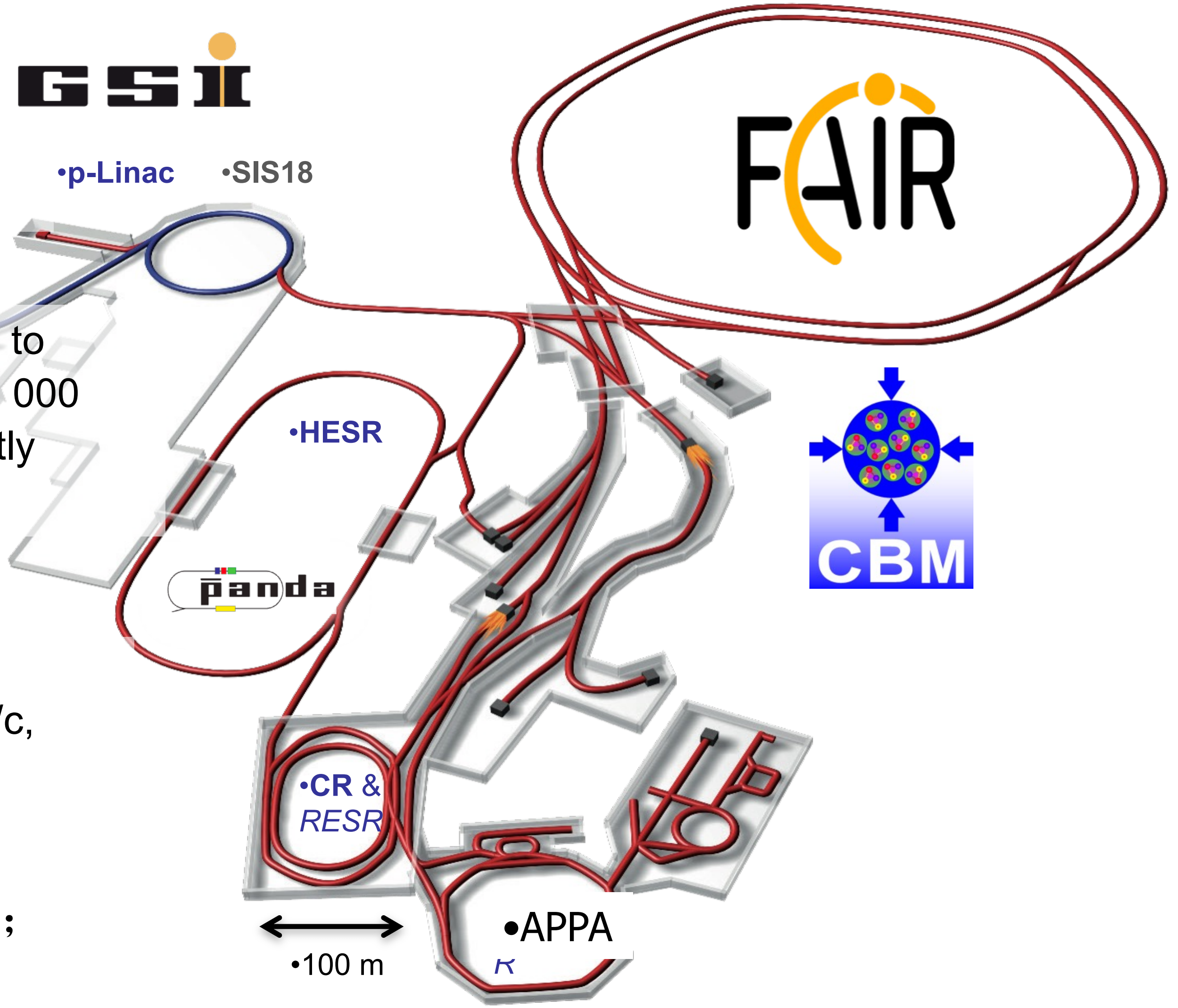
10^{11} antiprotons 1.5 - 15 GeV/c, stored and cooled

(1) 最新高科技加速器群

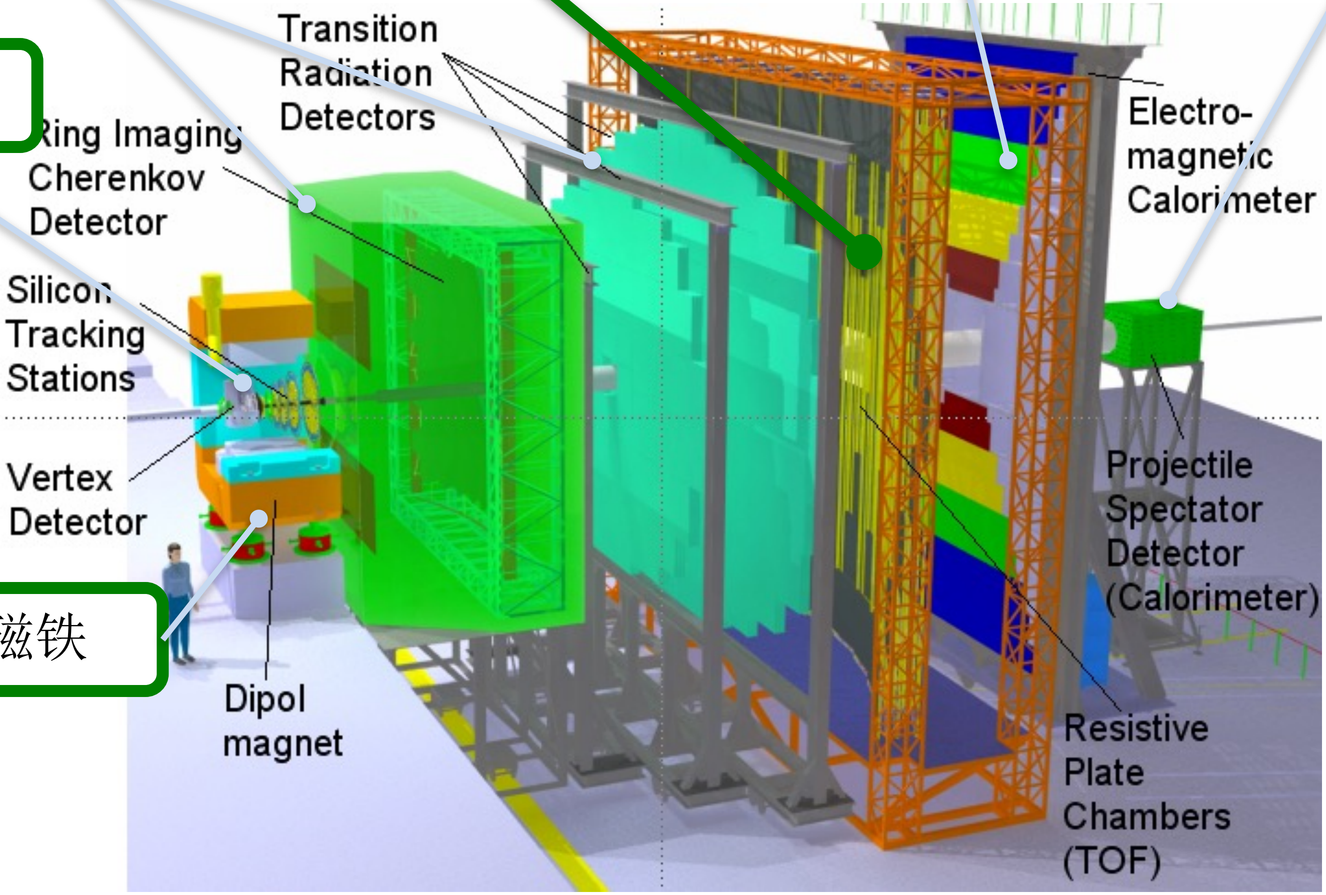
(2) 强子物理；天体物理；

放射性束流物理；

高重子密度物理(CBM)



The Compressed Baryonic Matter Experiment: **CBM**



径迹探测器

飞行时间探测器

电磁量能器

零度角量能器

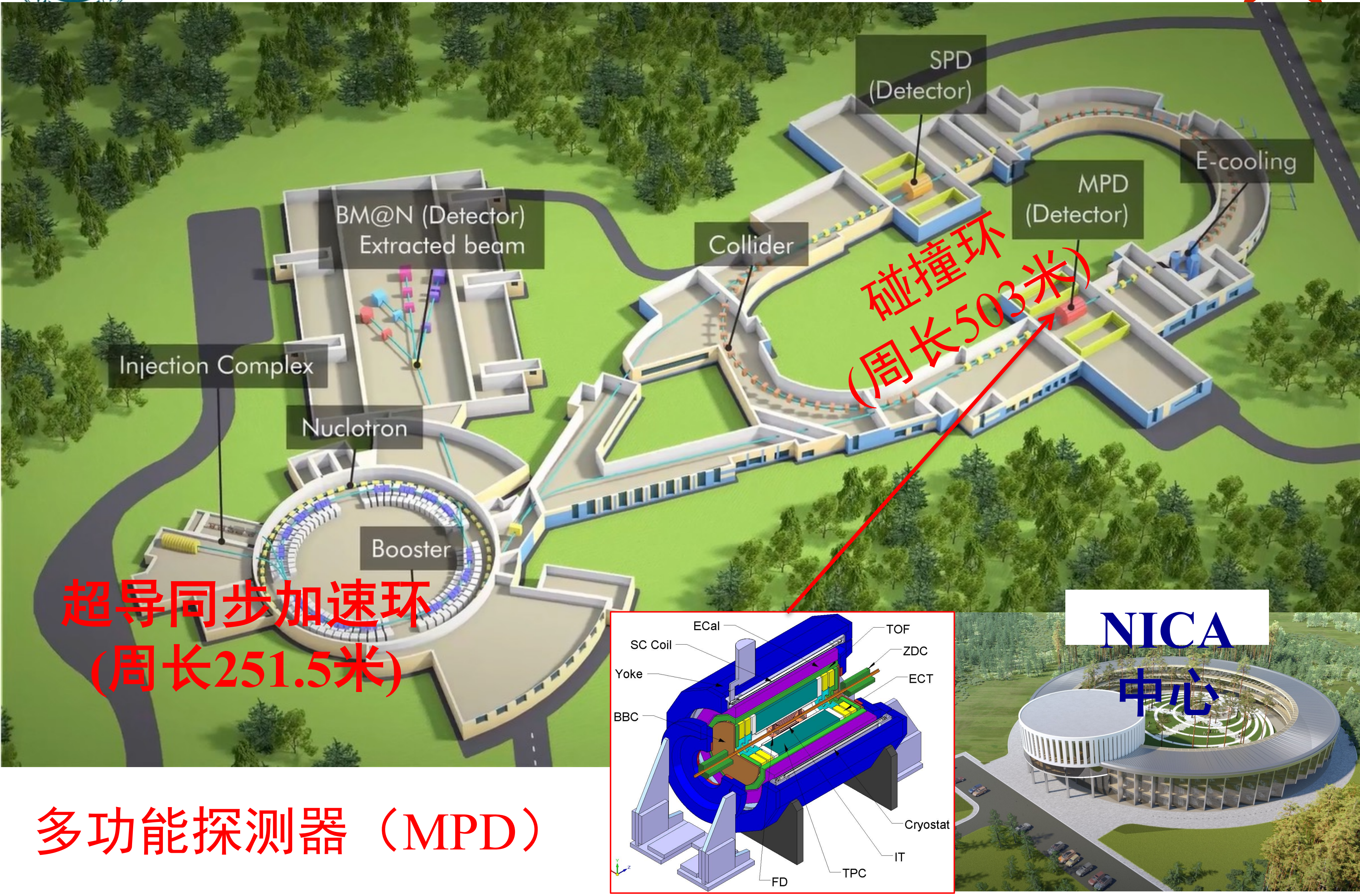
硅探测器

超导二极磁铁

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



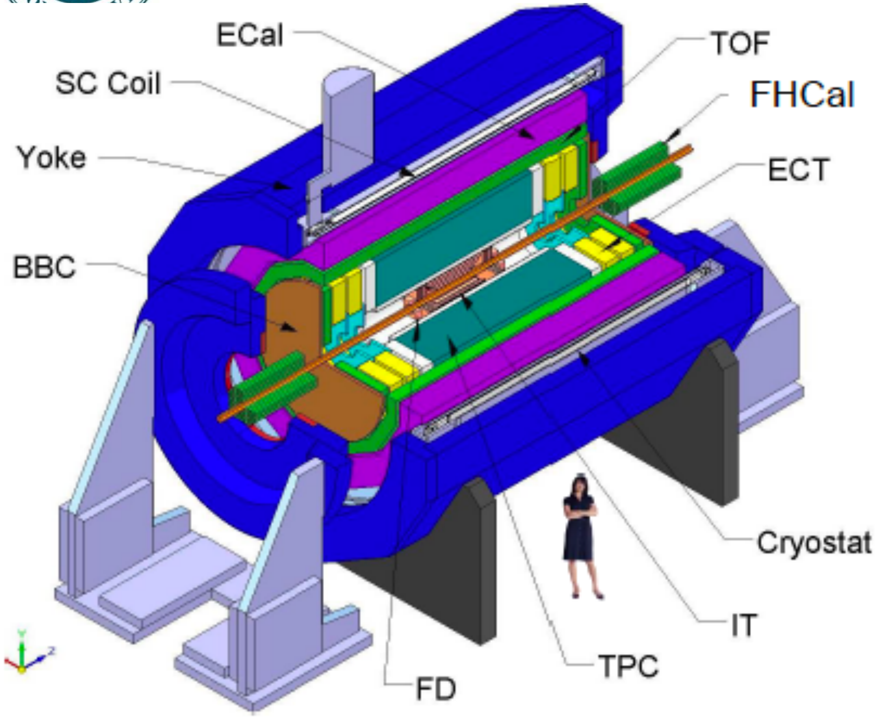
碰撞环
(周长503米)

超导同步加速环
(周长251.5米)

NICA
中心

多功能探测器（MPD）

NICA/MPD实验国际合作组

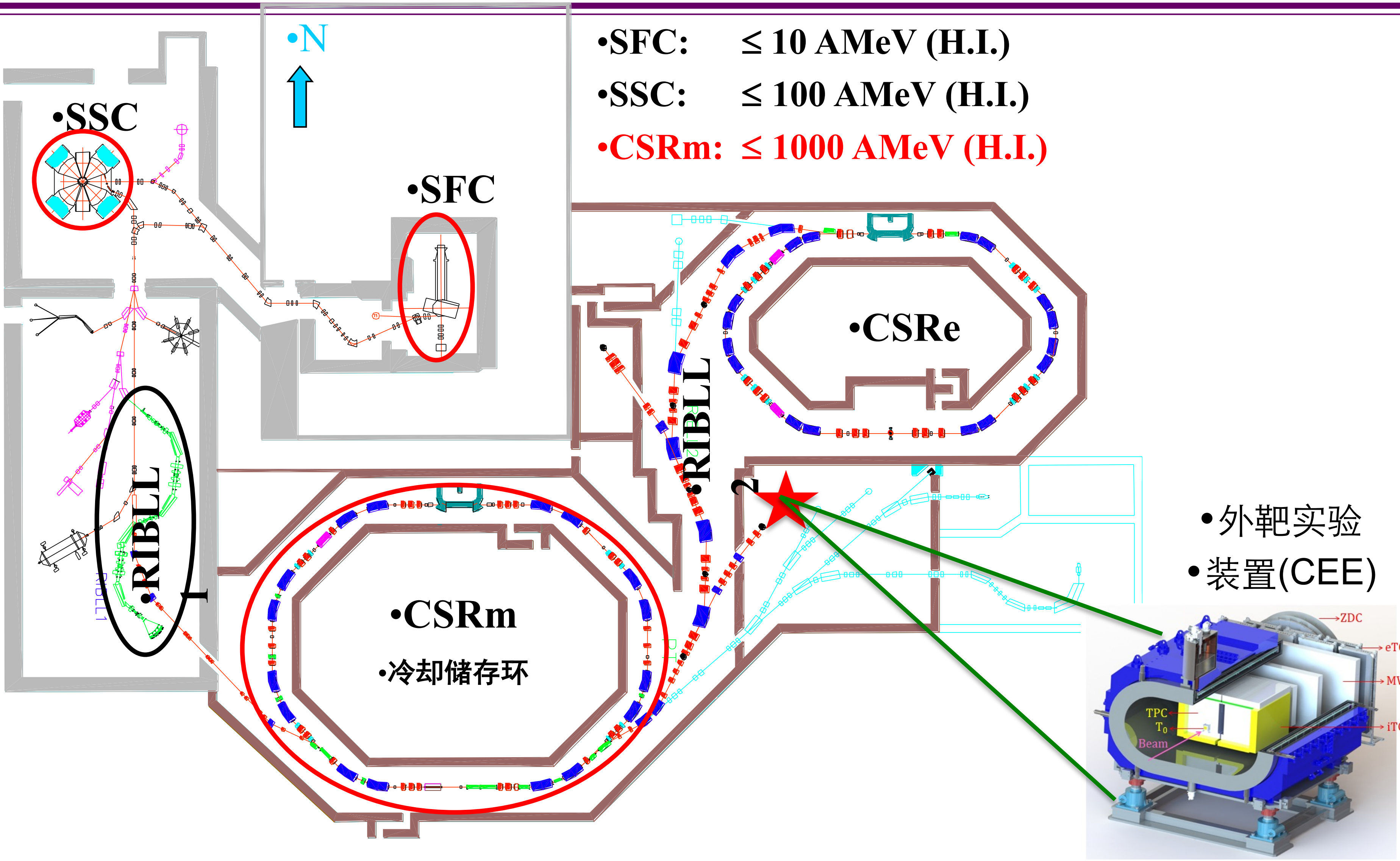


*Baku State University, NNRC, **Azerbaijan**;*
*University of Plovdiv, **Bulgaria;***
*University Tecnica Federico Santa Maria, Valparaiso, **Chili**;*
*Tsinghua University, Beijing, **China**;*
*USTC, Hefei, **China**;*
*Huizhou University, Huizhou, **China**;*
*Institute of Nuclear and Applied Physics,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

*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**;*

兰州重离子加速器冷却储存环(HIRFL-CSR）

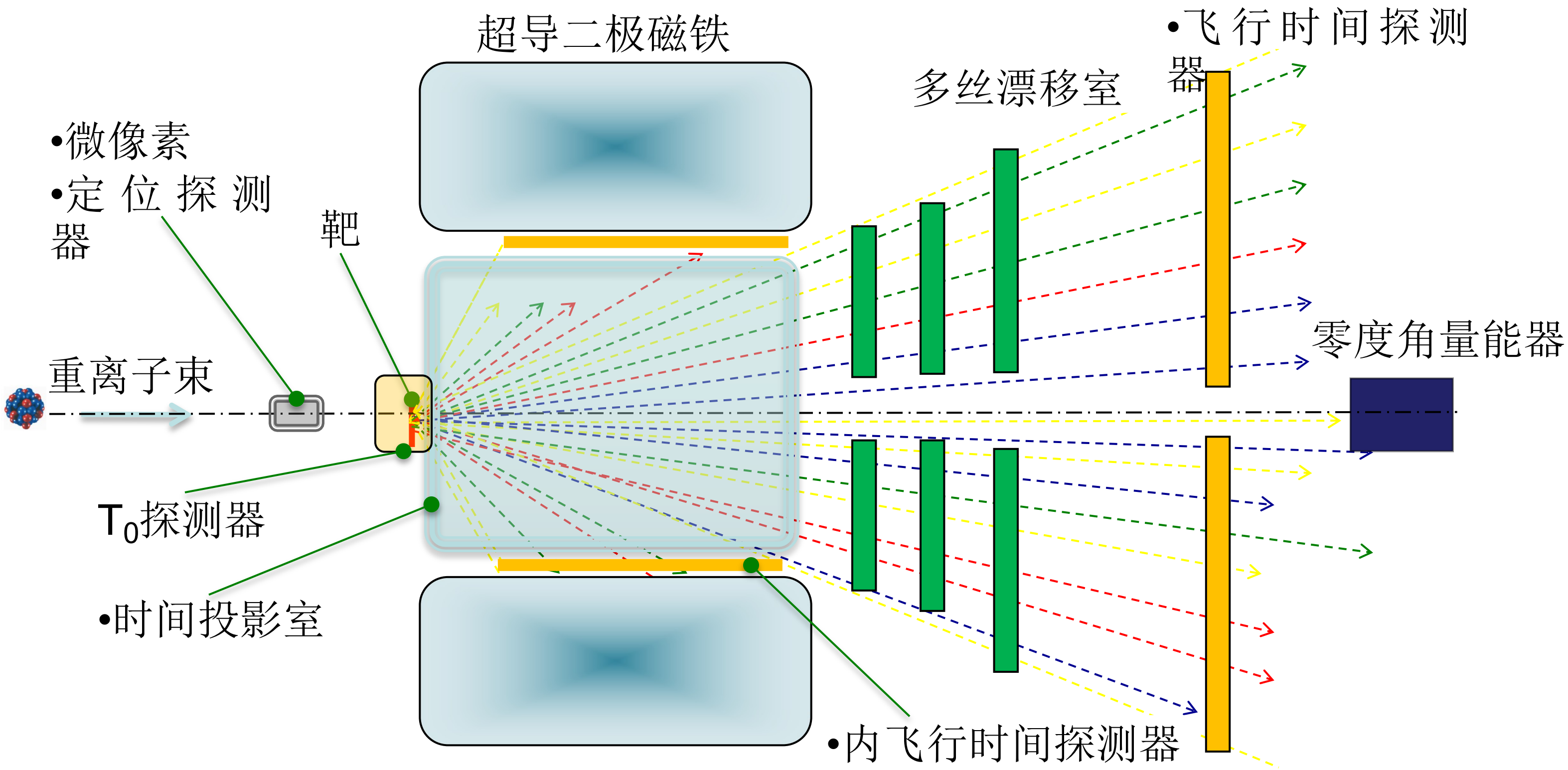
- SFC: ≤ 10 AMeV (H.I.)
- SSC: ≤ 100 AMeV (H.I.)
- CSRm: ≤ 1000 AMeV (H.I.)



- 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

- BES-I四阶涨落的实验测量结果显示出非单调能量依赖，具有3.1个σ显著性。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

- ϕ 介子v_2 与其它粒子的v_2 在7.7 和 11.5 GeV 在高pT时 ~ 2σ 偏离

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。

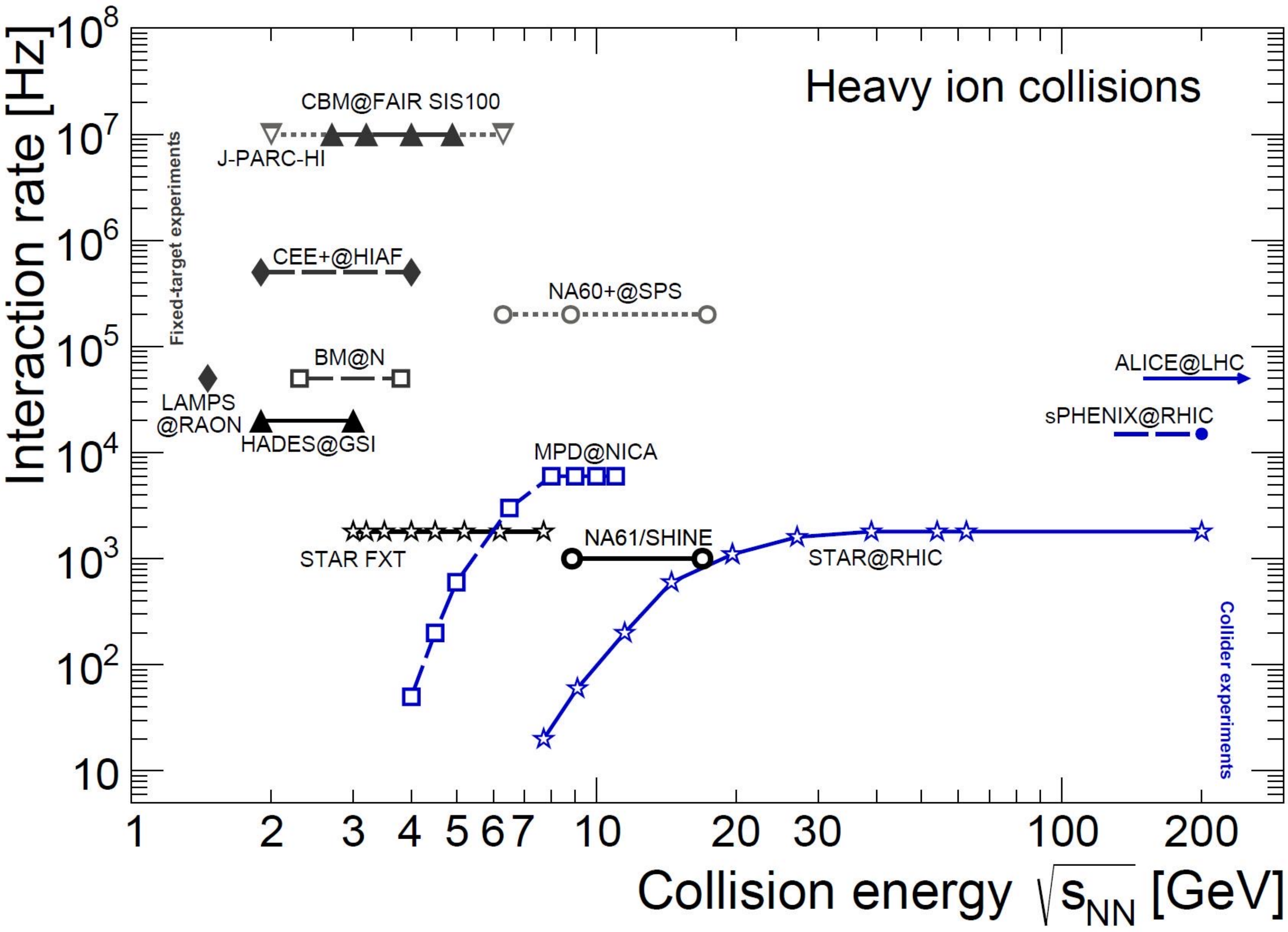
（III）2018 – QCD相变临界点及相边界的寻找

1）RHIC BES-II: focus at $\sqrt{s_{NN}} \leq 20$ GeV region

2）FAIR/CBM、NICA/MPD、HIAF/CEE （$\sqrt{s_{NN}}$ ≤12 GeV, μ_B≥300 MeV）

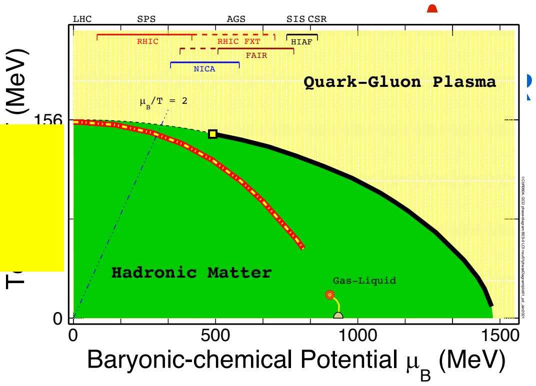
最新高科技加速器、探测器，亮度高

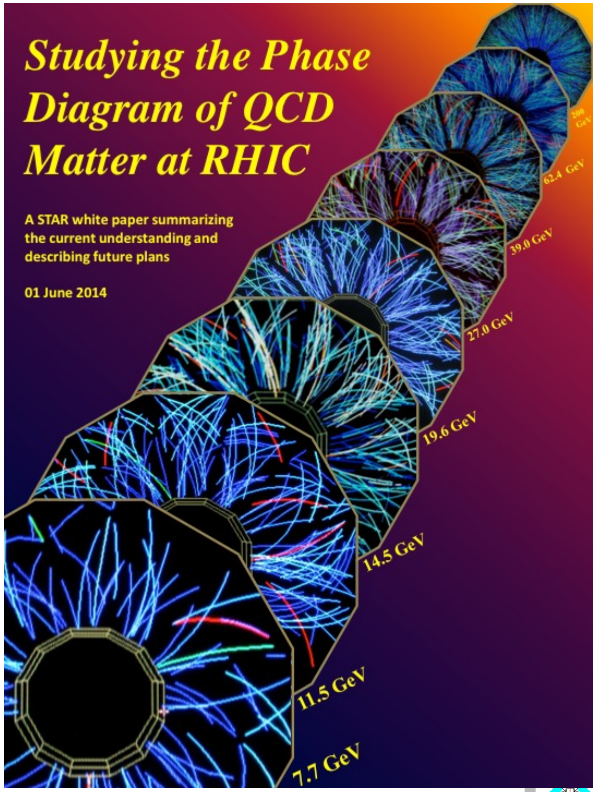
国际重离子碰撞实验


Heavy ion collisions
Interaction rate [Hz]
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
1
2
3
4
5
6
7
10
20
30
100
200
Collision energy $\sqrt{s_{NN}}$ [GeV]
Fixed-target experiments
Collider experiments
CBM@FAIR SIS100
J-PARC-HI
CEE+@HIAF
NA60+@SPS
BM@N
LAMPS @RAON
HADES@GSI
MPD@NICA
STAR FXT
NA61/SHINE
STAR@RHIC
ALICE@LHC
sPHENIX@RHIC

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

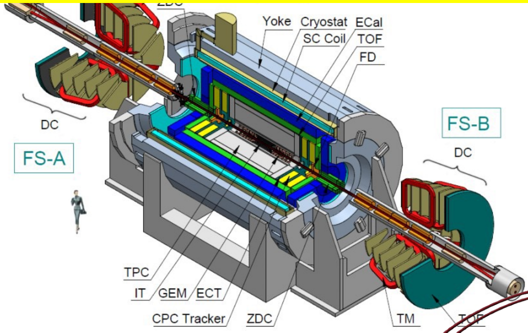




Studying the Phase Diagram of QCD Matter at RHIC

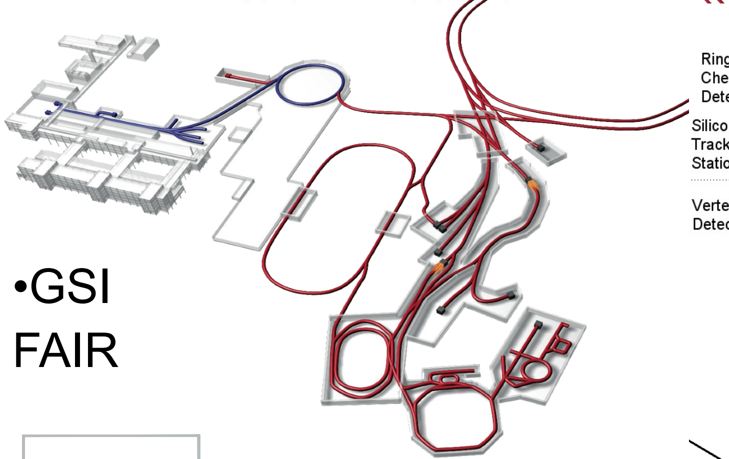
A STAR white paper summarizing the current understanding and describing future plans

01 June 2014

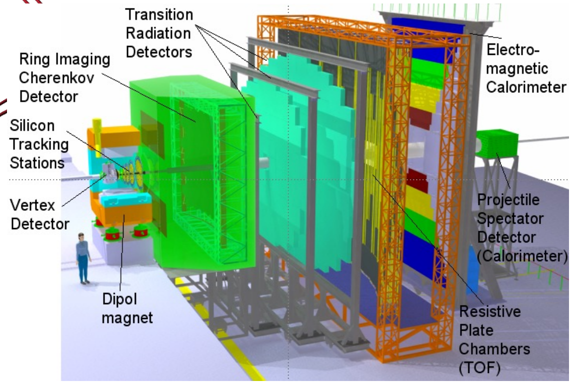


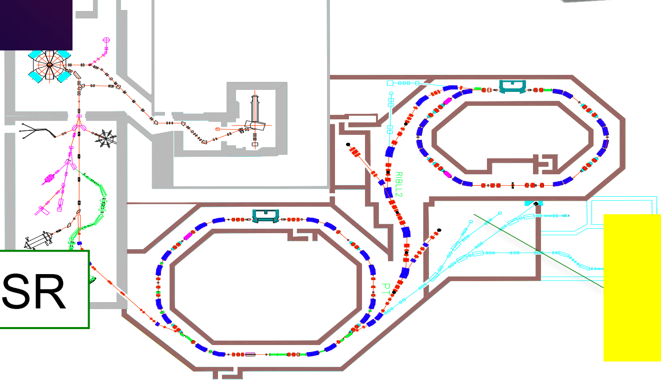
•NICA 科技部国际专项

CBM 973

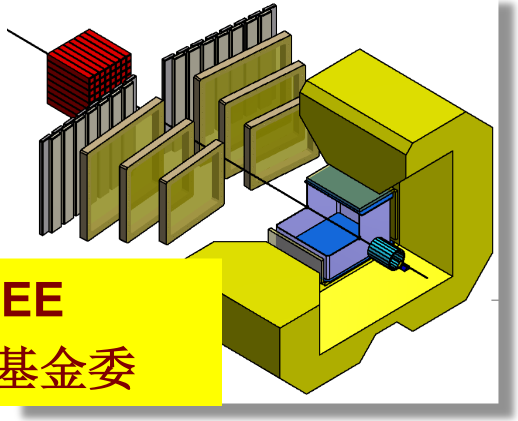


•GSI
FAIR





•HIRFL-CSR



•CEE
•国家基金委

Thanks !