重离子碰撞中的喷注
Jets in Heavy-Ion Collisions

秦广友（Guang-You Qin）
华中师范大学（Central China Normal University）

“微扰量子场论及其应用”前沿讲习班暨前沿研讨会
山东济南
2025 年7月6日-7月21日

Outline

- Lecture 1
  – Introduction to heavy-ion collisions and quark-gluon plasma

- Lecture 2
  – Jet probes (of QGP in HIC), jet quenching and energy loss (some simple discussion)

- Lecture 3
  – Jet probes of QGP in HIC: flavor dependence of parton energy loss and jet quenching

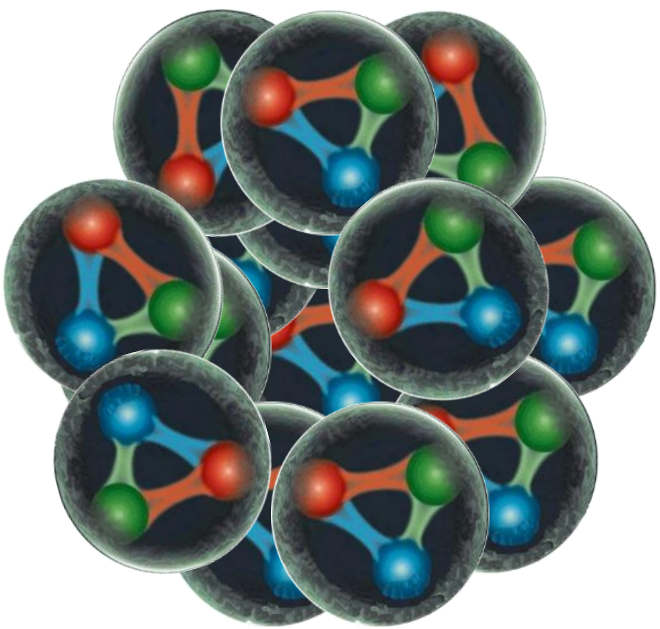
- Lecture 4
  – Jet probes of QGP in HIC: full jets, jet energy loss, medium response, jet (sub)structure

Outline

- Lecture 1
  - Introduction to heavy-ion collisions and quark-gluon plasma
- Lecture 2
  - Jet probes (of QGP in HIC), jet quenching and energy loss (some simple discussion)
- Lecture 3
  - Jet probes of QGP in HIC: flavor dependence of parton energy loss and jet quenching
- Lecture 4
  - Jet probes of QGP in HIC: full jets, jet energy loss, medium response, jet (sub)structure

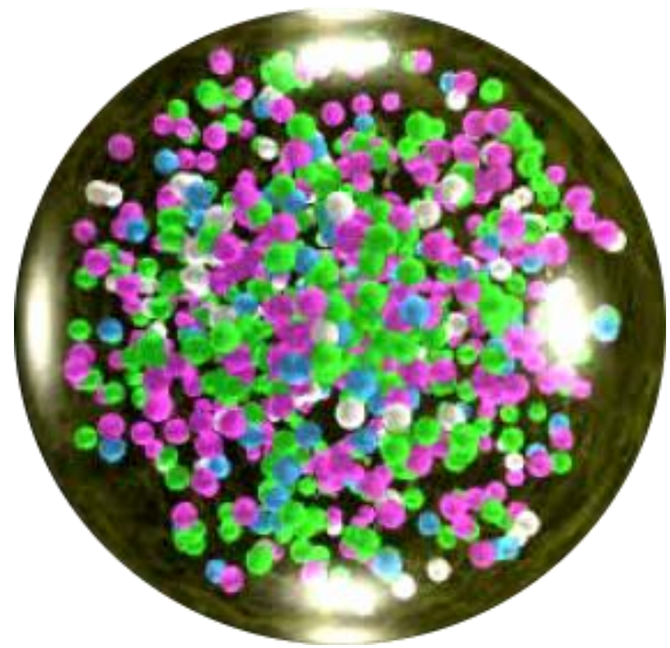
Why relativistic heavy-ion collisions?

Strong-interaction matter under extreme conditions & quark-gluon plasma



High Temperature

High Density



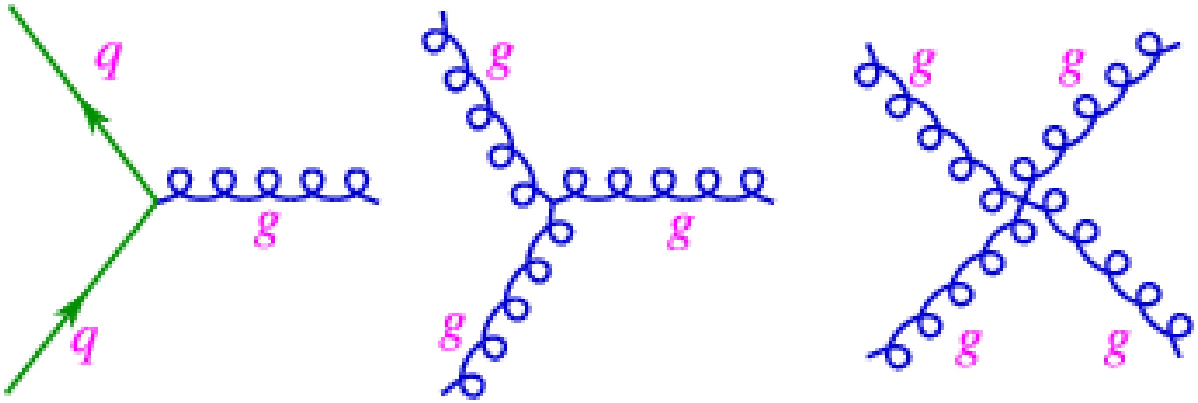
Hadronic Matter
Confined

Quark-Gluon Plasma
Deconfined

The theory of strong-interaction

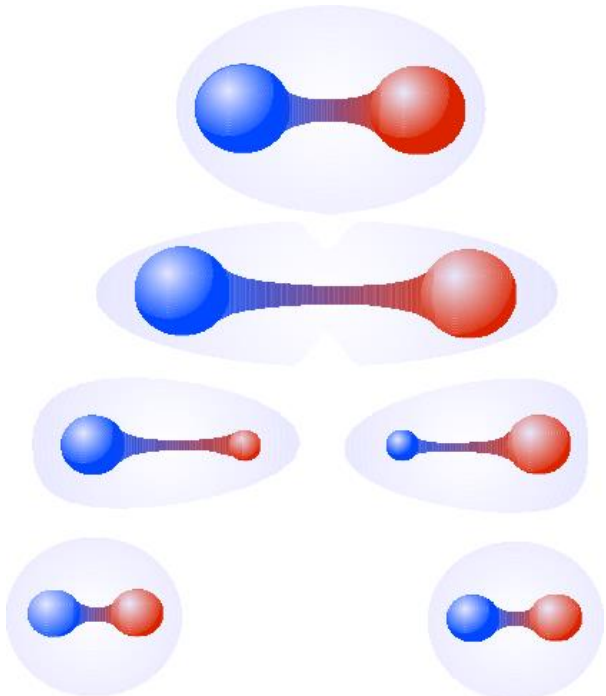
- Quantum chromodynamics (QCD): quantum field theory of strong-interaction
- Fundamental fields: quarks and gluons. Both carry "color" charges.

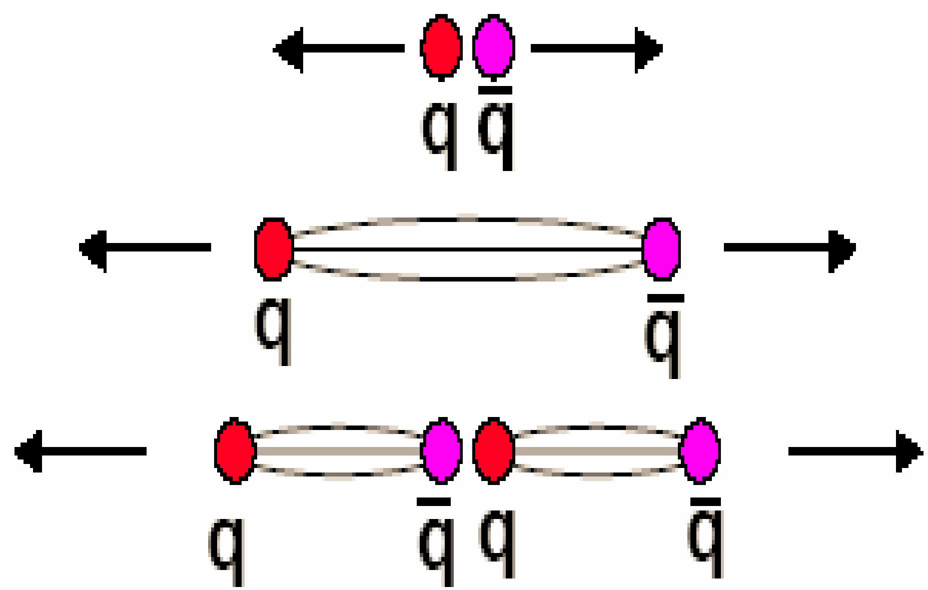
$$\mathcal{L} = \sum_f \overline{\psi}_f (i\gamma^\mu D_\mu - m_f)\psi_f - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu}$$



- Two main properties: color confinement and asymptotic freedom

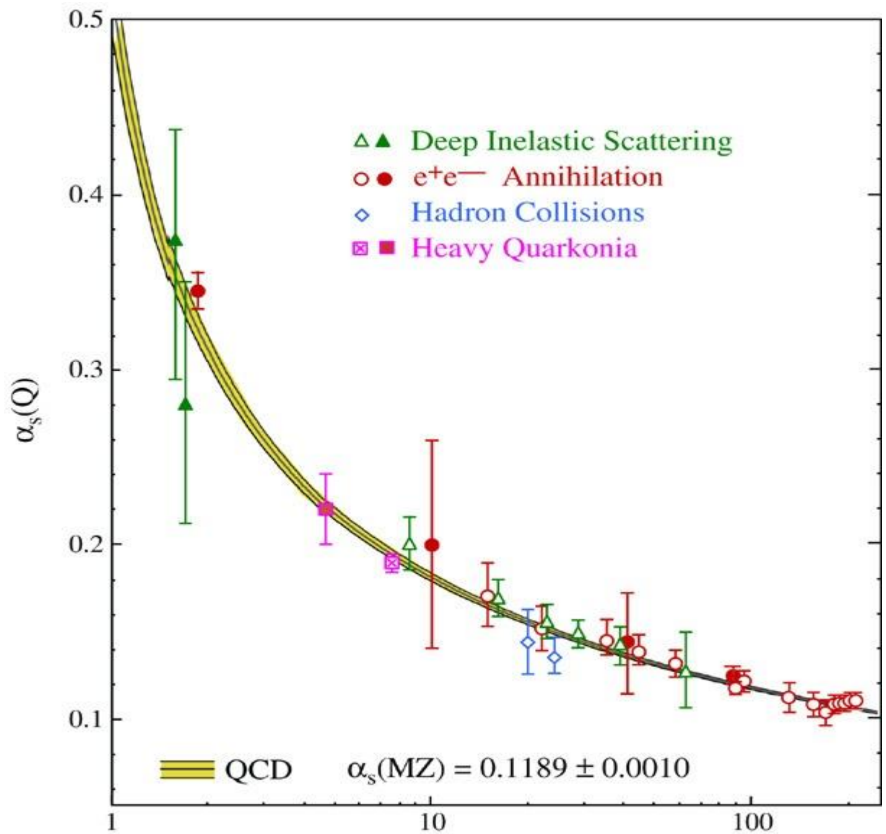
Color confinement of QCD





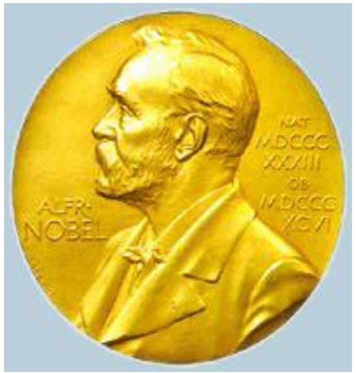
Due to the gluon self-interaction, effective color charges increase with distance =>
Coupling becomes large at large distance.
Quarks are confined within hadrons. No free quarks have been observed.

Asymptotic freedom of QCD



Long Distance ← → Short Distance

Confinement ← → Asymptotic Freedom

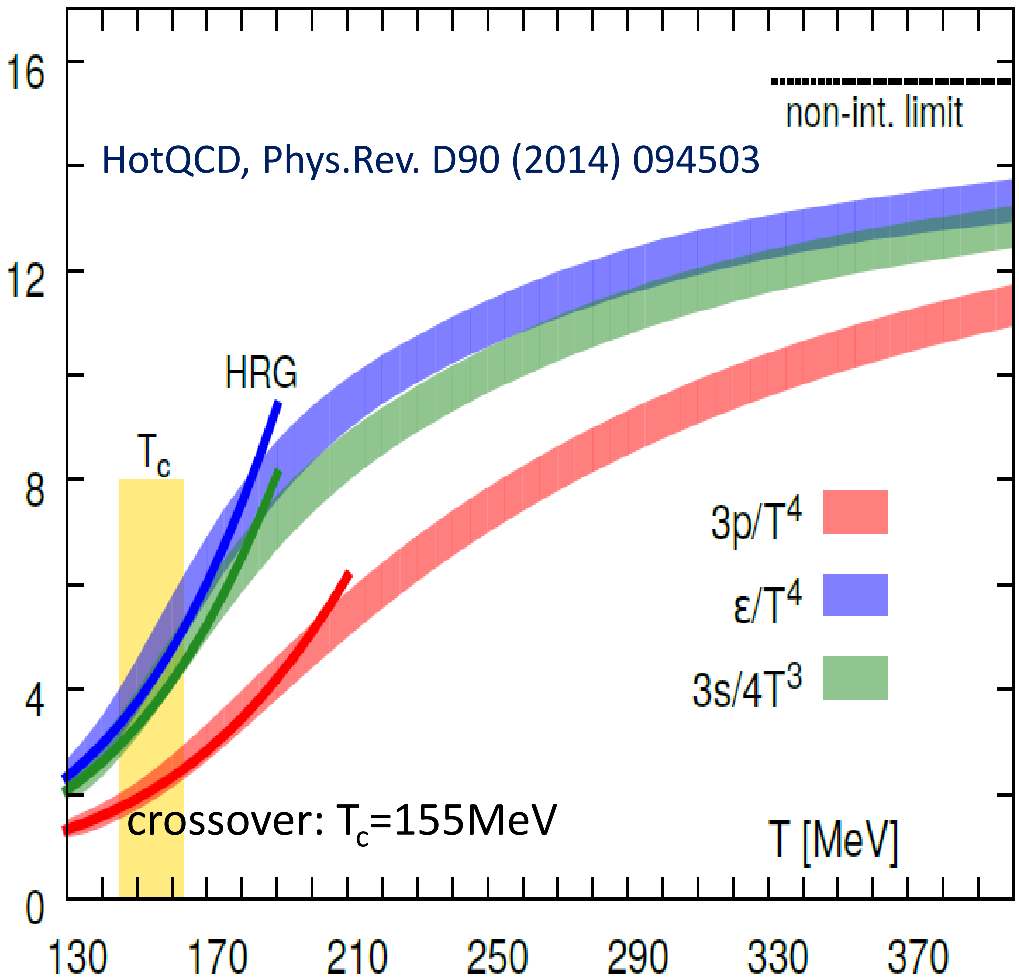


2004 Nobel Prize: *"for the discovery of asymptotic freedom in the theory of the strong interaction".*



David Gross, David Politzer, Frank Wilczek

Heating up the matter (via lattice QCD)



A transition (crossover) between hadronic matter and quark-gluon matter at $T_c \sim 155\text{MeV}$

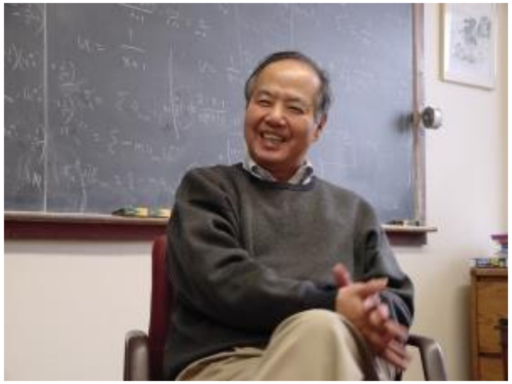
$T < T_c$, the thermodynamics of the system is described by HRG

$T \sim 400\text{MeV}$, not a non-interacting quark-gluon gas, but a strongly-interacting fluid

For a gas of massless particles,
$P = d\frac{\pi^2}{90}T^4, s = d\frac{2\pi^2}{45}T^3, \varepsilon = 3P$

$$T_c = 155\text{MeV}/\text{k}_B = (155 * 10^6\text{eV})(1.6 * 10^{-19}\text{J/eV})/(1.38 * 10^{-23}\text{J/K}) = 1.8 * 10^{12}\text{K}$$

How to make QGP?

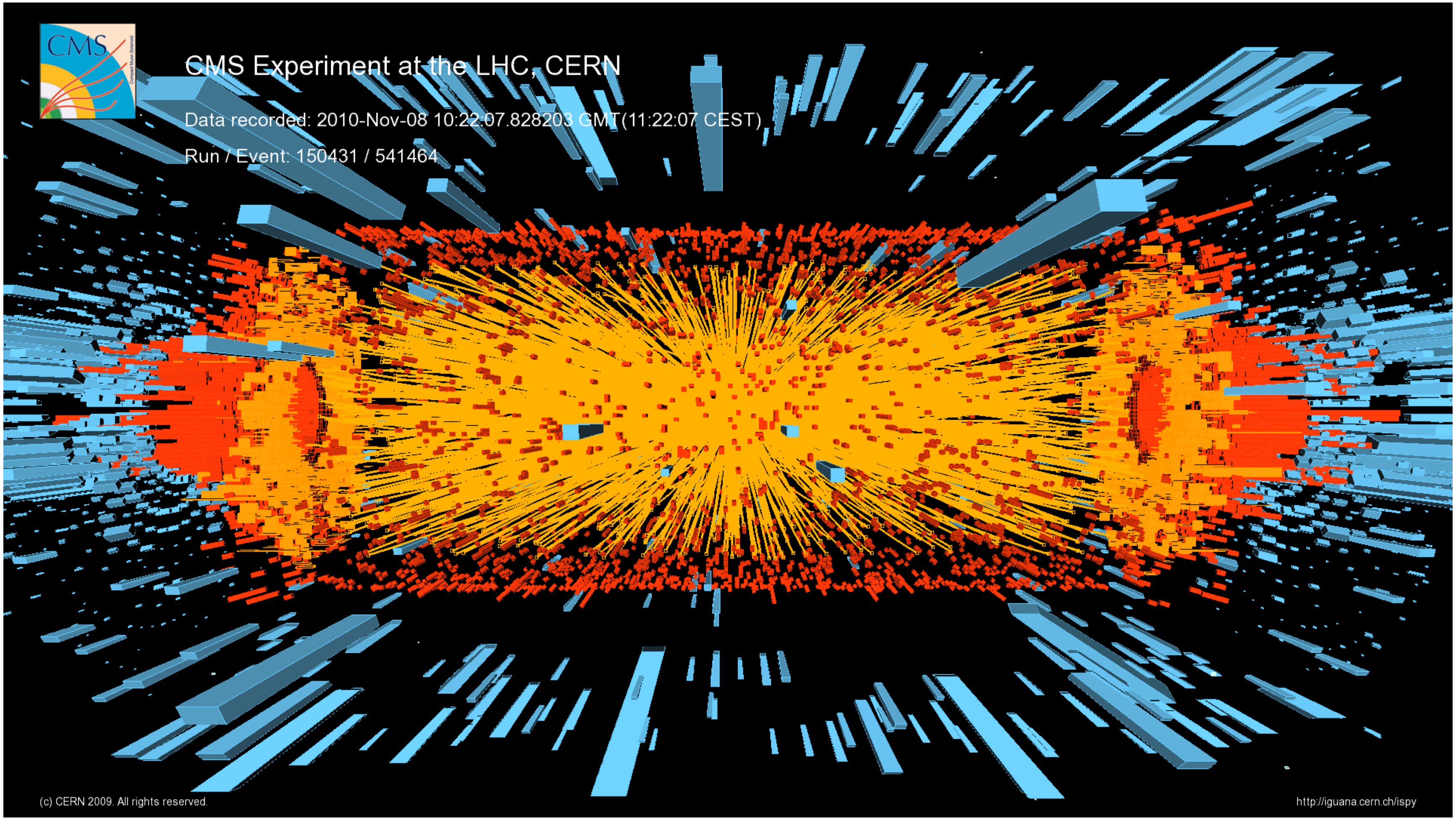


T. D. Lee, "A possible new form of matter", AIP Conf.Proc. 28 (1976) 65-81

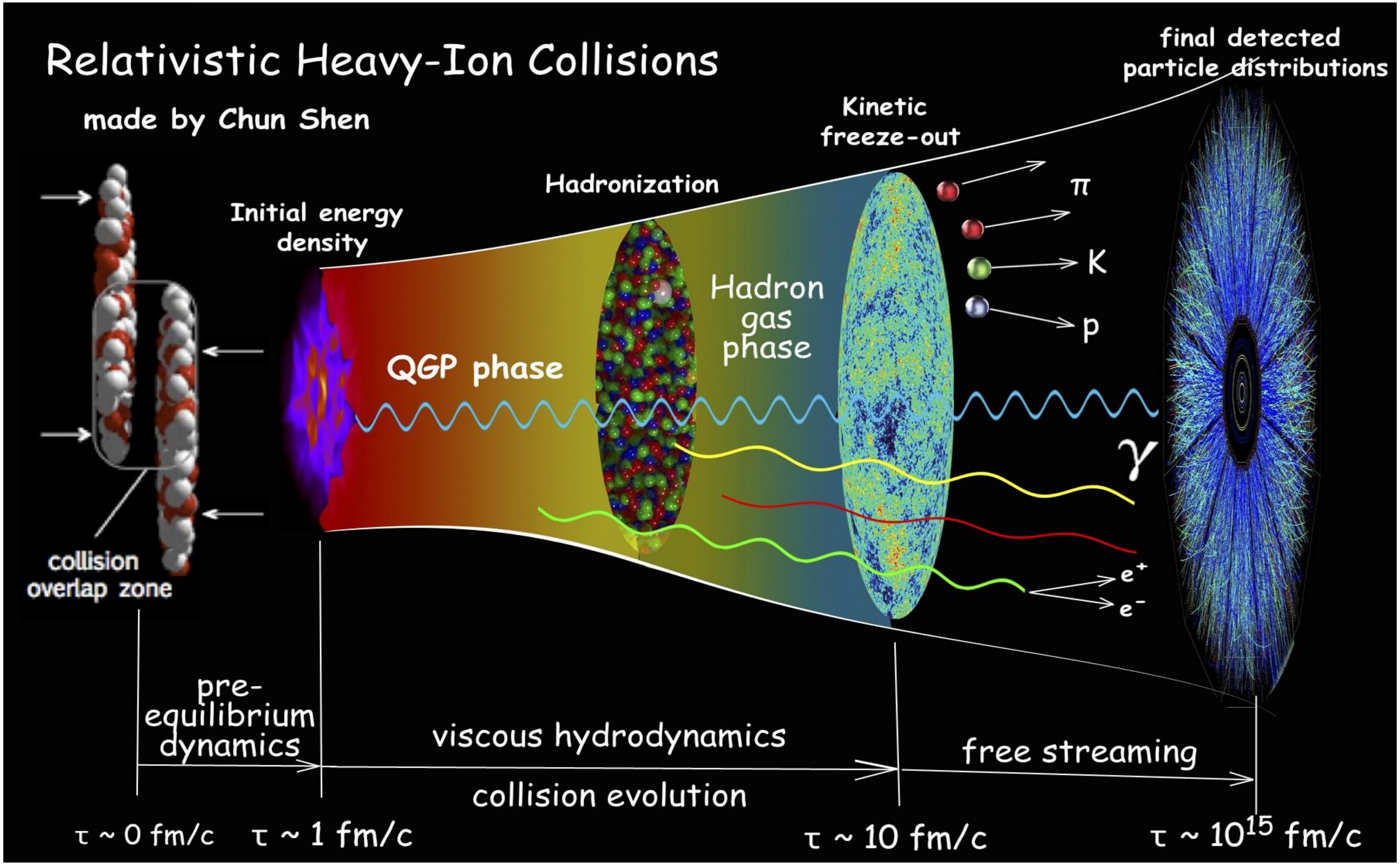
Relativistic Heavy-Ion Collider（RHIC）

Large Hadron Collider（LHC）

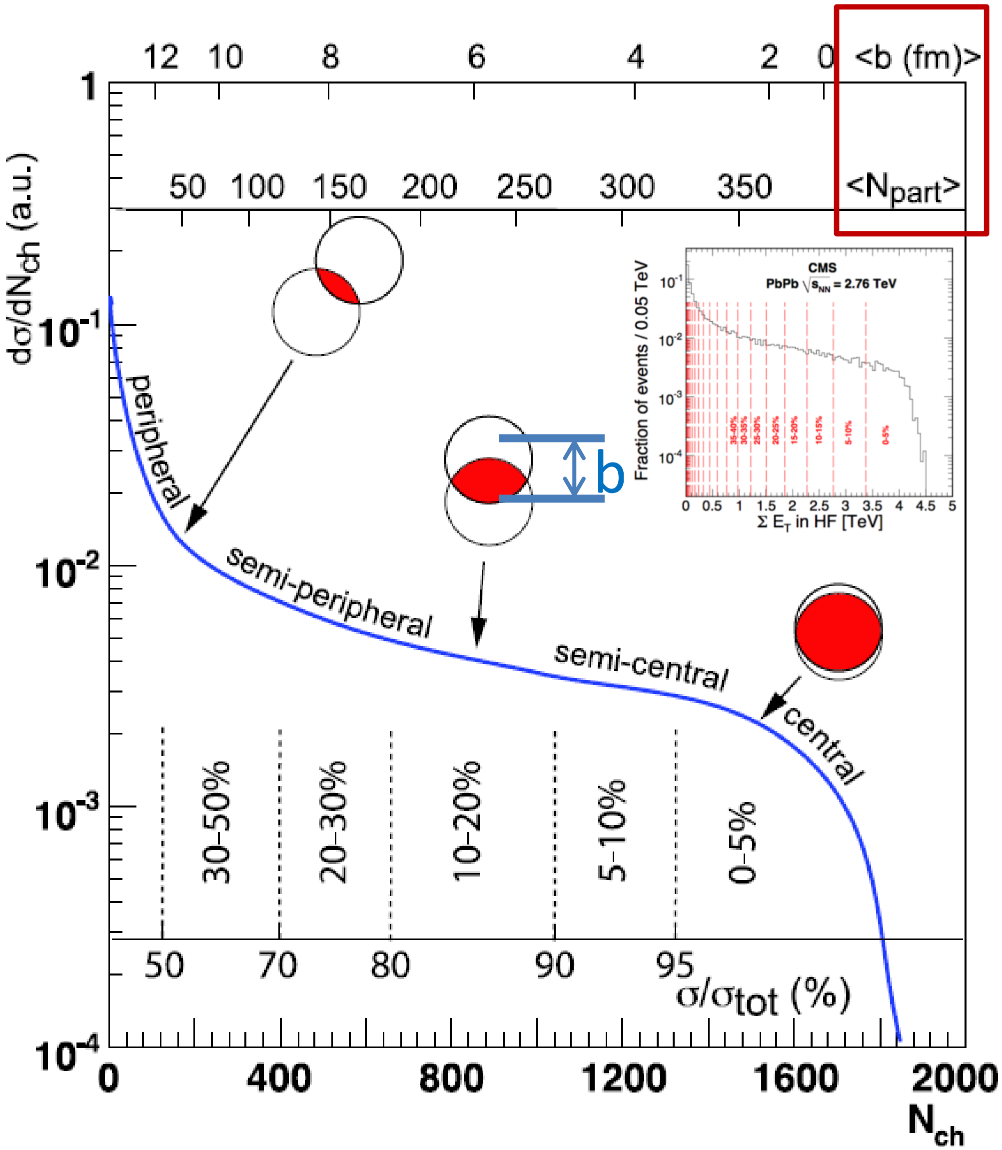
A relativistic-heavy ion collision

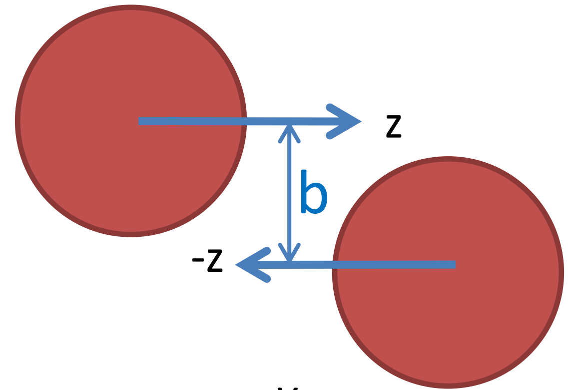


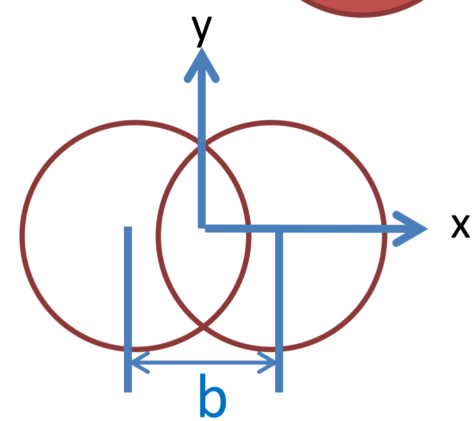
“Standard Model” of RHIC & LHC heavy-ion collisions



Collision centrality

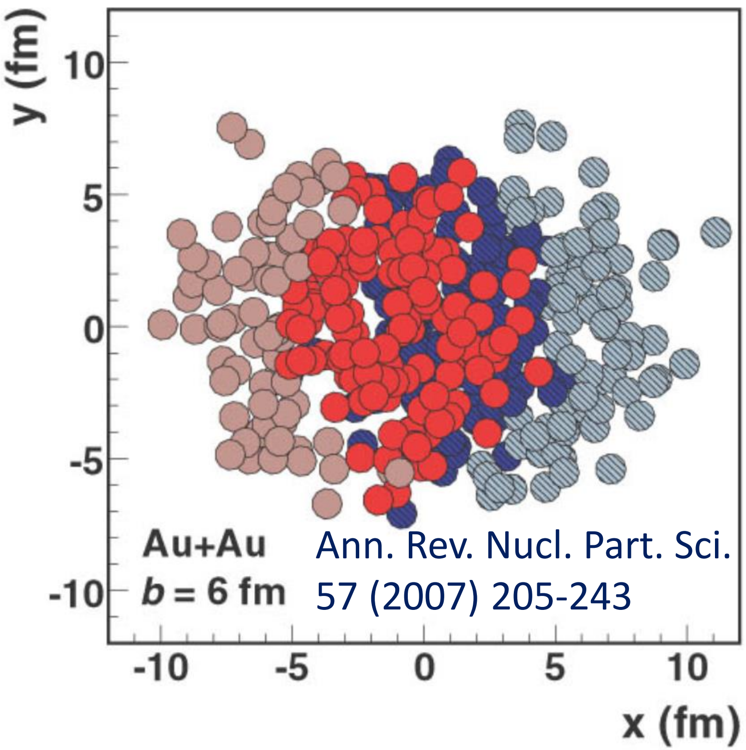


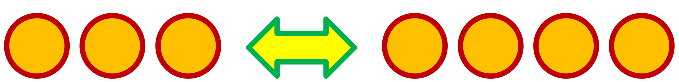




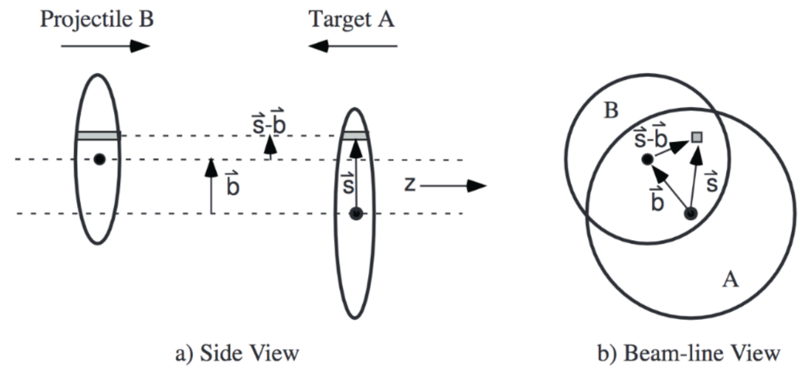
Miller, Reygers, Sanders, Steinberg, Ann. Rev. Nucl. Part. Sci. 57 (2007) 205-243

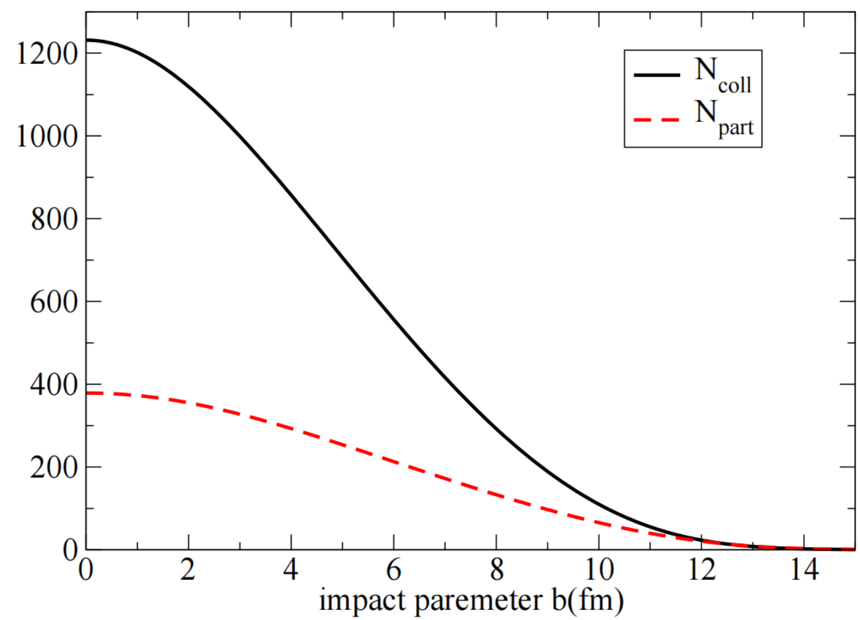
Glauber model: N_{part} and N_{coll}



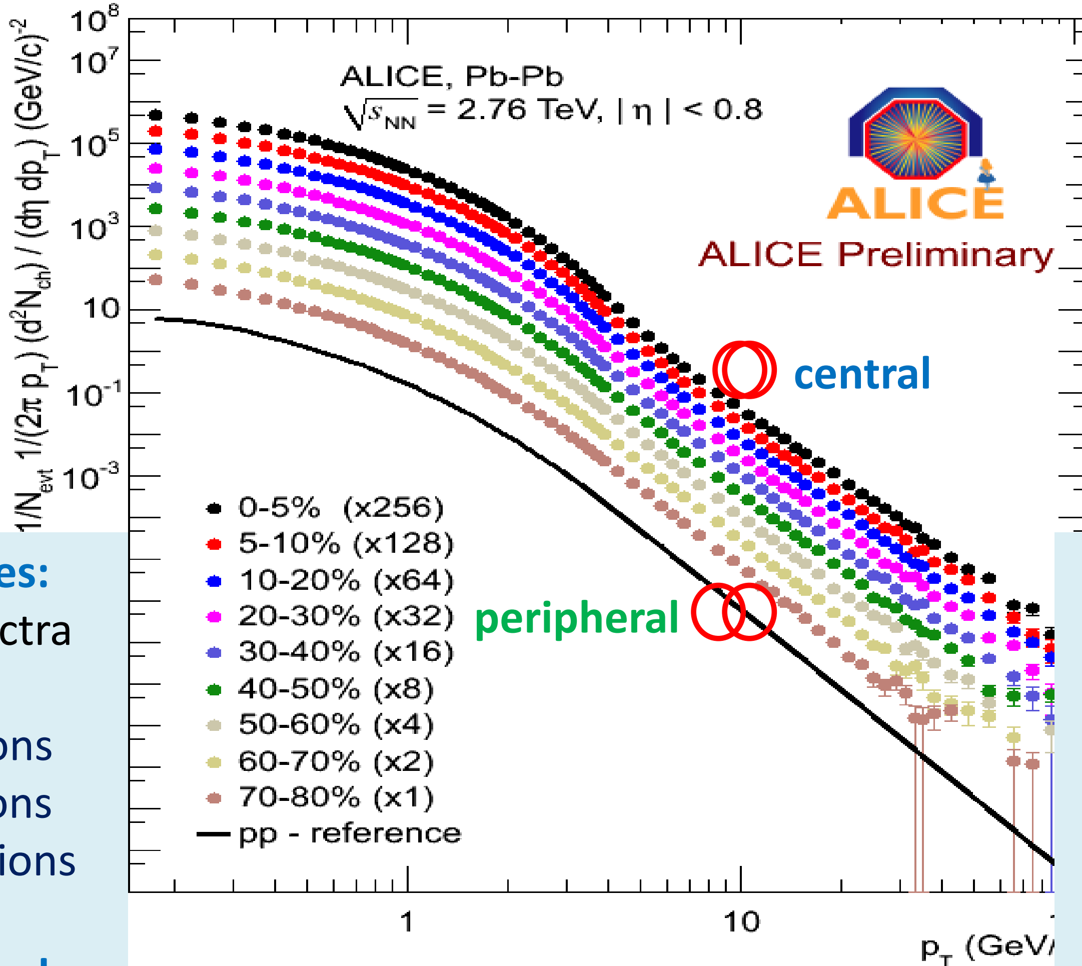


$$N_{part} = 7, N_{coll} = 12$$





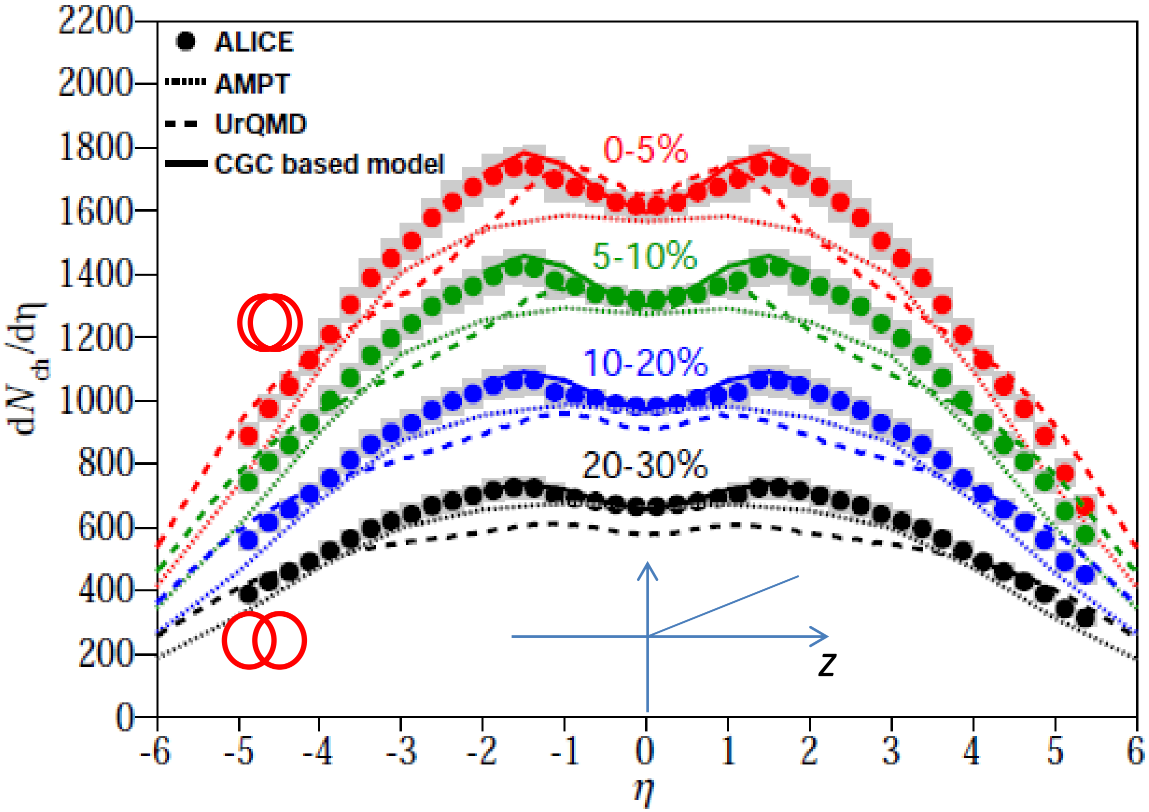
Probes of QGP in heavy-ion collisions



Soft Probes:
Yields/Spectra
Flows
Fluctuations
Correlations
Decorrelations
…
"Internal" probes

Hard Probes:
Jets
Large p_T hadrons
Heavy quark/hadrons
Quarkonia
EM probes
…
"External" probes

Particle distribution in longitudinal direction



$$\eta = \frac{1}{2}\ln\left(\frac{p+p_z}{p-p_z}\right) = -\ln\left(\tanh\frac{\theta}{2}\right)$$

$$LHC : \frac{dN_{ch}}{d\eta} = 1600$$

$$RHIC : \frac{dN_{ch}}{d\eta} = 700$$

$$LHC : \varepsilon_0 = 16GeV / fm^3$$

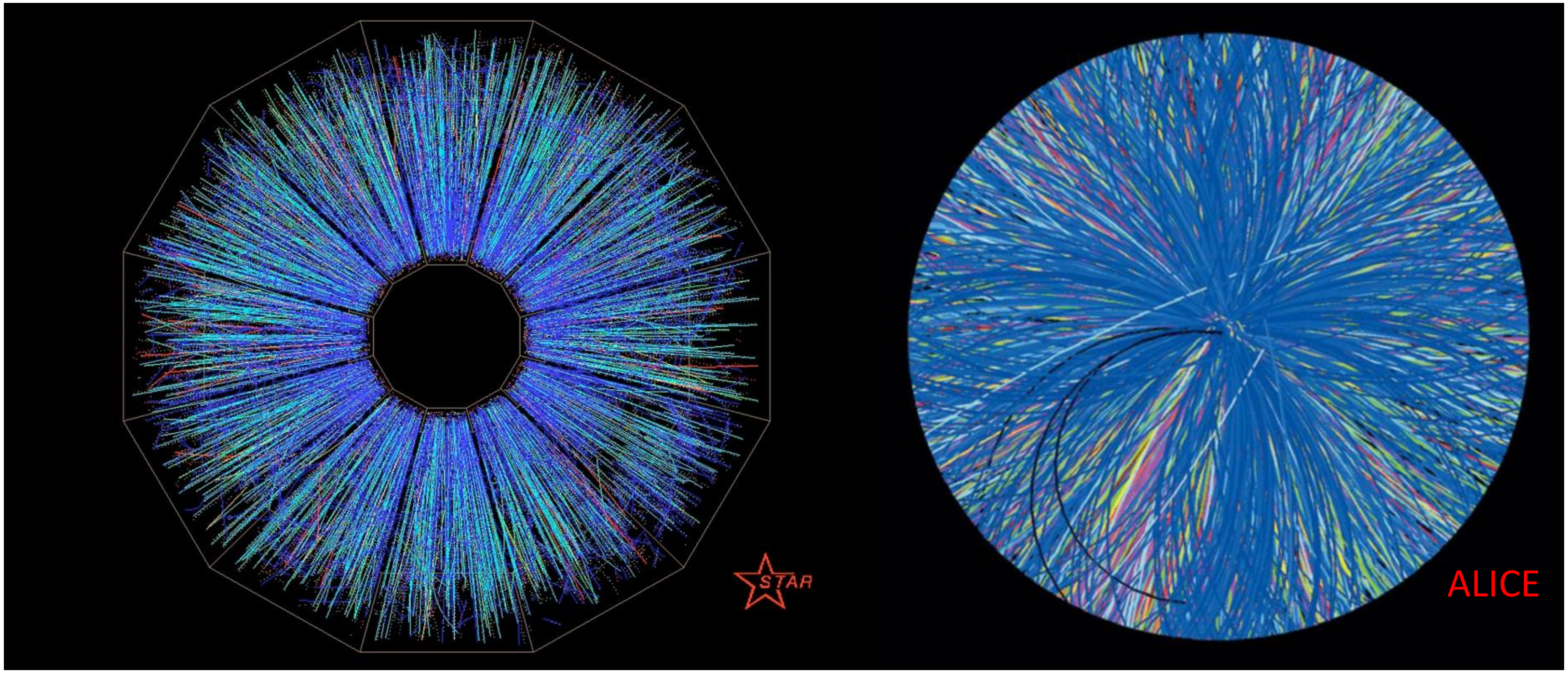
$$RHIC : \varepsilon_0 = 7GeV / fm^3$$

$$\varepsilon_0 = \frac{dE_T}{d\eta}\frac{1}{\tau_0 \pi R^2} = \frac{3}{2}\left\langle\frac{E_T}{N}\right\rangle\frac{dN_{ch}}{d\eta}\frac{1}{\tau_0 \pi R^2}$$

$$T_c = 155MeV$$

$$\varepsilon_c = 0.5GeV / fm^3$$

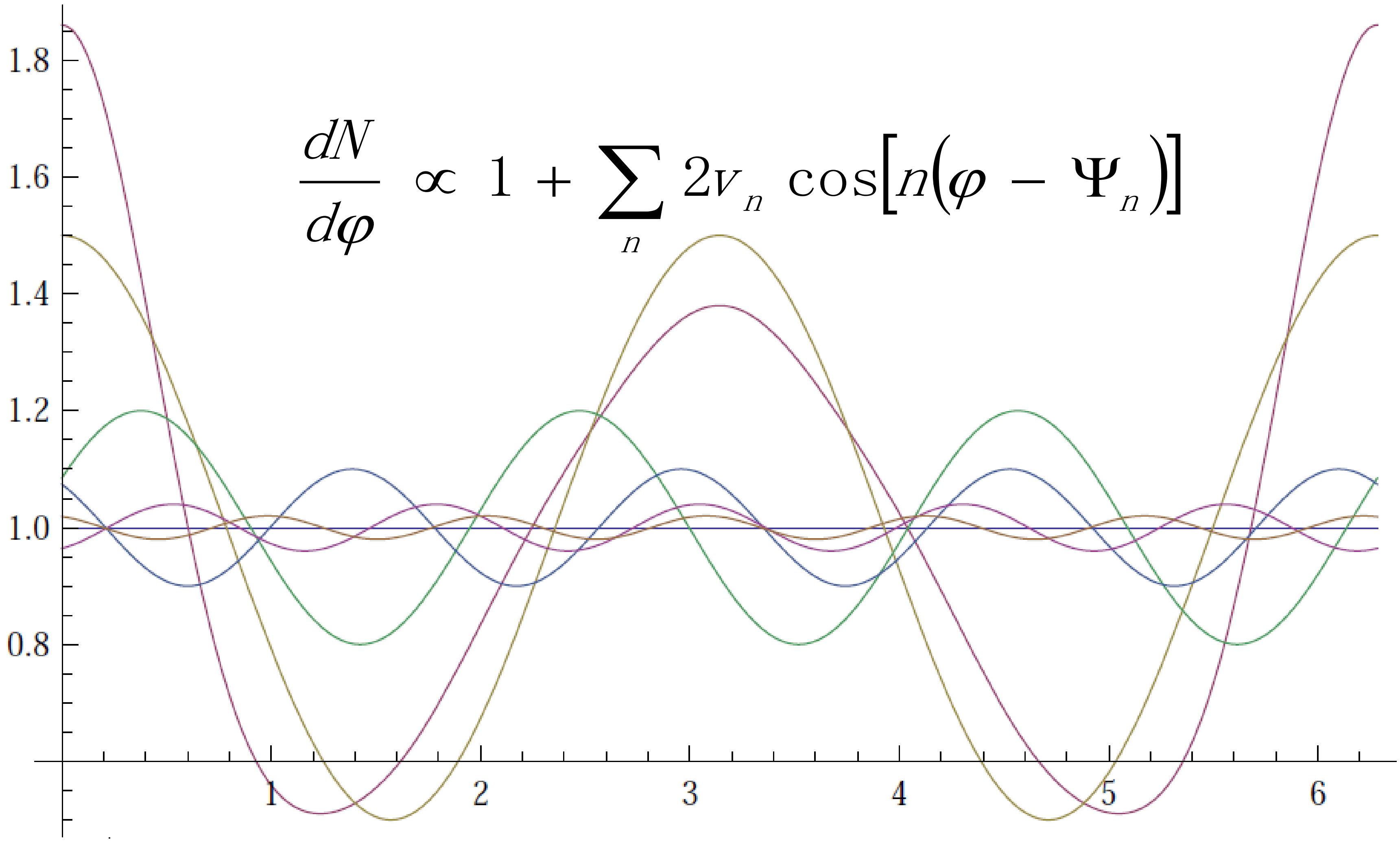
Particle distribution in transverse plane



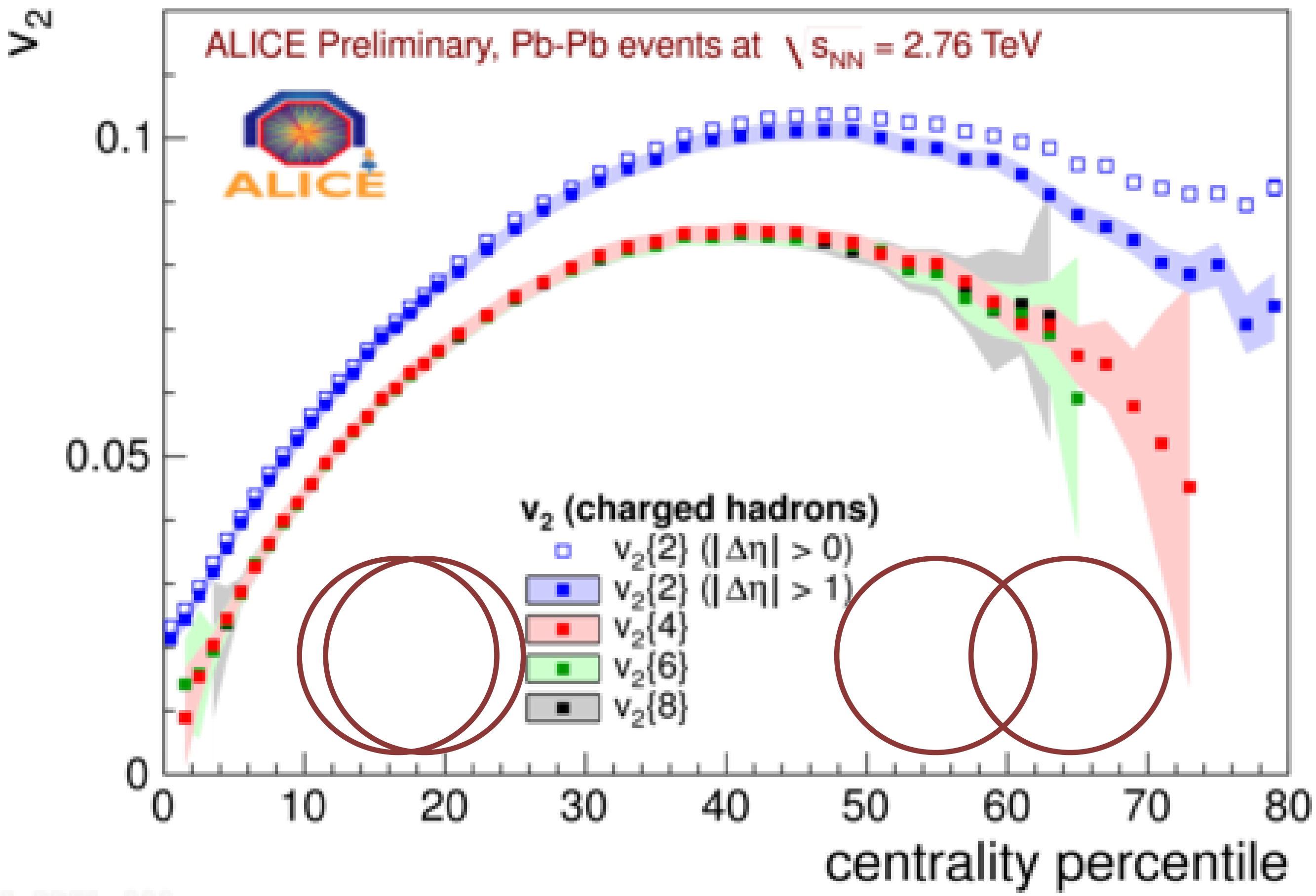
Particle production is not azimuthally symmetric.
The azimuthal anisotropy can be analyzed by Fourier decomposition:

$$\frac{dN}{d\varphi} \propto 1 + \sum_n 2v_n \cos\left[n\left(\varphi - \Psi_n\right)\right]$$

Anisotropy: Fourier decomposition

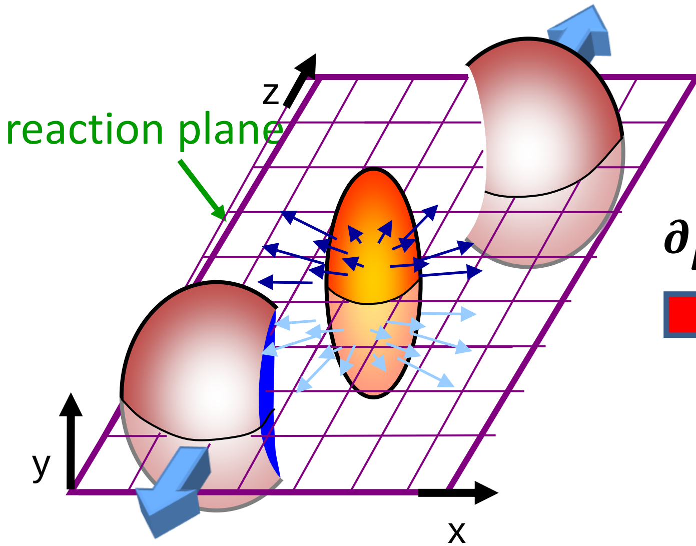


Elliptic flow depends on collision geometry

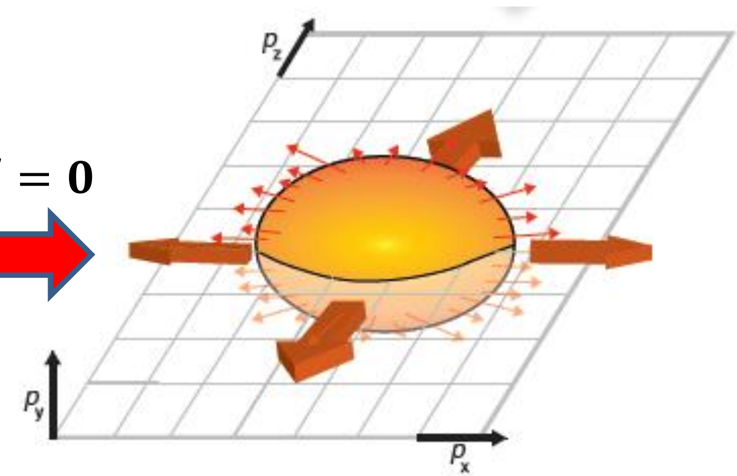


Strong elliptic flow depends on collision centrality (system size & geometry)

The origin of elliptic flow



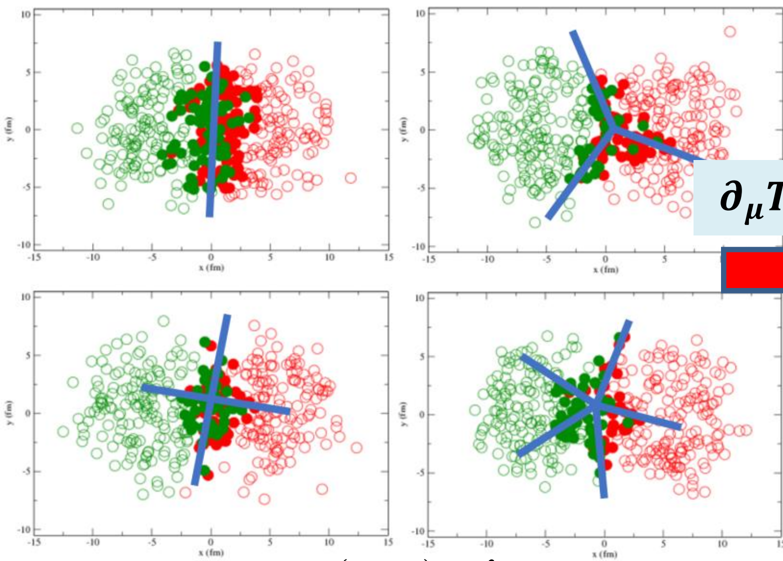
$$\partial_\mu T^{\mu\nu} = 0$$



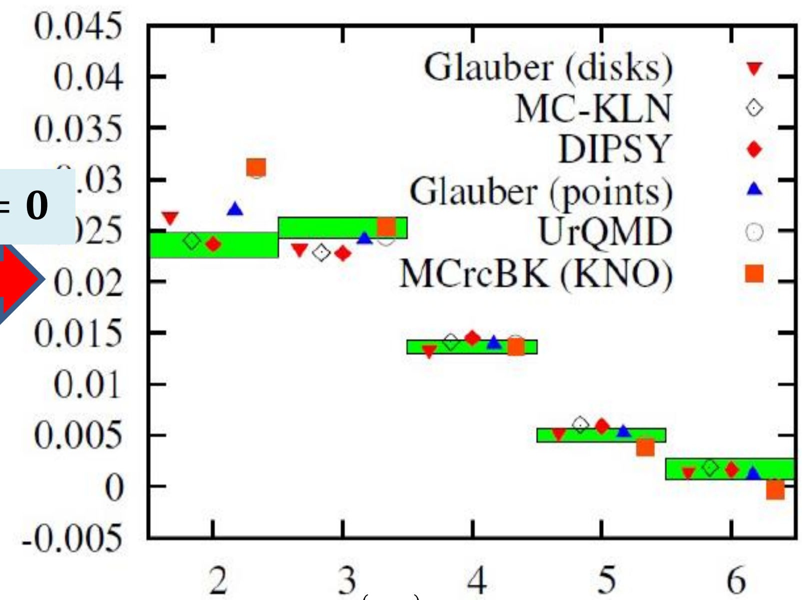
eccentricity $\varepsilon_2 = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$ elliptic flow $v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$

Relativistic hydrodynamics: the interaction among QGP constituents translates initial geometric anisotropy into final state momentum anisotropy.
=> QGP is a strongly-coupled fluid

Initial-state fluctuations and final-state flows



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



$$\vec{\varepsilon}_n = \varepsilon_n e^{in\Phi_n} = \frac{\{r^m e^{in\phi}\}}{\{r^m\}} = \frac{\int d^2 r_\perp \rho(r_\perp) r^m e^{in\phi}}{\int d^2 r_\perp \rho(r_\perp) r^m}$$

$$\vec{V}_n = v_n e^{in\Psi_n} = \{e^{in\varphi}\}$$

Event-by-event initial state density and geometry fluctuations are translated into final state anisotropic flows via hydrodynamic evolution.

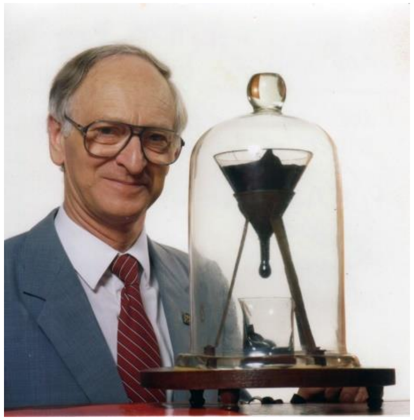
$$\frac{dN}{p_T dp_T dy d\phi} = \frac{dN}{2\pi p_T dp_T dy}\left(1 + \sum_n 2v_n(p_T, y)\cos\{n[\phi - \Psi_n(p_T, y)]\}\right)$$

Alver and Roland, PRC 2010; GYQ, Petersen, Bass, Muller, PRC 2010; Staig, Shuryak, PRC 2011; Teaney, Yan, PRC 2011; Gale, Jeon, Schenke, Tribedy, Venugopalan, PRL 2012; etc.

Fluidity

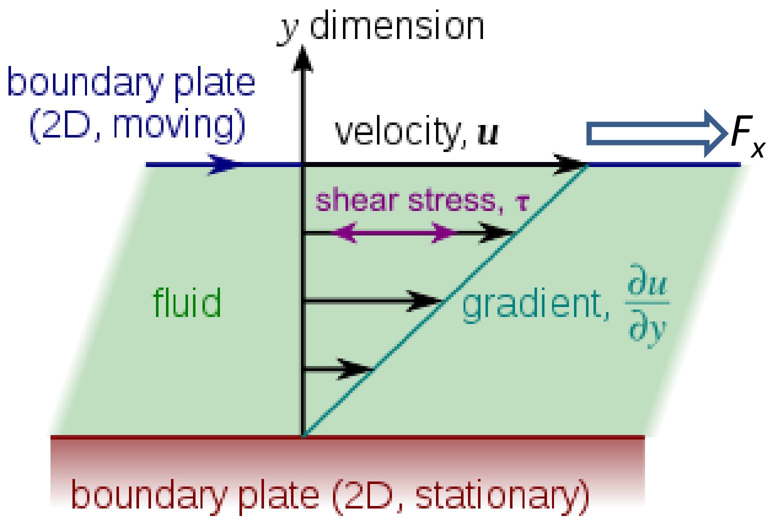




How the fluid flows depends on its viscosity.

Shear viscosity



$$\frac{F_x}{A_y} = \eta \frac{\partial u_x}{\partial y}$$

Shear viscosity measures the resistance to shear flow.
Shear viscosity measures the ability of momentum transport between different parts of the system.
From kinetic theory, shear viscosity is related to the strength of the interactions among the constituents of the system.

$$\eta \approx \frac{1}{3} n\lambda\overline{p}$$

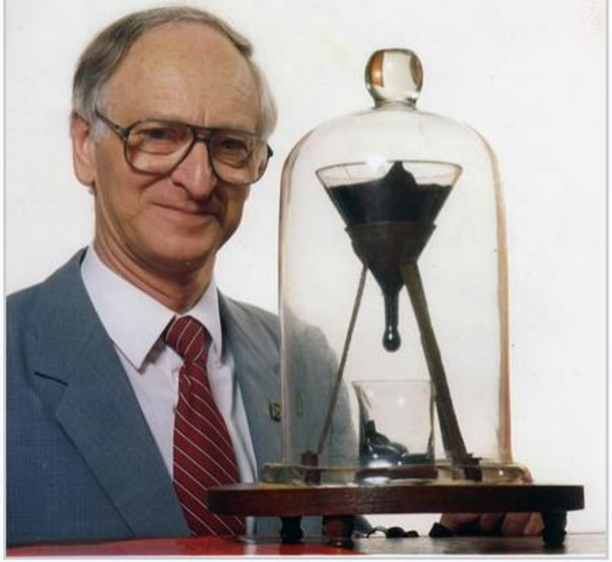
Viscosities of some fluids

Fluid	viscosity（Pa*s）
Air	$1.8*10^{-5}$
Water	$8.9*10^{-4}$
Milk	$1.8*10^{-3}$
Olive Oil	0.04
Honey	10
Peanut Butter	250
Pitch	$2*10^{8}$
Quark-Gluon Plasma	???

Pitch Drop Experiment

Time	Event	Duration (Year)
1927	Hot pitch poured	
1930.10	Stem cut	
1938.12	1st drop fell	8.1
1947.2	2nd drop fell	8.2
1954.4	3rd drop fell	7.2
1962.5	4th drop fell	8.1
1970.8	5th drop fell	8.3
1979.4	6th drop fell	8.7
1988.7	7th drop fell	9.2
2000.11	8th drop fell	12.3
2014.4	9th drop fell	13.4

2005 Ig Nobel Prize



The University of Queensland pitch drop experiment, featuring its then-current custodian, Professor John Mainstone (taken in 1990, two years after the seventh drop and 10 years before the eighth drop fell).

Edgeworth, Dalton, Parnell, Eur. J. Phys. (1984) 198.

Guinness World Record
for the longest-running laboratory experiment

Relativistic hydrodynamics for QGP evolution

- Energy-momentum conservation:

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

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

- Equations of motion (Israel-Stewart viscous hydrodynamics):

$$\dot{\varepsilon} = -(\varepsilon + P + \Pi)\theta + \pi^{\mu\nu}\sigma_{\mu\nu}$$

$$(\varepsilon + P + \Pi)\dot{U}^\alpha = \nabla^\alpha(P + \Pi) + \dot{U}_\mu \pi^{\mu\nu} - \Delta^\alpha_\nu \nabla_\mu \pi^{\mu\nu}$$

$$\dot{\Pi} = -\frac{1}{\tau_\Pi}\left[\Pi + \zeta\theta + \Pi\zeta T \partial_\alpha\left(\frac{\tau_\Pi}{2\zeta T} U^\alpha\right)\right]$$

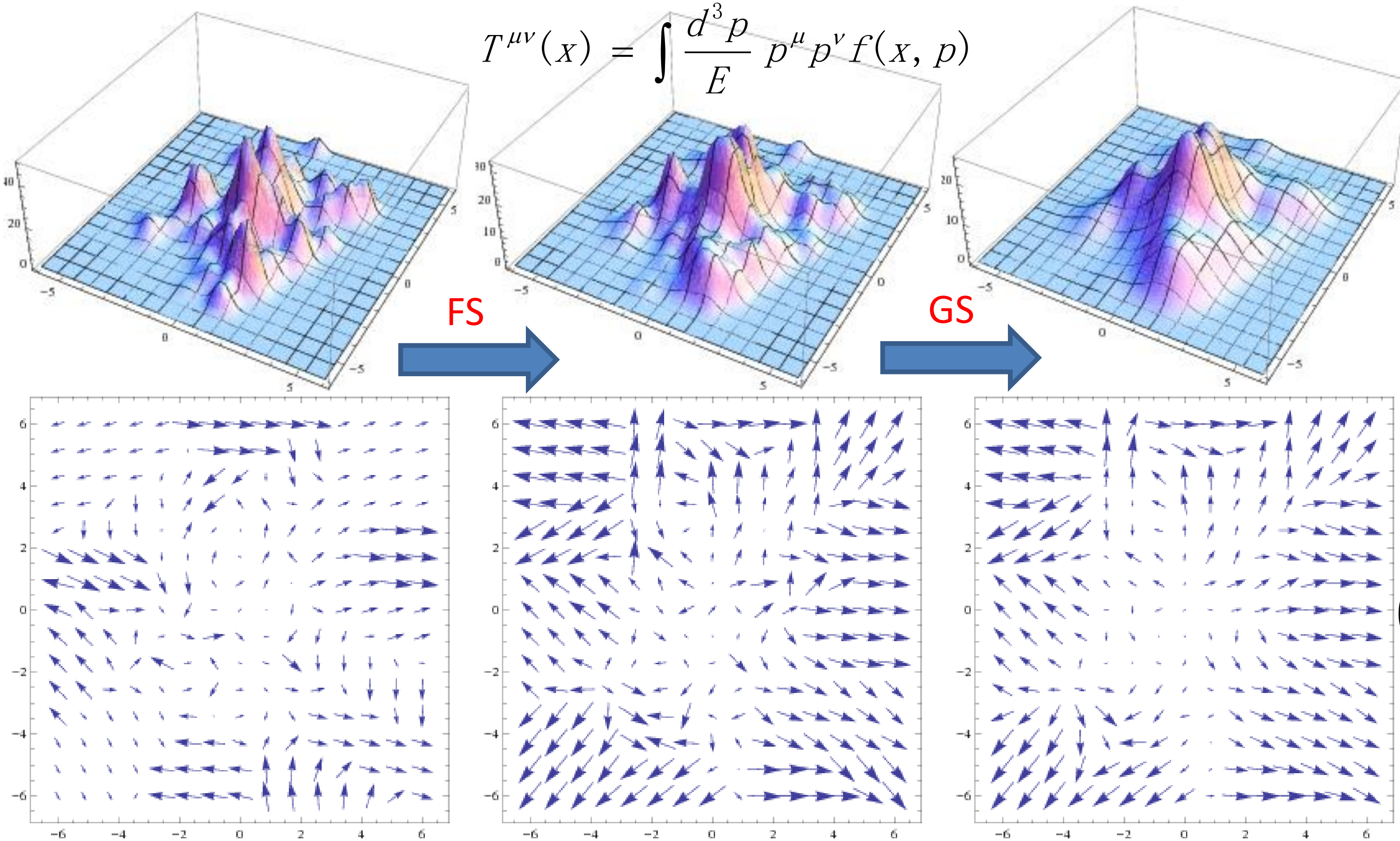
$$\Delta^{\mu\nu}_{\alpha\beta}\dot{\pi}^{\alpha\beta} = -\frac{1}{\tau_\pi}\left[\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu} + \pi^{\mu\nu}\eta T \partial_\alpha\left(\frac{\tau_\pi}{2\eta T} U^\alpha\right)\right]$$

- Equation of state: $P = P(\varepsilon)$

arXiv:0902.3663; arXiv:1301.2826; arXiv:1301.5893; arXiv:1311.1849; arXiv:1401.0079…

Initial conditions before hydro

$$T^{\mu\nu}(x) = \int \frac{d^3p}{E} p^\mu p^\nu f(x, p)$$



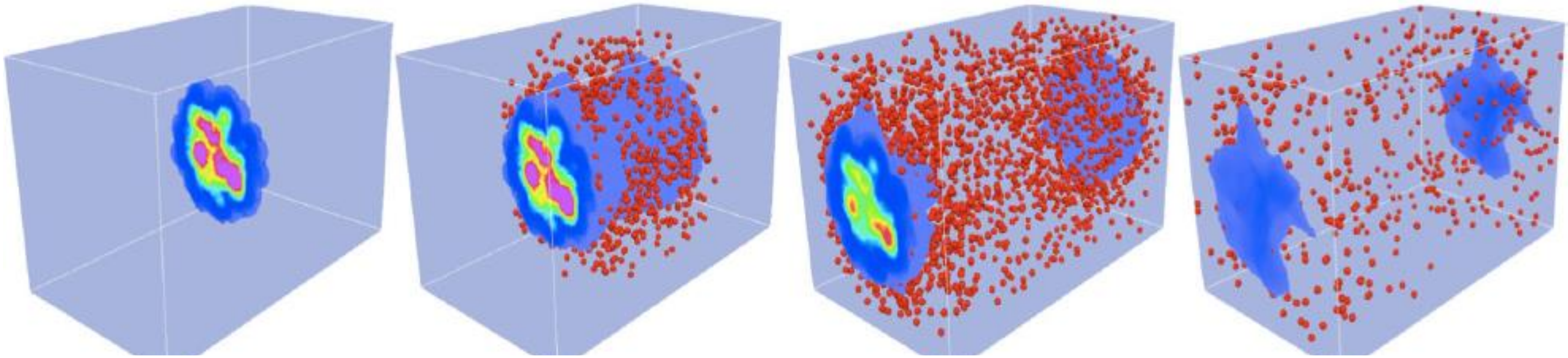
T^{00}

(T^{0x}, T^{0y})

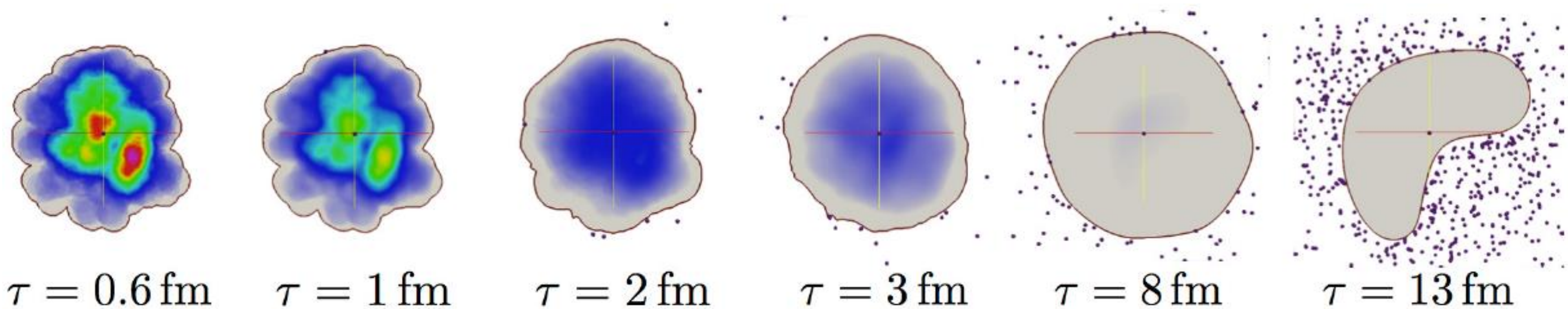
t_0=0, σ_{xy}=0.3fm   **t_0=0.6fm/c, σ_{xy}=0.3fm**   **t_0=0.6fm/c, σ_{xy}=0.5fm**   **b=8fm**

GYQ, Petersen, Bass, Muller, PRC, 2010

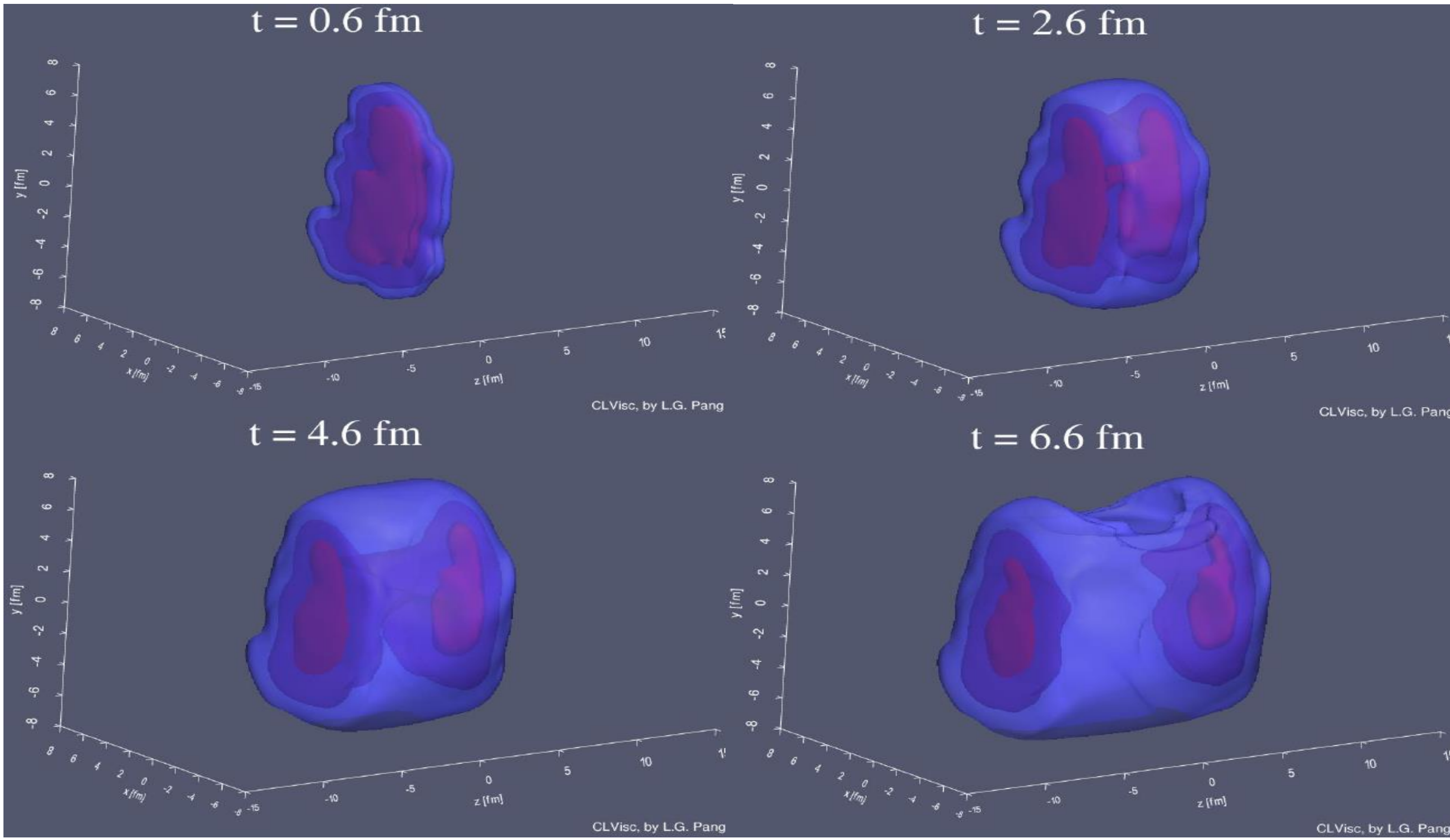
Hydrodynamic evolution of QGP



The color patches are the QGP, and the balls are the final hadrons emitted from the QGP
(from Zhi Qiu's Ph.D. thesis, arXiv:1308.2182)

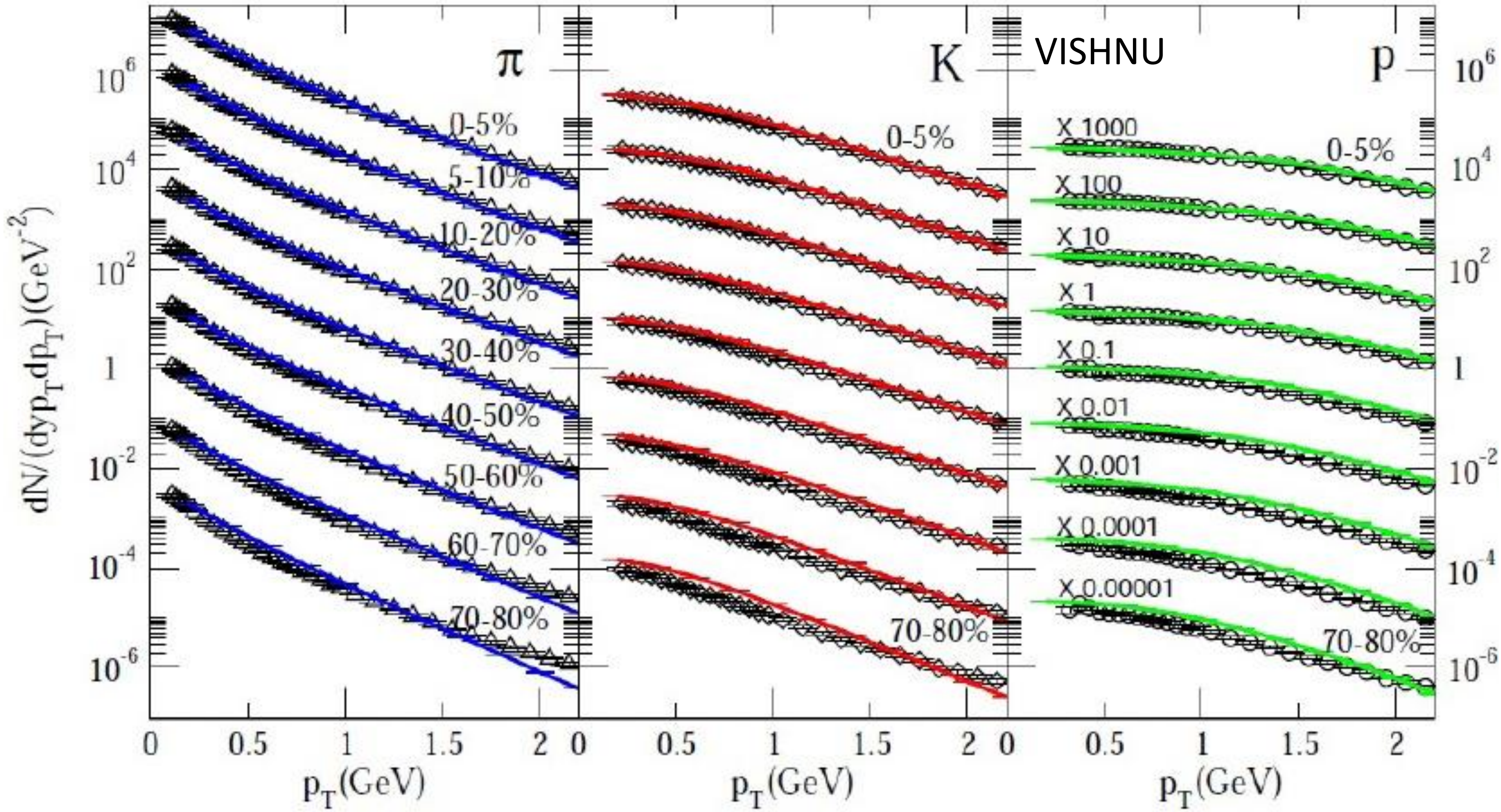


Hydrodynamic evolution of QGP



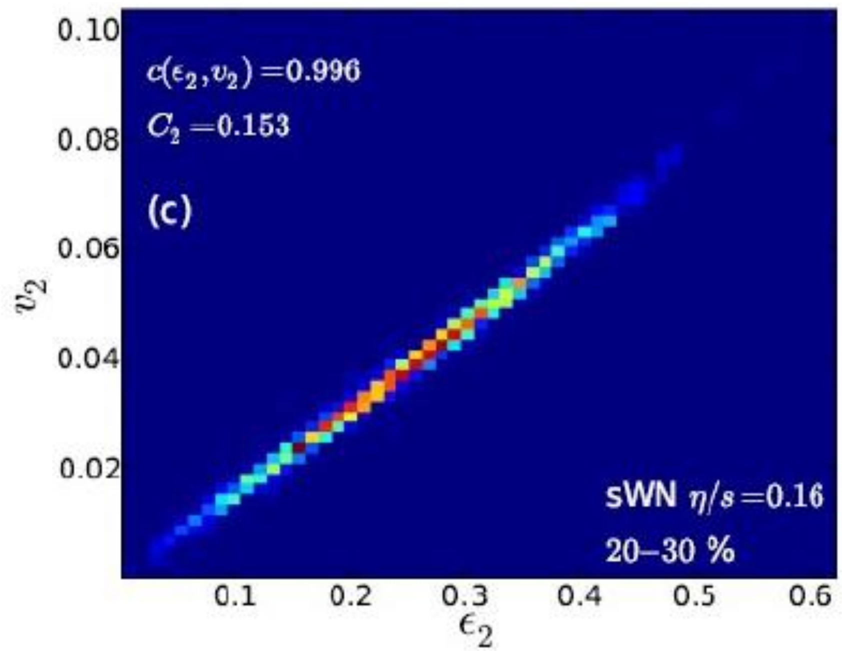
CCNU-LBNL viscous hydrodynamics (CLVisc) simulation, courtesy of L. G. Pang

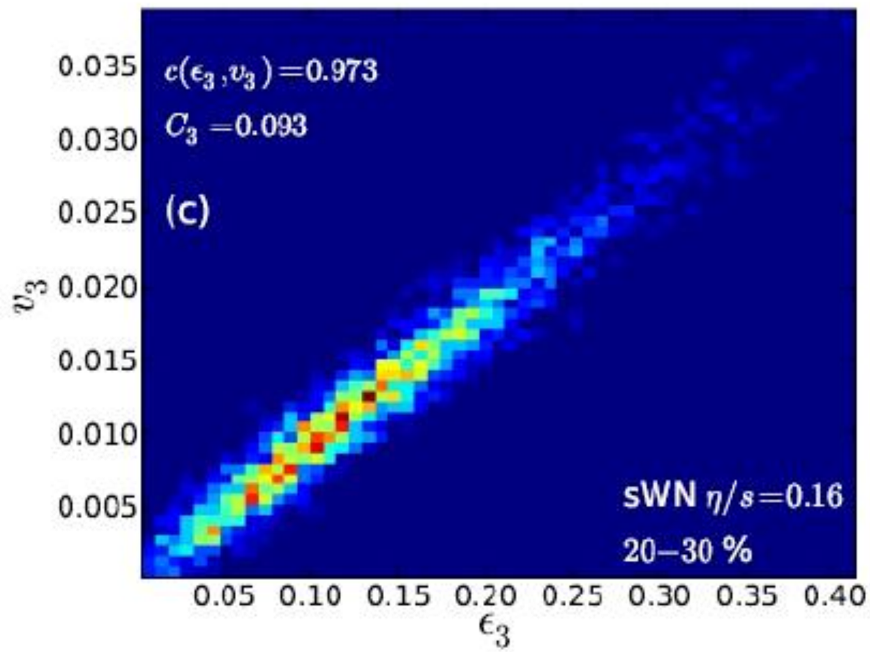
Identified particle spectra



Song, Bass, Heinz, PRC 2014

Hydrodynamic response to initial geometry



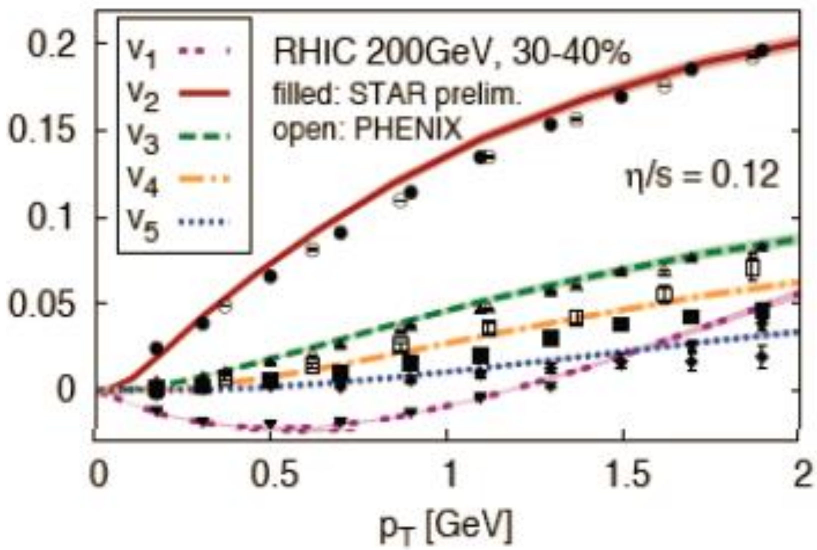


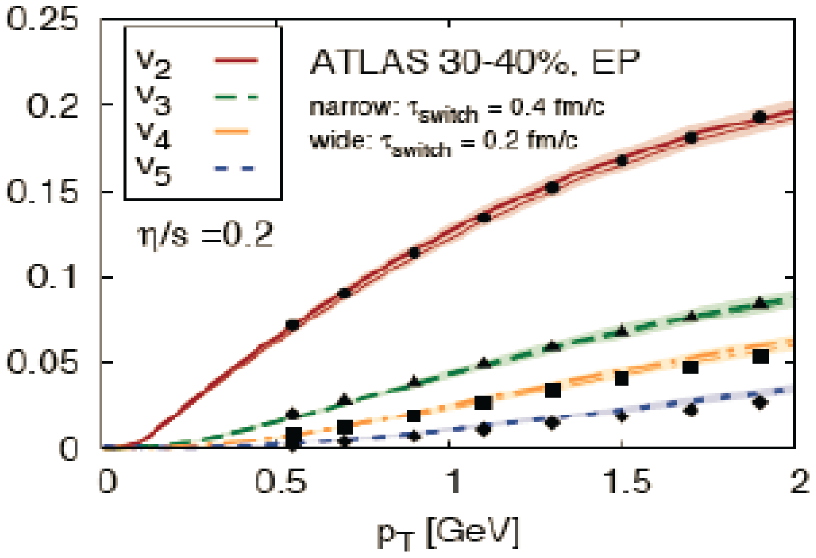
Final state v_2 and v_3 respond approximately linearly to initial state e_2 and e_3, except peripheral collisions

Higher-order harmonic flows can be contributed from the combinations of initial eccentricities and lower order harmonic flows (non-linear hydrodynamic evolution)

Qiu, Heinz, PRC, 2011, Gardim, Grassi, Luzum, Ollitrault, PRC 2012, Niemi, Denicol, Holopainen, Huovinen, PRC 2013, Fu, PRC 2015, Niemi, Eskola, Paatelainen, PRC 2016, Noronha-Hostler, Yan, Gardim, Ollitrault, PRC 2016

Collective flow of QGP => T & η/s





Fluctuating IC + Hydrodynamics => Collective Flows and Correlations

Strong anisotropic flows => strongly-interacting QGP

$T_0 > T_c$ =155MeV => QGP is created: T_0 = 350MeV @RHIC & 470MeV @LHC

Small η/s => nearly-perfect QGP: η /s=0.12 @RHIC & 0.2 @LHC

$$\frac{dN}{p_T dp_T dy d\phi} = \frac{dN}{2\pi p_T dp_T dy}\left(1 + \sum_n 2v_n(p_T, y)\cos\{n[\phi - \Psi_n(p_T, y)]\}\right)$$

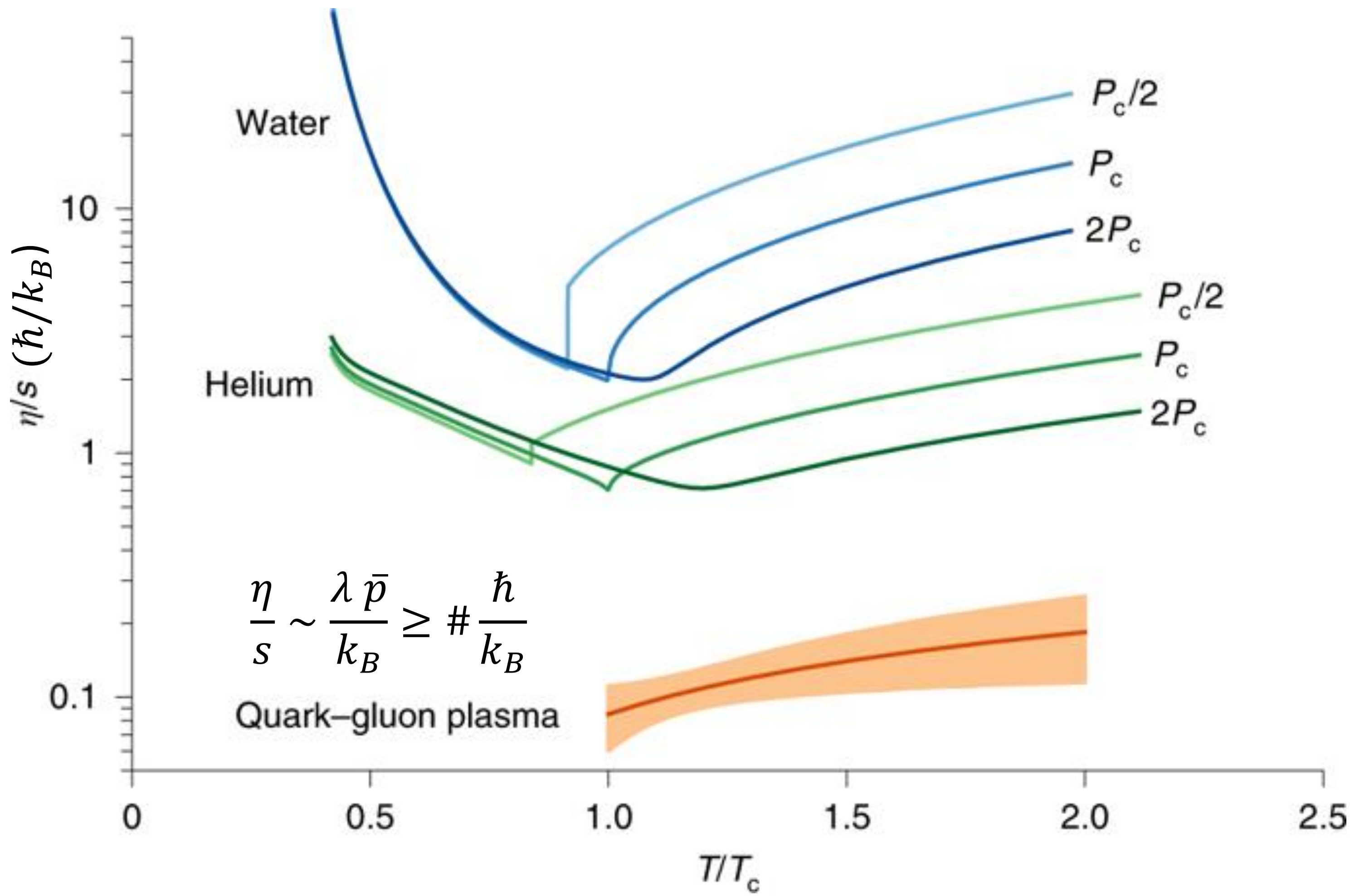
Gale, Jeon, Schenke, Tribedy, Venugopalan, PRL 2012

Highest Man-Made Temperatures: TWO Guinness World Records

- **Jun 26, 2012:**
  - **Highest Man-Made Temperature: 4 TRILLION Degrees (345MeV)!**
  - “**The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory** doesn't have anywhere near the name recognition of the Large Hadron Collider (LHC) at CERN. **But for the time being**, it can lay claim to its own impressive achievement: it's just been recognized by **Guinness World Records** for achieving the "Highest Manmade Temperature." **Go, RHIC!**
  - http://www.seeker.com/highest-man-made-temperature-4-trillion-degrees-1765840520.html

- **13 August 2012:**
  - Scientists at **CERN’s Large Hadron Collider**, Geneva, Switzerland, announced that they had achieved temperatures of over 5 trillion K and perhaps as high as **5.5 trillion K (350,000 times hotter than the center of the sun, 475MeV).** The team had been using the ALICE experiment to smash together lead ions at 99% of the speed of light to create a quark gluon plasma – an exotic state of matter believed to have filled the universe just after the Big Bang.
  - http://www.guinnessworldrecords.com/world-records/highest-man-made-temperature

Most perfect fluid



Bernhard, Moreland, Bass, Nature Physics 2019

Most perfect liquid

Brookhaven National Laboratory Newsroom Media & Communications Office

Newsroom Photos Videos Fact Sheets Lab History News Categories

Contact: Karen McNulty Walsh, (631) 344-8350, or Peter Genzer, (631) 344-3174

share:

RHIC Scientists Serve Up 'Perfect' Liquid

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

April 18, 2005

TAMPA, FL — The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) — a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory — say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

Collectivity!

Strongly-coupled!

Perfect liquid!

Brookhaven National Laboratory Newsroom Media & Communications Office

Newsroom Photos Videos Fact Sheets Lab History News Categories

By Karen McNulty Walsh

share:

RHIC's Perfect Liquid a Study in Perfection

Systematic analysis of particle flow in heavy ion experiments suggests that RHIC's shear viscosity is close to ideal limit

June 17, 2013

Home > News > Science & Astronomy

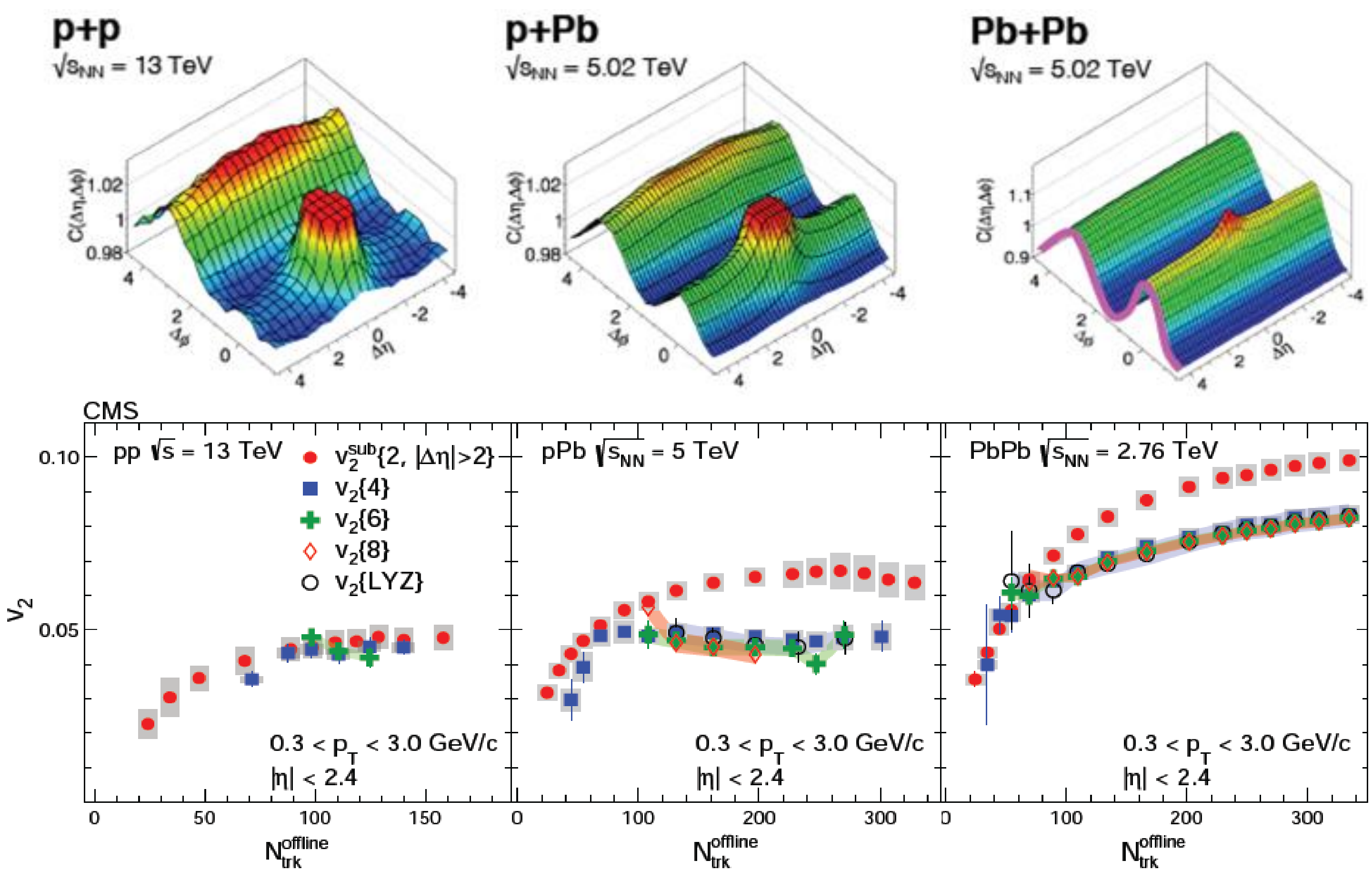
1st matter in the universe may have been a perfect liquid

By Mara Johnson-Groh published June 05, 2021

Scientists have recreated the first matter that appeared after the Big Bang in the Large Hadron Collider.

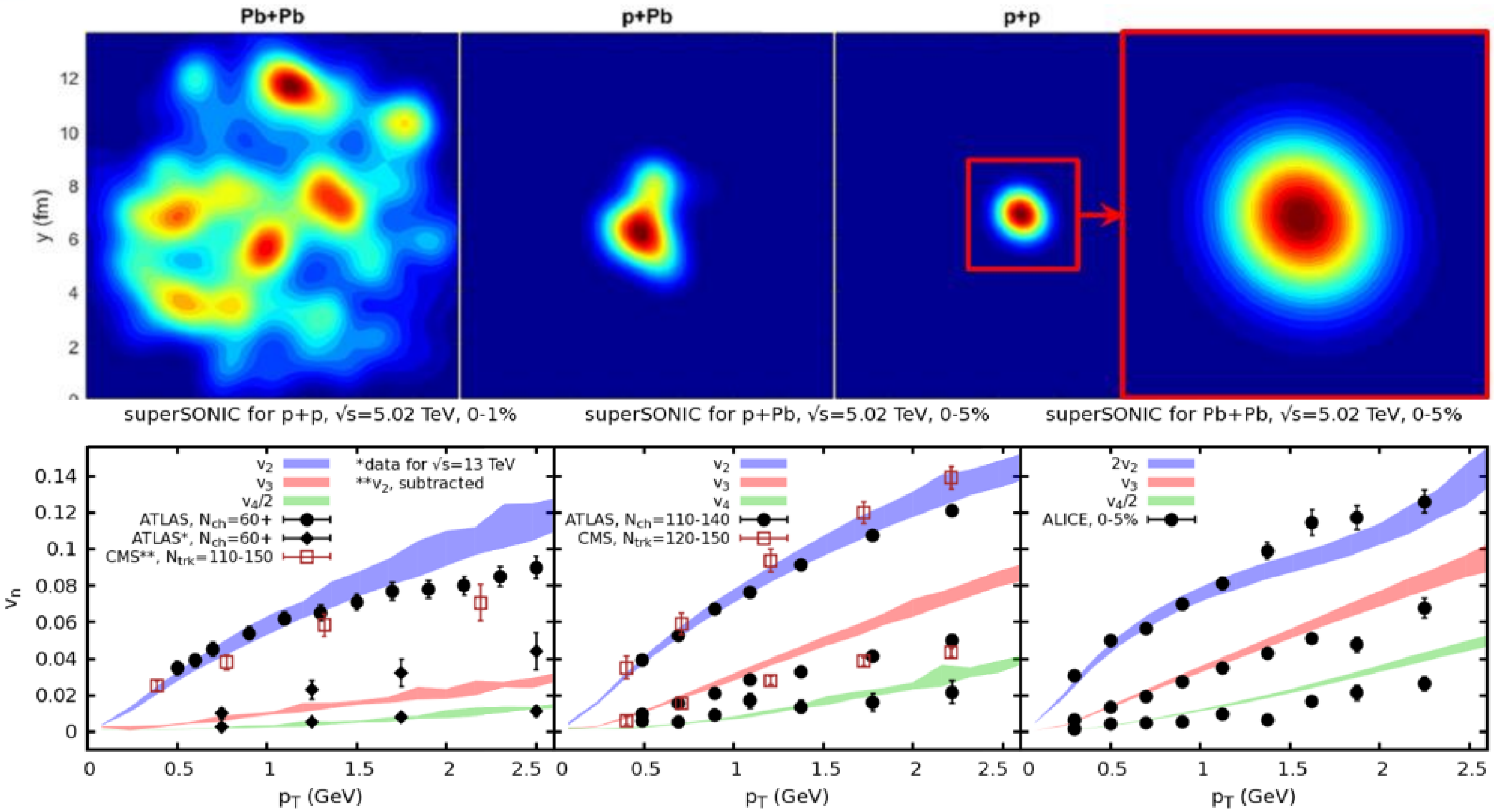
Flow in small system: mini-QGP?

Plenty of evidences for strong collectivity/correlations in small collision systems



What is the dynamical origin of the observed collectivity in small systems?

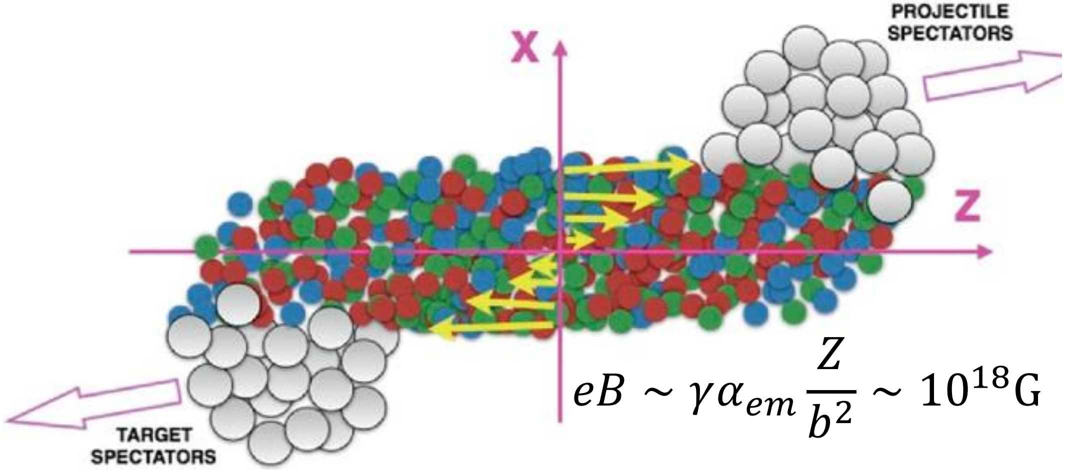
Flow in small system: mini-QGP?



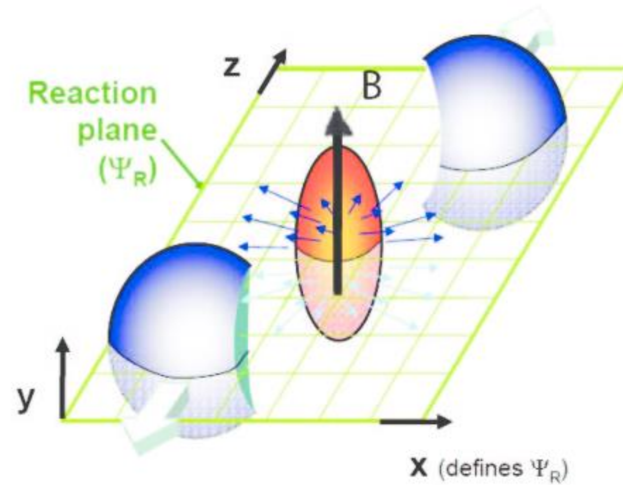
The flow harmonics can be viewed as the final-state effect due to hydrodynamic evolution of small collisional systems with certain amount of initial anisotropy.

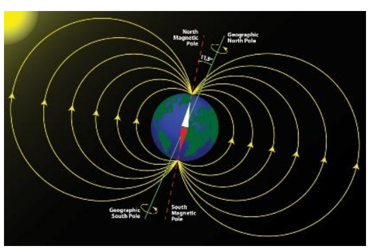
Bozek, Broniowski, Torrieri, PRL 2013; Bzdak, Schenke, Tribedy, Venugopalan, PRC 2013; GYQ, Muller, PRC 2014; Bzdak, Ma, PRL 2014; Weller, Romatschke, PLB 2017; Zhao, Zhou, Xu, Deng, Song, PLB 2018; Zhao, Ko, Liu, GYQ, Song, PRL 2020; etc.

Strongest magnetic field



$$eB \sim \gamma \alpha_{em} \frac{Z}{b^2} \sim 10^{18}\mathrm{G}$$

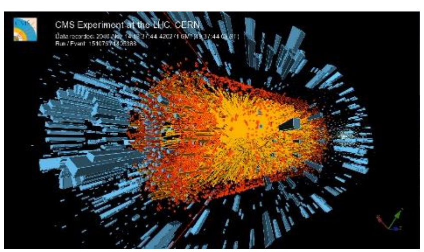




1G

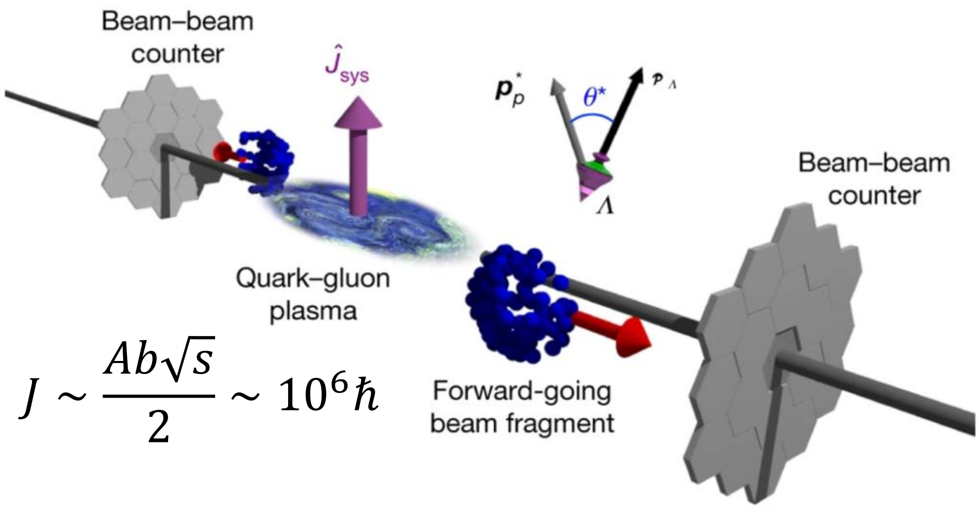
10^2-10^5G

10^{12}-10^{15}G

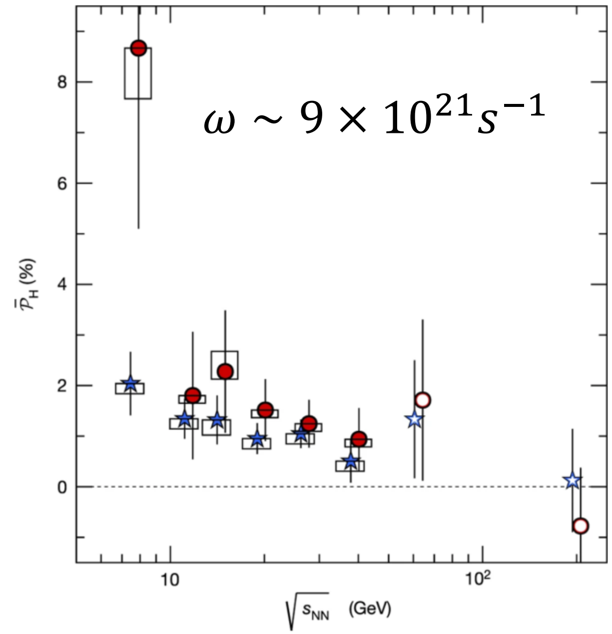


10^{18}-10^{20}G

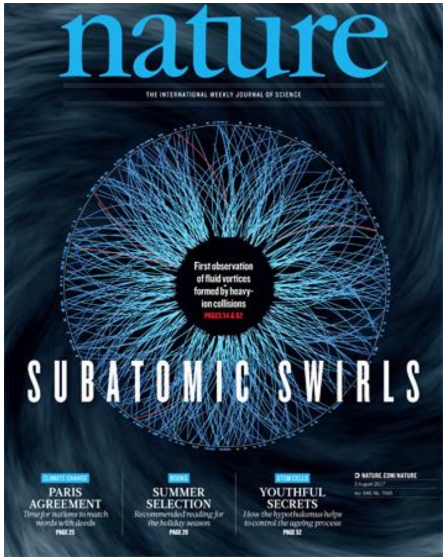
Most vortical fluid



$$J \sim \frac{Ab\sqrt{s}}{2} \sim 10^6 \hbar$$

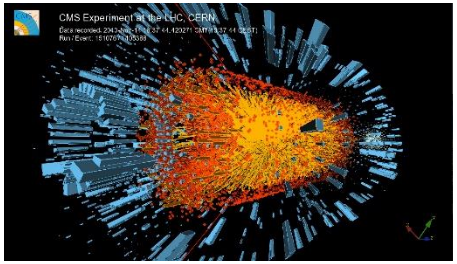


$$\omega \sim 9 \times 10^{21} s^{-1}$$



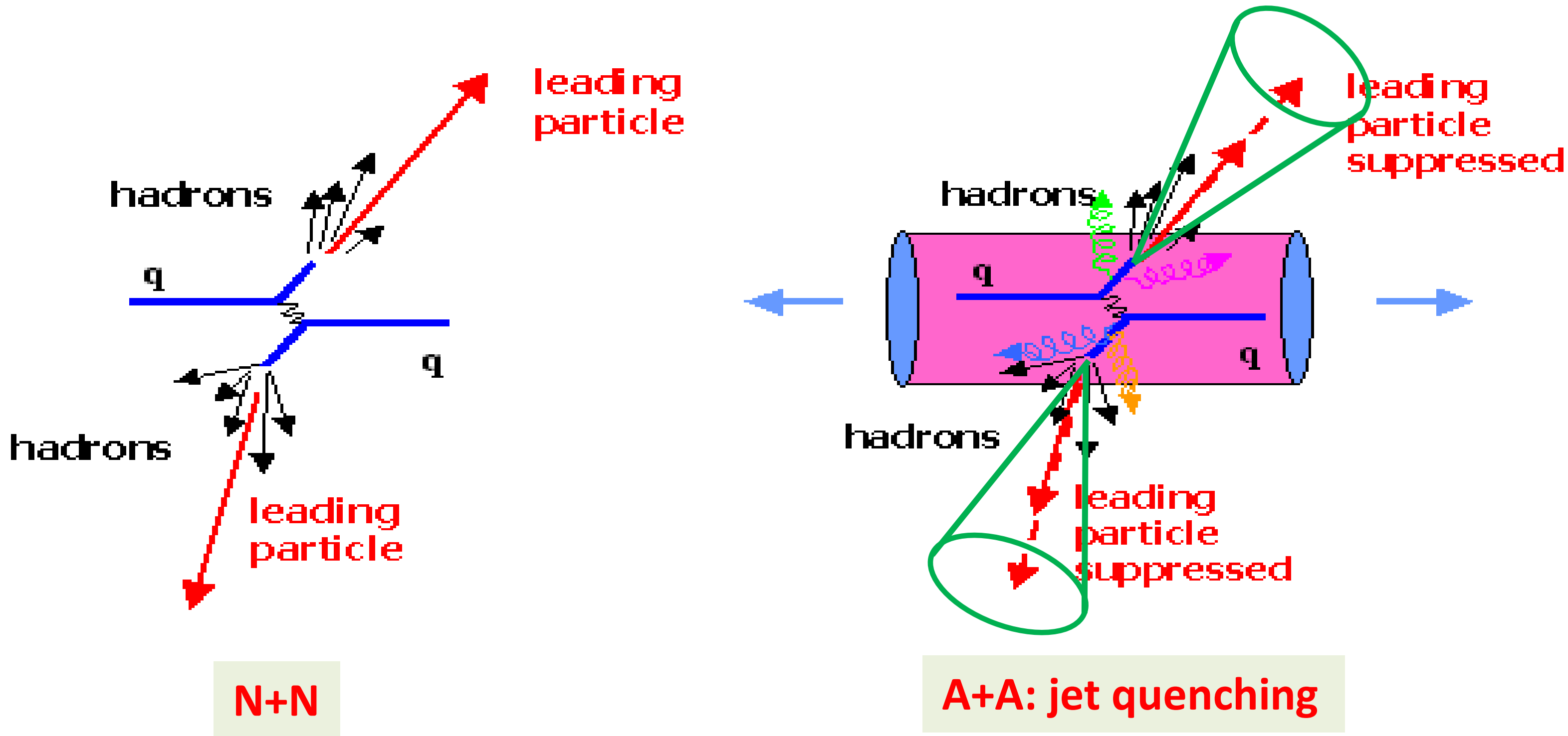
10^{-16}/s

10^{-2}-10^{2}/s



10^{20}-10^{21}/s

QGP is opaque to colored hard jets



Jets provide valuable tools to probe QGP in heavy-ion collisions

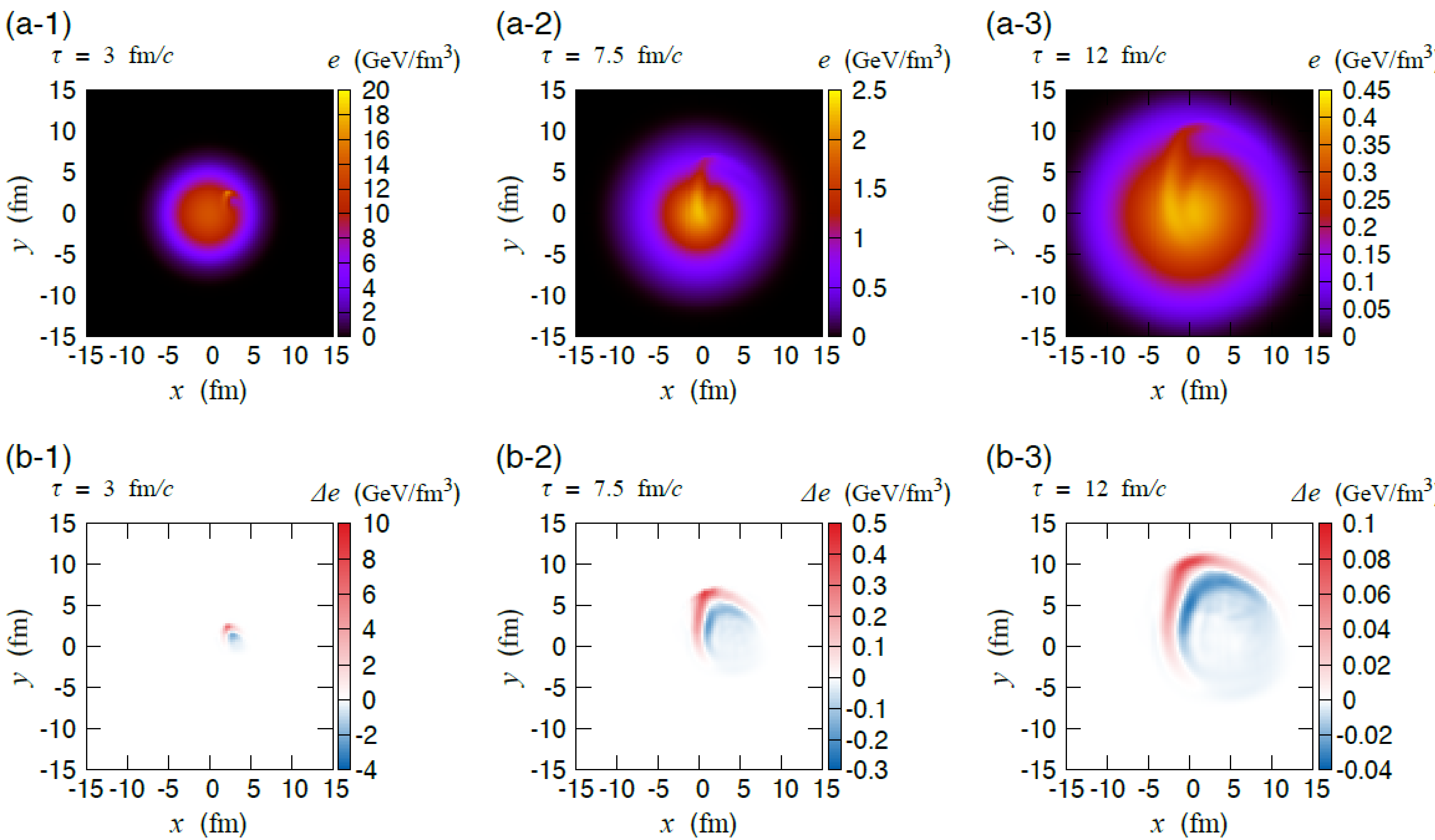
(1) energy loss => quenching

(2) deflection => broadening

(3) modification of jet structure/substructure

(4) jet-induced medium excitation (response)

Jet-induced medium excitation



Tachibana, Chang, GYQ, PRC 2018

Summary for Lecture I

- The produced matter thermalizes/hydrodynamizes extremely fast
- The QGP shows strong collectivity, well described by relativistic hydrodynamics
  - QGP is a strongly-coupled liquid (extremely small η/s)
- Quantum fluctuations of initial states manifest themselves in the final states correlations
  - Can use final state flow to probe initial state nuclear structure
- Detailed study of anisotropic flows can improve our quantitative understanding of the QGP in heavy-ion collisions
  - The QGP is less strongly-coupled (larger η/s) at the LHC
- Evidence of anisotropic collective flows in small collision systems
- QGP is opaque to colored hard jets (to be continued in next 3 lectures)
- The hottest, most perfect, most vortical and highly opaque fluid on Earth!

Some questions

- How is the QGP formed in relativistic heavy-ion collisions?
- Why does the system thermalize/hydrodynamize so fast?
- What is the role of pre-equilibrium stage?

- How does QCD medium change from weakly-coupled (asymptotically free) quark-gluon gas at extremely high temperature to strongly-interacting QGP at relatively “low” temperature?
- Can we see quasi-particles (quarks and gluons) in strongly-interacting QGP? (see next 3 lectures)

- What is the nature of color confinement?
- How does colored QGP turn into colorless hadrons?

- ……

重离子碰撞中的喷注
Jets in Heavy-Ion Collisions

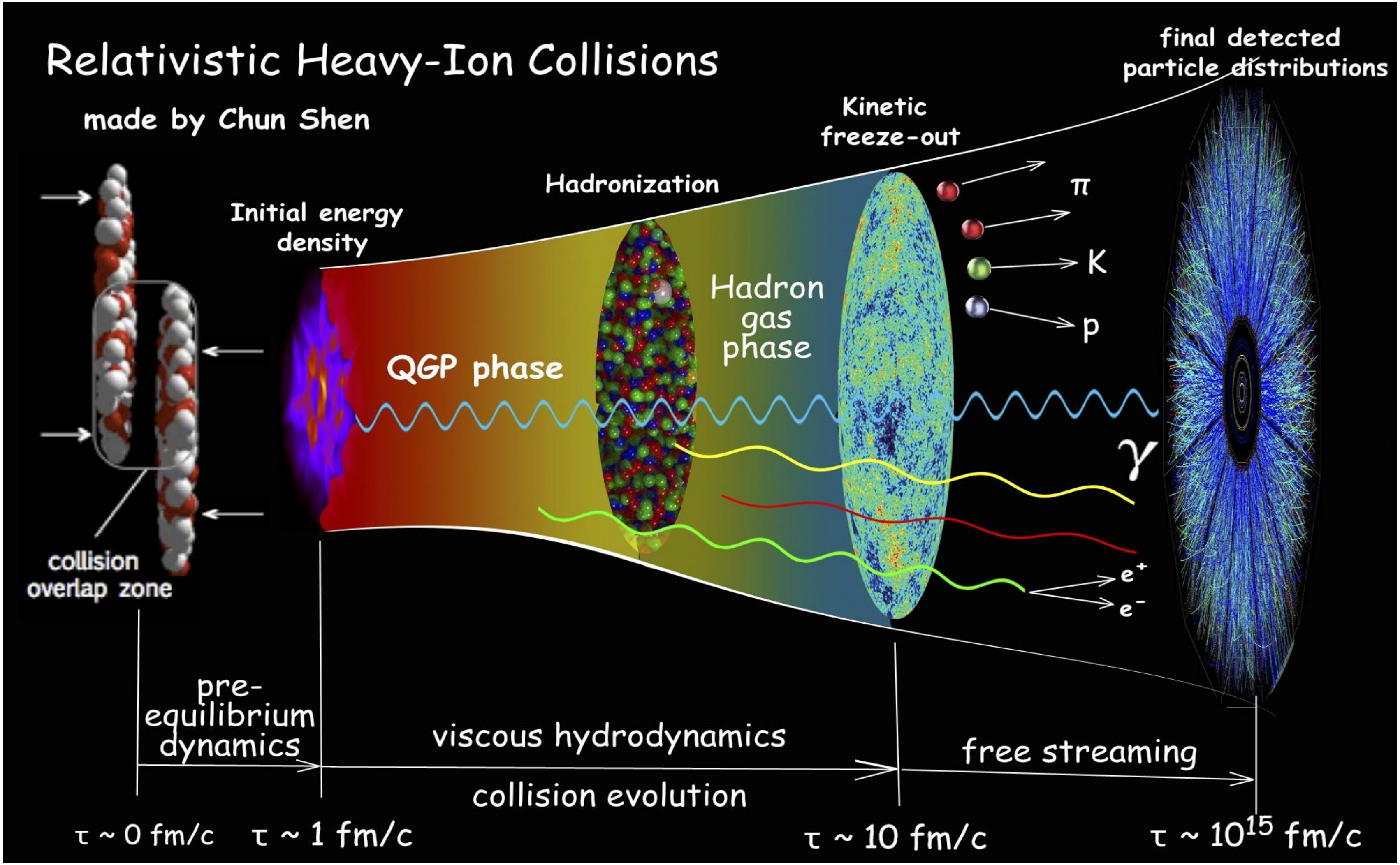
秦广友（Guang-You Qin）
华中师范大学（Central China Normal University）

“微扰量子场论及其应用”前沿讲习班暨前沿研讨会
山东济南
2025 年7月6日-7月21日

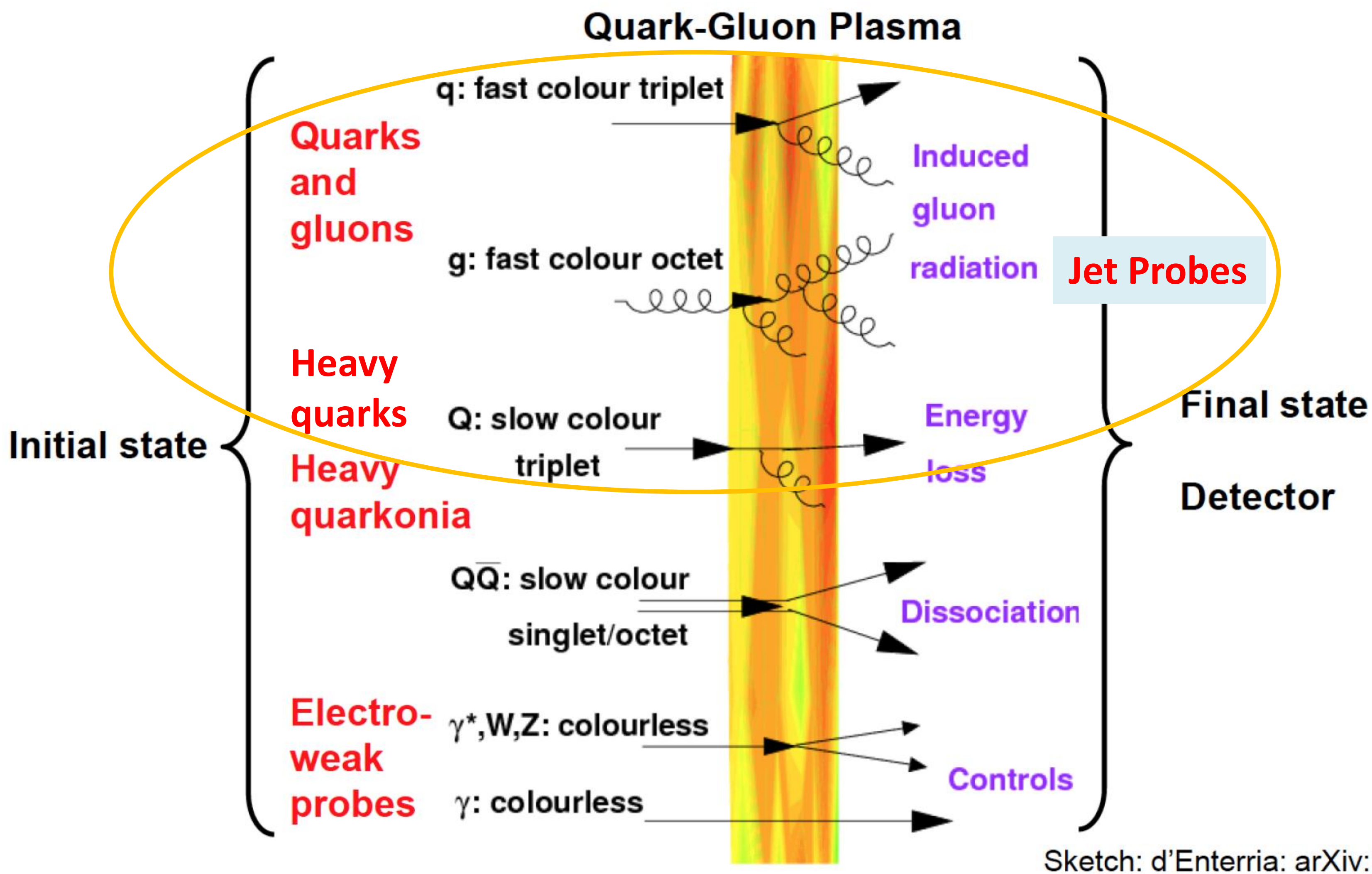
Outline

- Lecture 1
  - Introduction to heavy-ion collisions and quark-gluon plasma
- Lecture 2
  - Jet probes (of QGP in HIC), jet quenching and energy loss (some simple discussion)
- Lecture 3
  - Jet probes of QGP in HIC: flavor dependence of parton energy loss and jet quenching, jet Monte-Carlo models
- Lecture 4
  - Jet probes of QGP in HIC: full jets, jet energy loss, medium response, jet (sub)structure

“Standard Model” of RHIC & LHC heavy-ion collisions



Penetrating probes of QGP



Sketch: d'Enterria: arXiv:1207.4362

What are jets? A bit history.

Hadron production in e^+e^- collisions proceeds through e^+e^- annihilation into a virtual photon which typically produces a quark-anti-quark pair, each of which decays into a jet (collimated spray) of hadrons.

EVIDENCE FOR JET STRUCTURE IN HADRON

PRODUCTION BY e^+e^- ANNIHILATION*

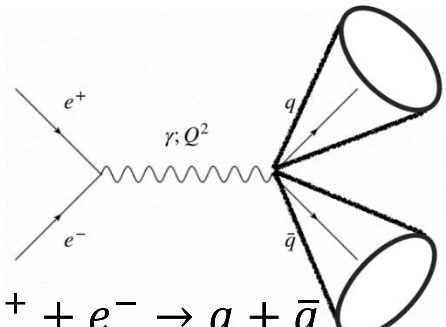
G. Hanson, G.S. Abrams, A.M. Boyarski, M. Breidenbach, F. Bulos, W. Chinowsky, G.J. Feldman, C.E. Friedberg, D. Fryberger, G. Goldhaber, D.L. Hartill,† B. Jean-Marie, J.A. Kadyk, R.R. Larsen, A.M. Litke, D. Lüke,†† B.A. Lulu, V. Lüth, H.L. Lynch, C.C. Morehouse, J.M. Paterson, M.L. Perl, F.M. Pierre,‡ T.P. Pun, P.A. Rapidis, B. Richter, B. Sadoulet, R.F. Schwitters, W. Tanenbaum, G.H. Trilling, F. Vannucci,‡‡ J.S. Whitaker, F.C. Winkelmann, and J.E. Wiss

Lawrence Berkeley Laboratory and Department of Physics
University of California, Berkeley, California 94720

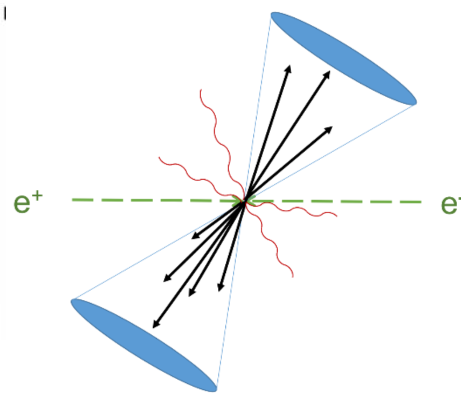
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

ABSTRACT

We have found evidence for jet structure in $e^+e^- \rightarrow$ hadrons at center-of-mass energies of 6.2 and 7.4 GeV. At 7.4 GeV the jet axis angular distribution integrated over azimuthal angle was determined to be proportional to $1 + (0.78 \pm 0.12) \cos^2\theta$.



$$e^+ + e^- \rightarrow q + \bar{q}$$



JETS FROM QUANTUM CHROMODYNAMICS

George Sterman*
Institute for Theoretical Physics
State University of New York at Stony Brook
Stony Brook, New York 11790

and

Steven Weinberg†
Lyman Laboratory of Physics
Harvard University
Cambridge, Massachusetts 02138

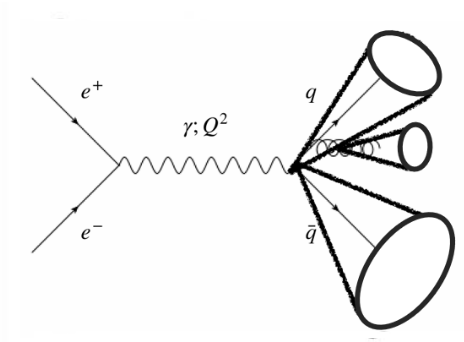
ABSTRACT

The properties of hadronic jets in e^+e^- annihilation are examined in quantum chromodynamics, without using the assumptions of the parton model. We find that two-jet events dominate the cross section at high energy, and have the experimentally observed angular distribution. Estimates are given for the jet angular radius and its energy dependence. We argue that the detailed results of perturbation theory for production of arbitrary numbers of quarks and gluons can be reinterpreted in quantum chromodynamics as predictions for the production of jets.

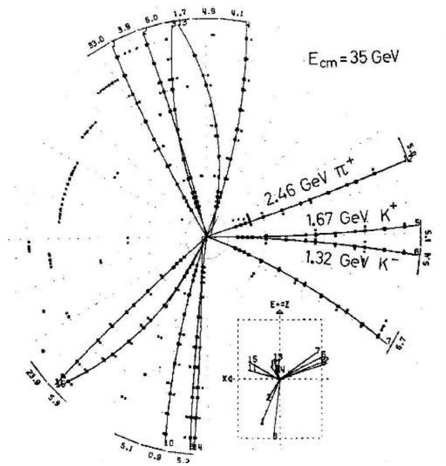
Jets are proxy of hard partons. Ideally, we would like to measure hard partons directly. But in reality, we could only measure final state particles produced from hard partons.

Phys. Rev. Lett. 35, 1609 (1975); Phys.Rev.Lett. 39 (1977) 1436

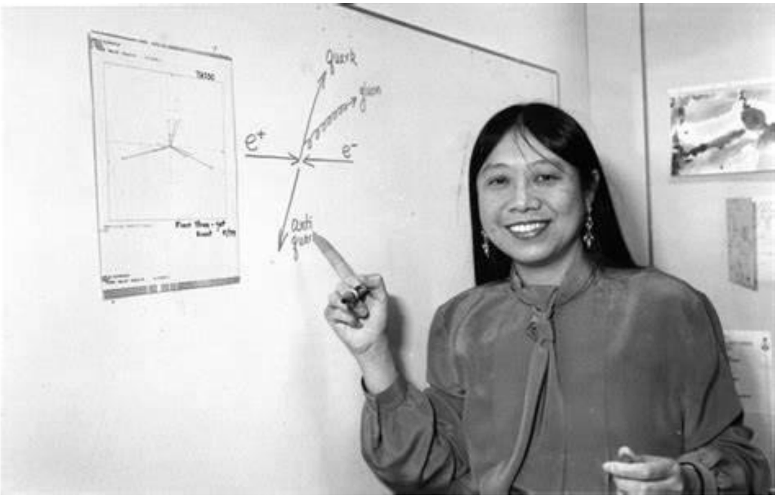
The discovery of the gluon (jet)



$$e^+ + e^- \to q + \bar{q} + g$$



DESY/PETRA/TASSO

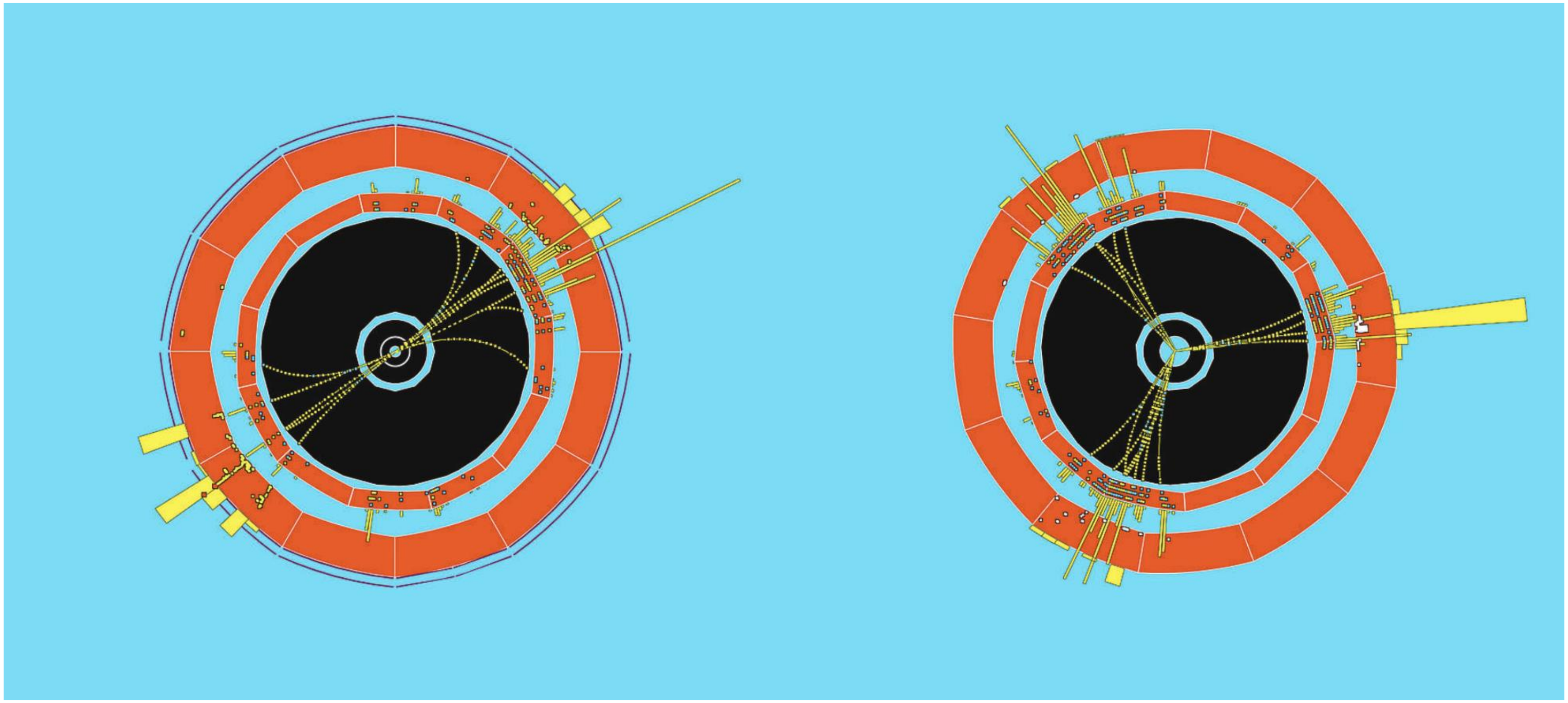


Researchers **Sau Lan Wu and Georg Zobernik**, from the University of Wisconsin, had written an extremely efficient program to analyze the collisions in which **quarks** were formed, and had also calculated that it ought to be possible to create **gluons** in **PETRA** by means of bremsstrahlung at collision energies above around 22 GeV. Finally, in **June 1979**, a few days before a conference in Bergen (Norway), the **TASSO** scientists identified the first event consisting of **three distinctive jets** in their data, as **Event 13177 of Run 447**. Freshly analyzed, so to speak, Bjorn Wiik took it along to the “**Neutrino 79**” in Bergen on 18 June and placed it on the overhead projector as the last transparency of his presentation “**First Results from PETRA**”. It was to become the transparency with the greatest repercussions: **the gluon had seen the light of (the scientific) day**.

Jets as proxy of quarks and gluons

A dijet event @ CERN/LEP/ALEPH

A trijet event @ CERN/LEP/ ALEPH

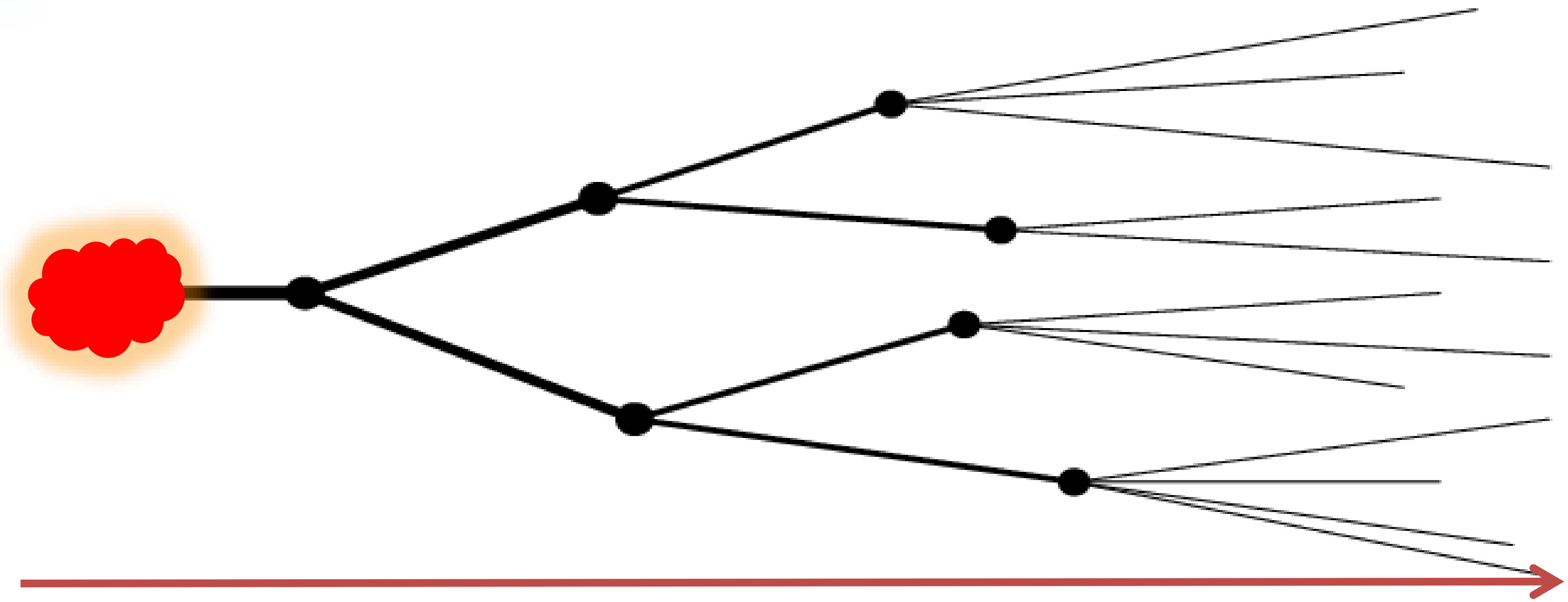


$e^+ + e^- \to q + \bar{q}$

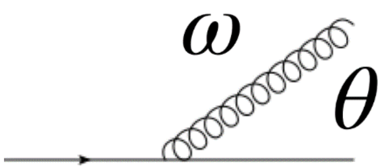
$e^+ + e^- \to q + \bar{q} + g$

Jets, defined by jet clustering algorithm, are used as a proxy of quarks and gluons.

QCD jets in vacuum



Hard scattering **Parton shower (radiation)** **Hadronization**



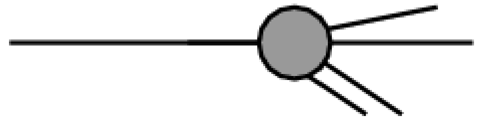
$$\frac{dP}{dz\,dk_\perp^2} = \frac{\alpha_s}{2\pi} P(z) \frac{1}{k_\perp^2}, \qquad \left(\frac{dP}{d\omega\, d\theta}\right)_{q\to g} = \frac{2\alpha_s}{\pi} C_F \frac{1}{\omega}\frac{1}{\theta}$$

Formation time: $\tau_{form} = \frac{\omega}{k_\perp^2} = \frac{1}{\omega\theta^2}$

Given ω, narrower emission => later time, whereas wider emission => earlier time.

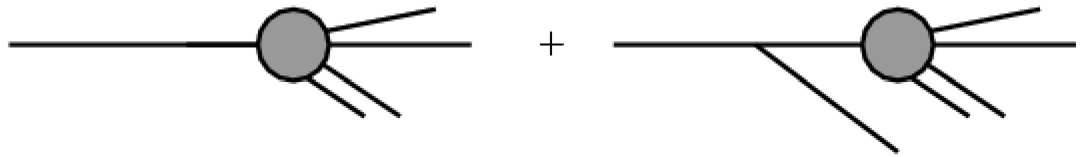
Multiple emissions

$D(z, \mu^2) =$

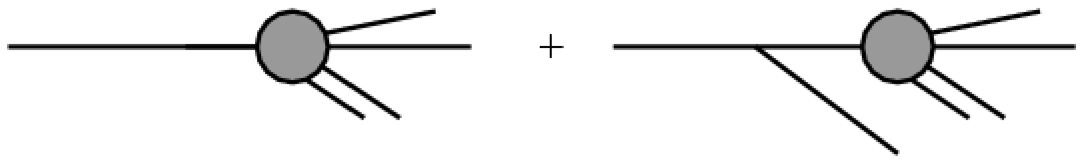


Contains all emissions up to scale μ

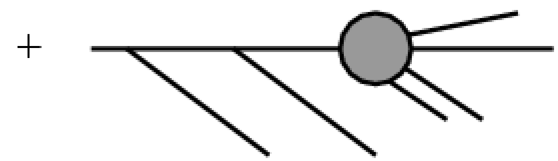
$D(z, \mu^2 + \delta\mu^2) =$



$D(z, \mu^2 + \delta\mu^2 + \delta\mu^2) =$



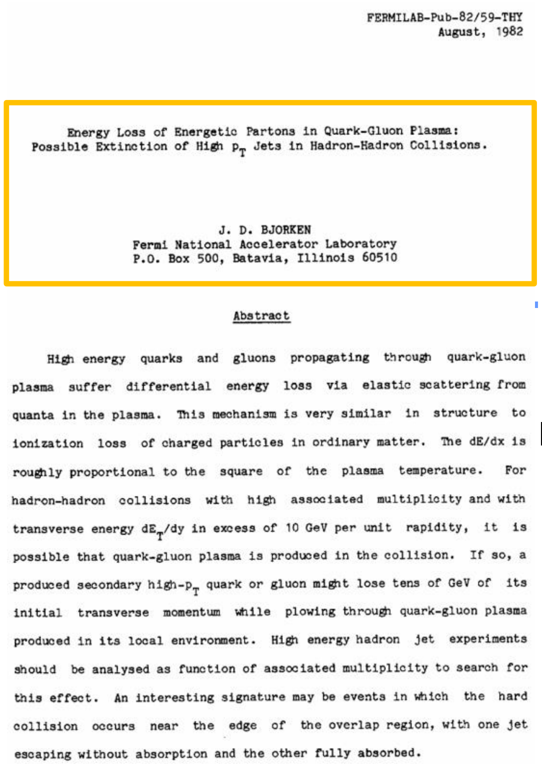
Increasing the scale => rebuilding the shower



The shower evolution is governed by DGLAP equations:

$$\frac{\partial \bar{D}_{i \to h}(z, Q^2)}{\partial \ln Q^2} = \sum_j \frac{\alpha_s}{2\pi} \int \frac{dy}{y} P_{i \to j}(y) D_{j \to h}(z/y, Q^2)$$

Jets in heavy-ion collisions: what to expect?



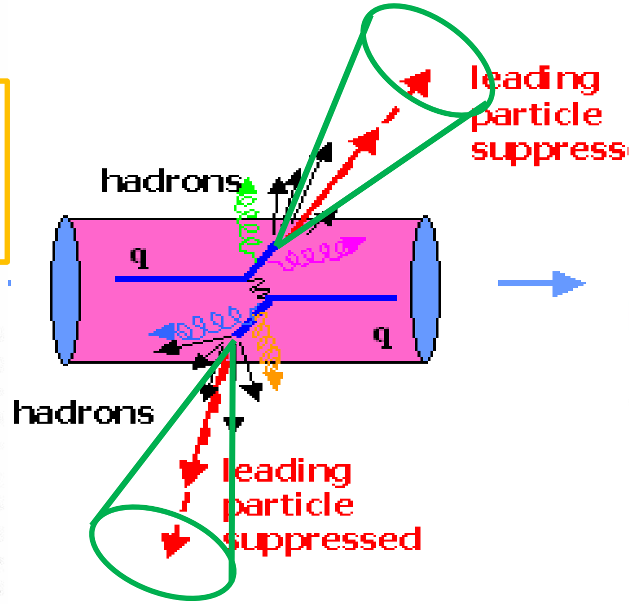
FERMILAB-Pub-82/59-THY
August, 1982

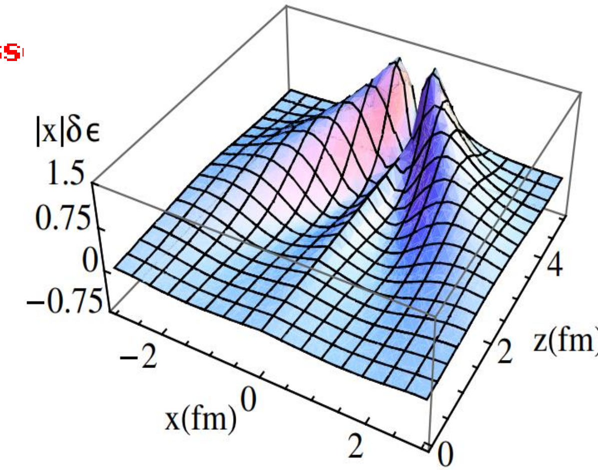
Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.



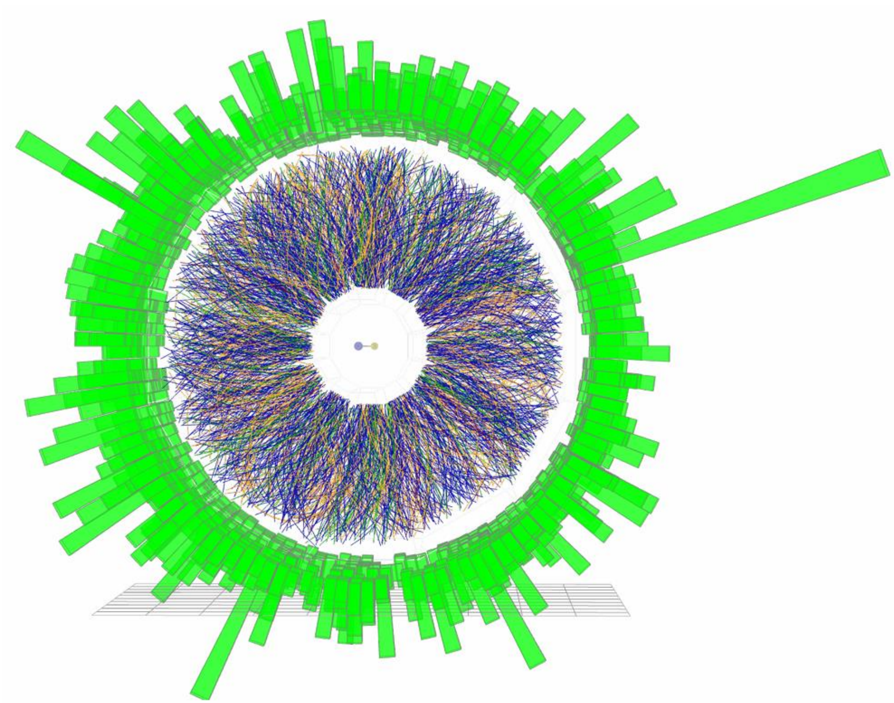


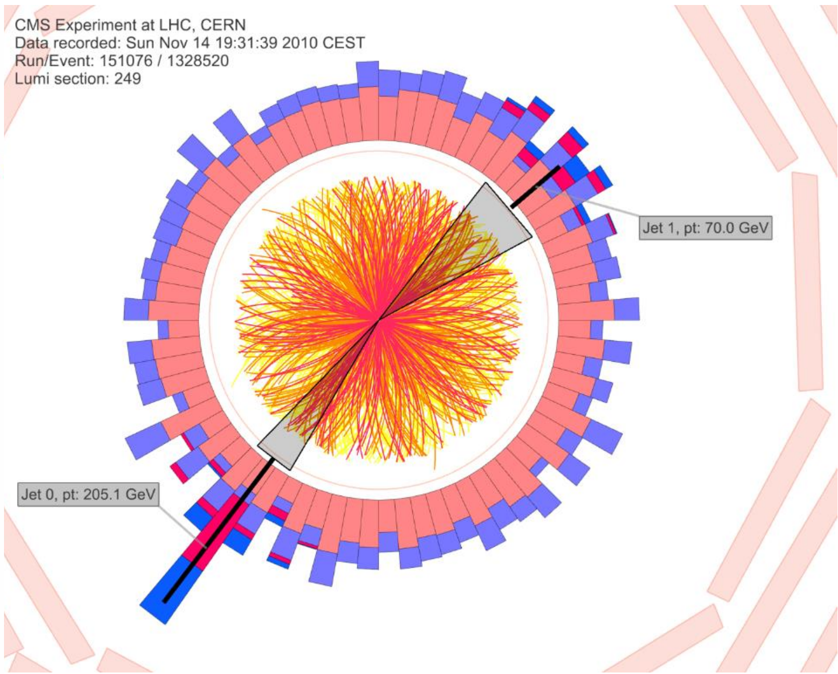
A+A: jet quenching

QGP is opaque to colored hard jets

(1) energy loss => quenching
(2) deflection => broadening
(3) modification of jet structure/substructure
(4) jet-induced medium excitation (response)

Jets in heavy-ion collisions: how to measure?





Where are the jets here? How to measure jets in relativistic heavy-ion collisions?

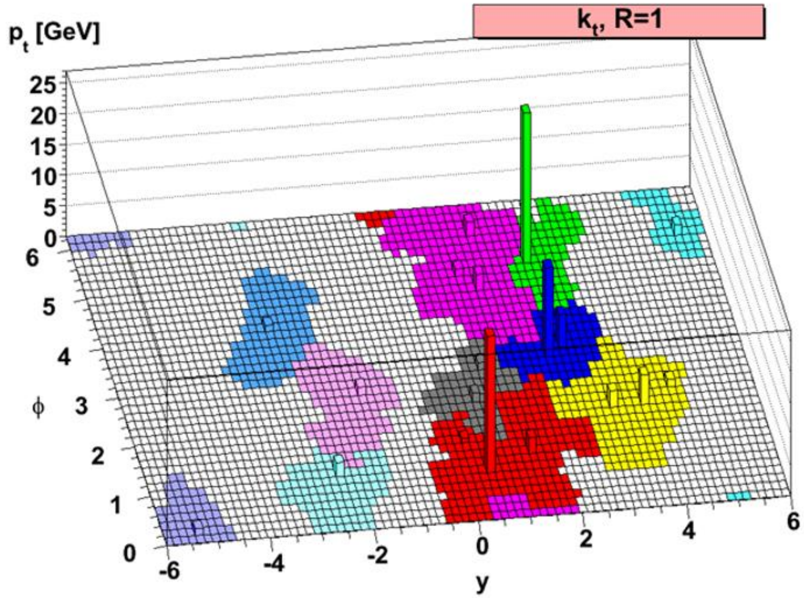
General idea to find (define) a jet

- Jet is a collection of particles grouped by an iterative algorithm
- Jet works as a proxy to hard-scattered high-energy parton
- With an appropriate jet radius parameter and constituent momentum threshold, one hopes to recover the originating parton

- From theoretical point of view, the jet finding algorithm should meet the following criteria:
  - Infrared safe: jet finding algorithm is not sensitive to the addition of soft parton
  - Collinear safe: jet finding algorithm is not sensitive to collinear emission

- In general, jet algorithms can be categorized into two classes:
  - Cone algorithms, such as SISCone (Seedless Infrared Safe Cone)
  - Sequential recombination algorithms, which cluster pair of objects relatively close in momentum, such as k_T family of jet finding algorithms

k_T algorithm



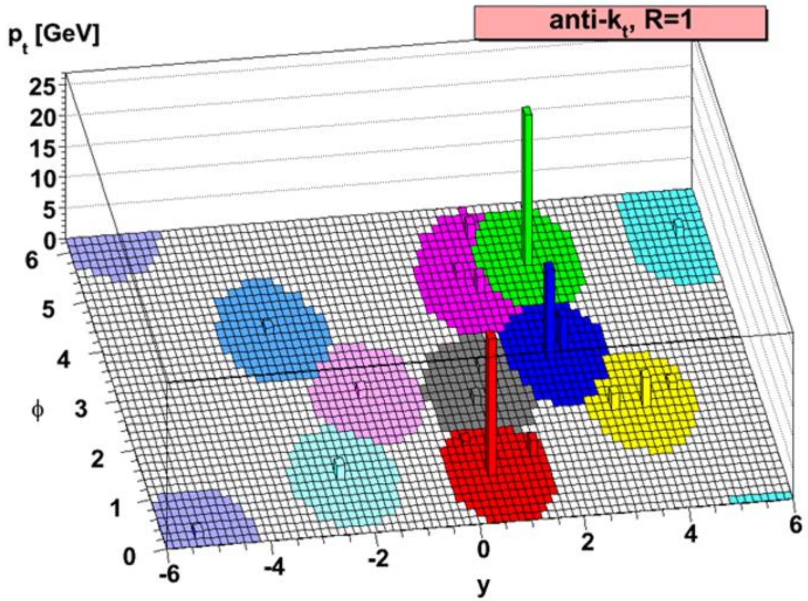
$$d_{ij} = \min\left(p_{T,i}^2, p_{T,j}^2\right)\frac{\Delta R_{ij}^2}{R^2}$$
$$d_{iB} = p_{T,i}^2$$
$$\Delta R_{ij}^2 = \left(\eta_i - \eta_j\right)^2 + \left(\phi_i - \phi_j\right)^2$$

1. For all particles, compute d_{ij}, d_{iB}
2. Find the smallest of d_{ij}, d_{iB}
3. If d_{iB}, call i particle a jet and remove it from the list of particles
4. If d_{ij}, recombine them to a new "particle"
5. Repeat from step 1 until no particle left

k_T algorithm clusters from low p_T particle. Clustered area has irregular shape.
It is not suitable in heavy-ion collisions due to large soft background fluctuation.

M. Cacciari, G. P. Salam, G. Soyez: The anti-kt jet clustering algorithm, JHEP 0804 (2008) 063, arXiv:0802.1189v2 [hep-ph]

Anti-k_T algorithm



$$d_{ij} = \min\left(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{T,i}^2$$

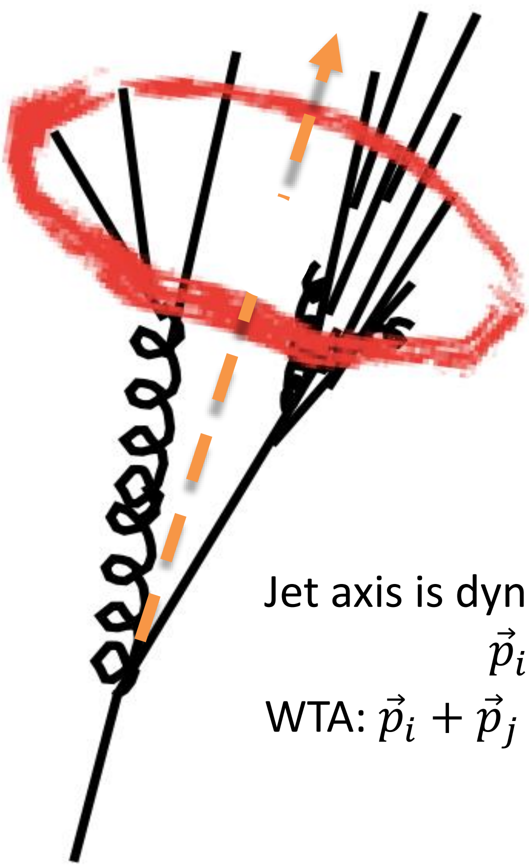
$$\Delta R_{ij}^2 = \left(\eta_i - \eta_j\right)^2 + \left(\phi_i - \phi_j\right)^2$$

1. For all particles, compute d_{ij}, d_{iB}
2. Find the smallest of d_{ij}, d_{iB}
3. If d_{iB}, call i particle a jet and remove it from the list of particles
4. If d_{ij}, recombine them to a new "particle"
5. Repeat from step 1 until no particle left

kT algorithm clusters from high p_T particle. Clustered area has circular shape.
It is now commonly used in heavy-ion (& pp) collisions by ALICE, ATLAS and CMS.

M. Cacciari, G. P. Salam, G. Soyez: The anti-kt jet clustering algorithm, JHEP 0804 (2008) 063, arXiv:0802.1189v2 [hep-ph]

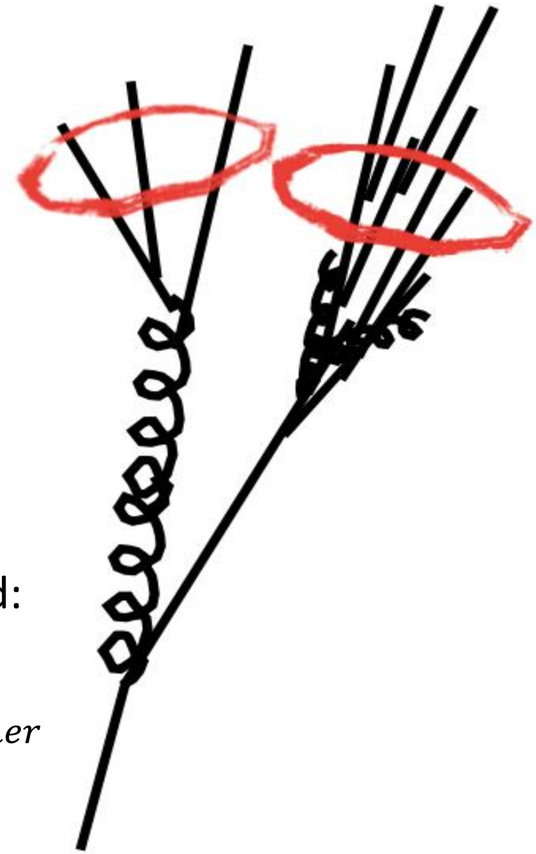
What is the role of jet radius R?



Jet axis is dynamically determined:

$$\vec{p}_i + \vec{p}_j = \vec{p}_k$$

WTA: $\vec{p}_i + \vec{p}_j = \left(|\vec{p}_i| + |\vec{p}_j|\right)\hat{p}_{winner}$



Large radius parameter R

Small radius parameter R

R is not an intrinsic size of the jet, but just a parameter to define the energy flow. Note that the radiation outside the jet cone can be significant.

FastJet package

Home About Releases Quick start Manual Doxygen Tools Contrib FAQ

FastJet

https://fastjet.fr/

A software package for jet finding in pp and e^+e^- collisions. It includes fast native implementations of many sequential recombination clustering algorithms, plugins for access to a range of cone jet finders and tools for advanced jet manipulation.

Release of FastJet 3.4.3 (latest stable release), 5 July 2024 (release notes).
This is a bug-fix release of FastJet with updates to the build system. See the full release notes for details.

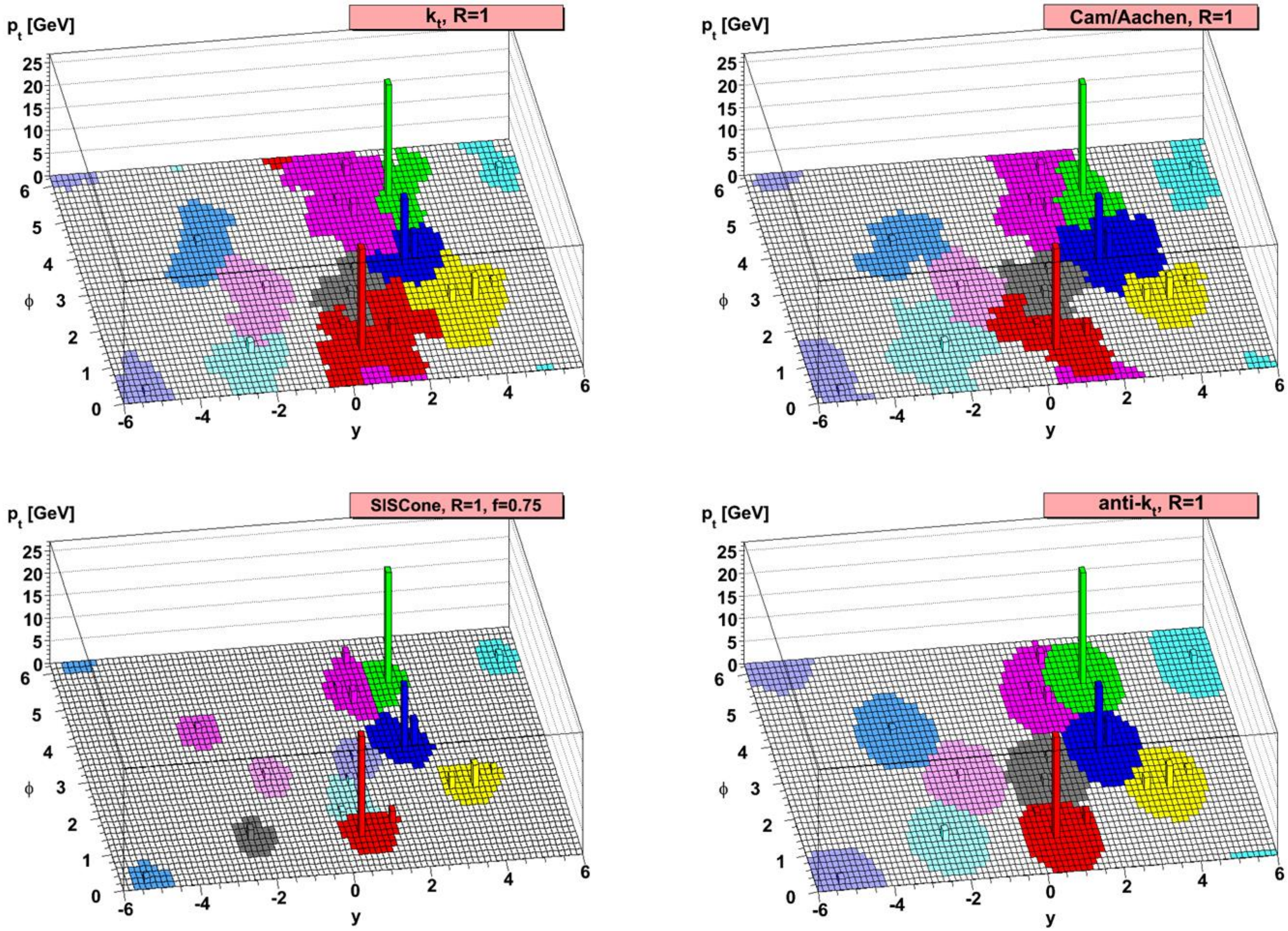
Download

Latest stable release of fjcore (v3.4.3), 5 July 2024.
Lightweight access to the core FastJet functionality (PseudoJet, JetDefinition, ClusterSequence and Selector).
It consists of just two files, fjcore.hh and fjcore.cc, which can easily be included in 3rd party projects. Compile time: a few seconds. A fortran interface and basic examples are also included in the distribution. Download size: 75k.

Release of FastJet Contrib 1.100, 13 December 2024.
A package of contributed add-ons to FastJet. This release (see NEWS for details) makes it possible for a contrib to depend on another contrib from fjcontrib. It introduces two jet flavour contribs: IFNPlugin and CMPPlugin. It also updates RecursiveTools to 2.0.4 and LundPlane to 2.1.2. Fastjet contrib 1.100 and later requires FastJet 3.4.1 or higher. FastJet contrib 1.047 and later requires C++11 support in the compiler (if using GCC's g++ it should be version 5.1.0 or later). Direct download.

M. Cacciari, G. Salam and G. Soyez, Eur.Phys.J.C 72 (2012) 1896. arXiv:1111.6097 [hep-ph]

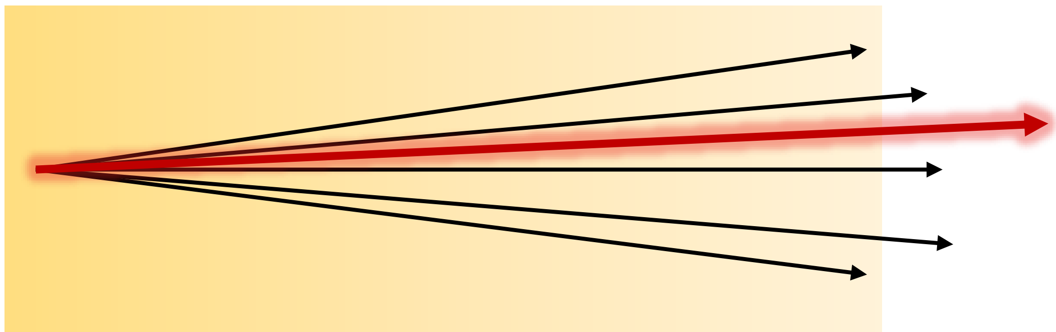
Different jet finding algorithms



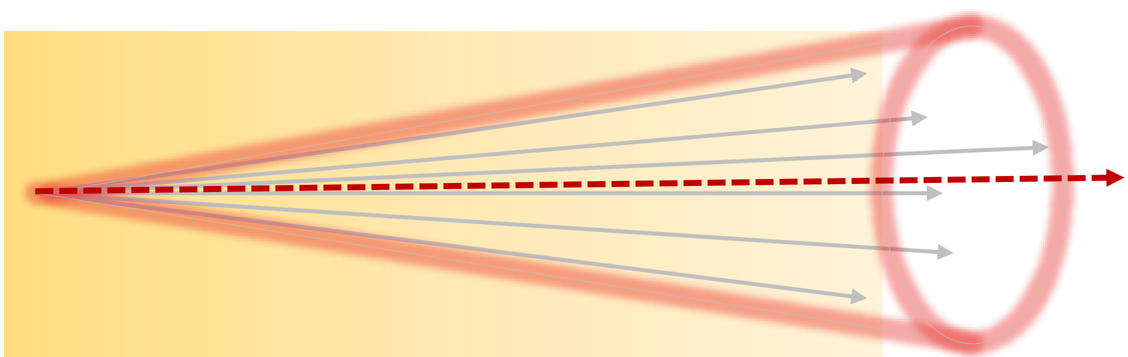
M. Cacciari, G. P. Salam, G. Soyez: The anti-kt jet clustering algorithm, JHEP 0804 (2008) 063, arXiv:0802.1189v2 [hep-ph]

Jet observables (measurements)

- 1st type of observables: leading (high momentum) hadron as a proxy for a jet

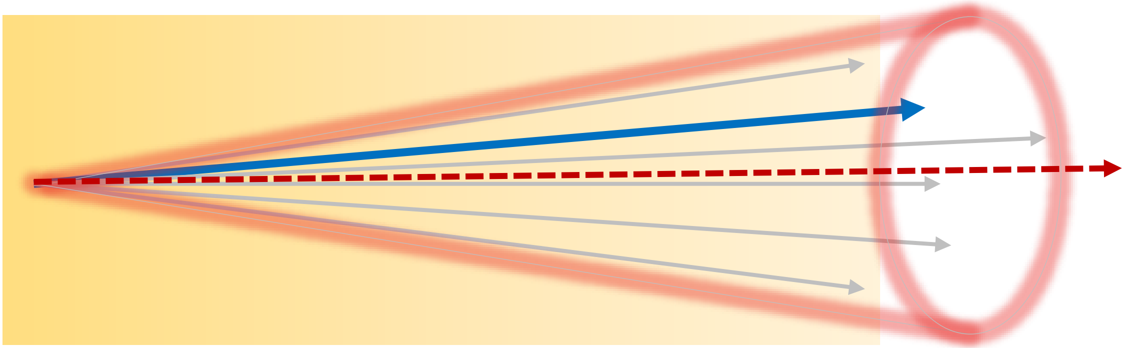


- 2nd type of observables: fully-reconstructed jet as a proxy for hard-scattered high-energy parton

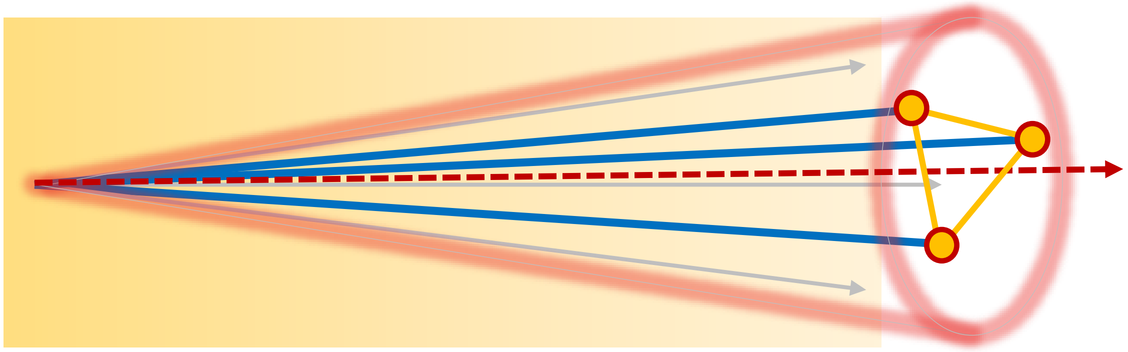


Jet observables (measurements)

- 3rd type of observables: looking at particle distribution inside the jet, such as jet shape and fragmentation function,



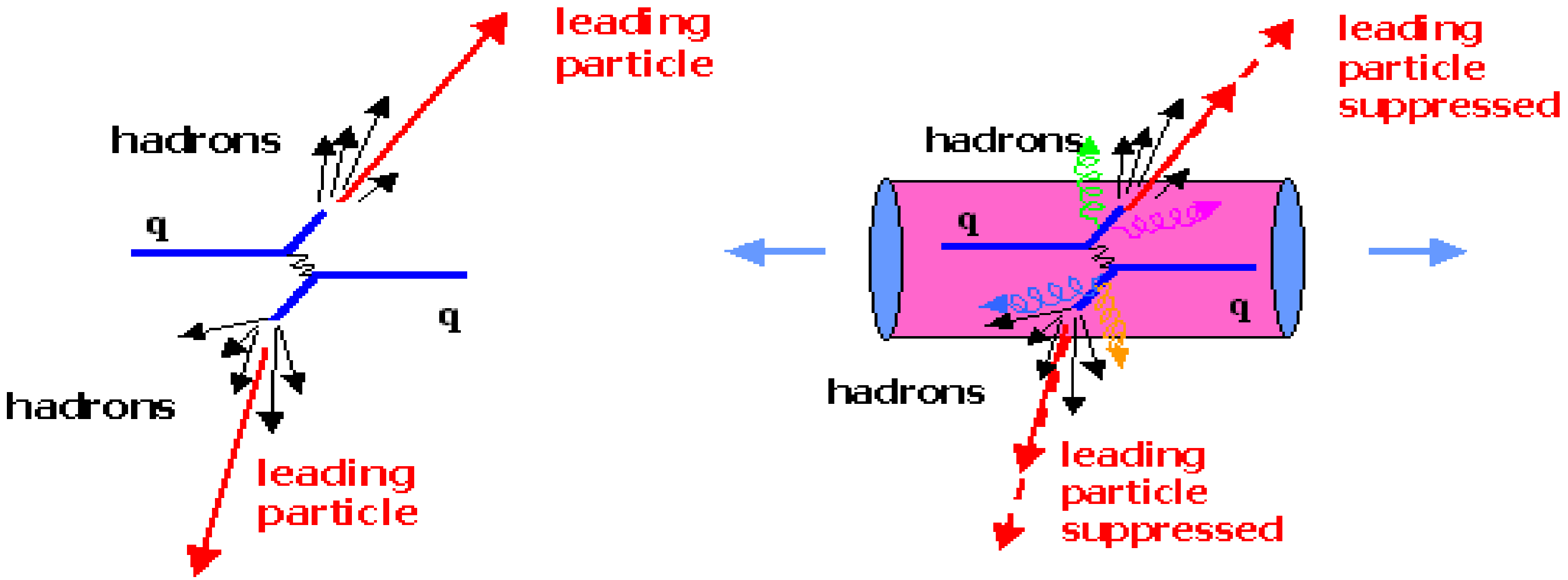
- 4th type of observables: looking at particle correlations inside the jet, such as jet splitting function, splitting angle, EEC



Jet quenching: some simple discussion

How to measure medium effect on jets?

A common practice is to compare AA collisions to pp reference collisions.



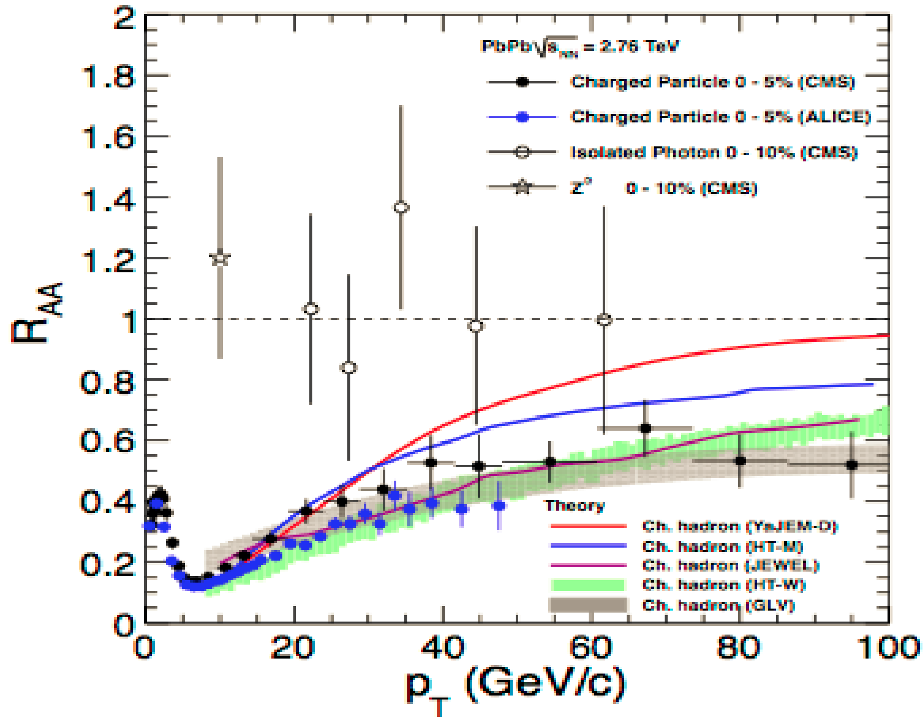
N+N

A+A: jet quenching

Nuclear modification factor:

$$R_{AA} = \frac{\sigma_{pp}}{N_{coll}} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} \approx \frac{QCD\ medium}{QCD\ vacuum} = \begin{cases} R_{AA} > 1 & (enhancement) \\ R_{AA} = 1 & (no\ medium\ effect) \\ R_{AA} < 1 & (suppression) \end{cases}$$

Evidence for jet quenching



If AA collisions are a simple geometric combination of many NN collisions, then R_{AA}=1

Confirmation of N_{coll}-scaling: photon & Z boson R_{AA}=1

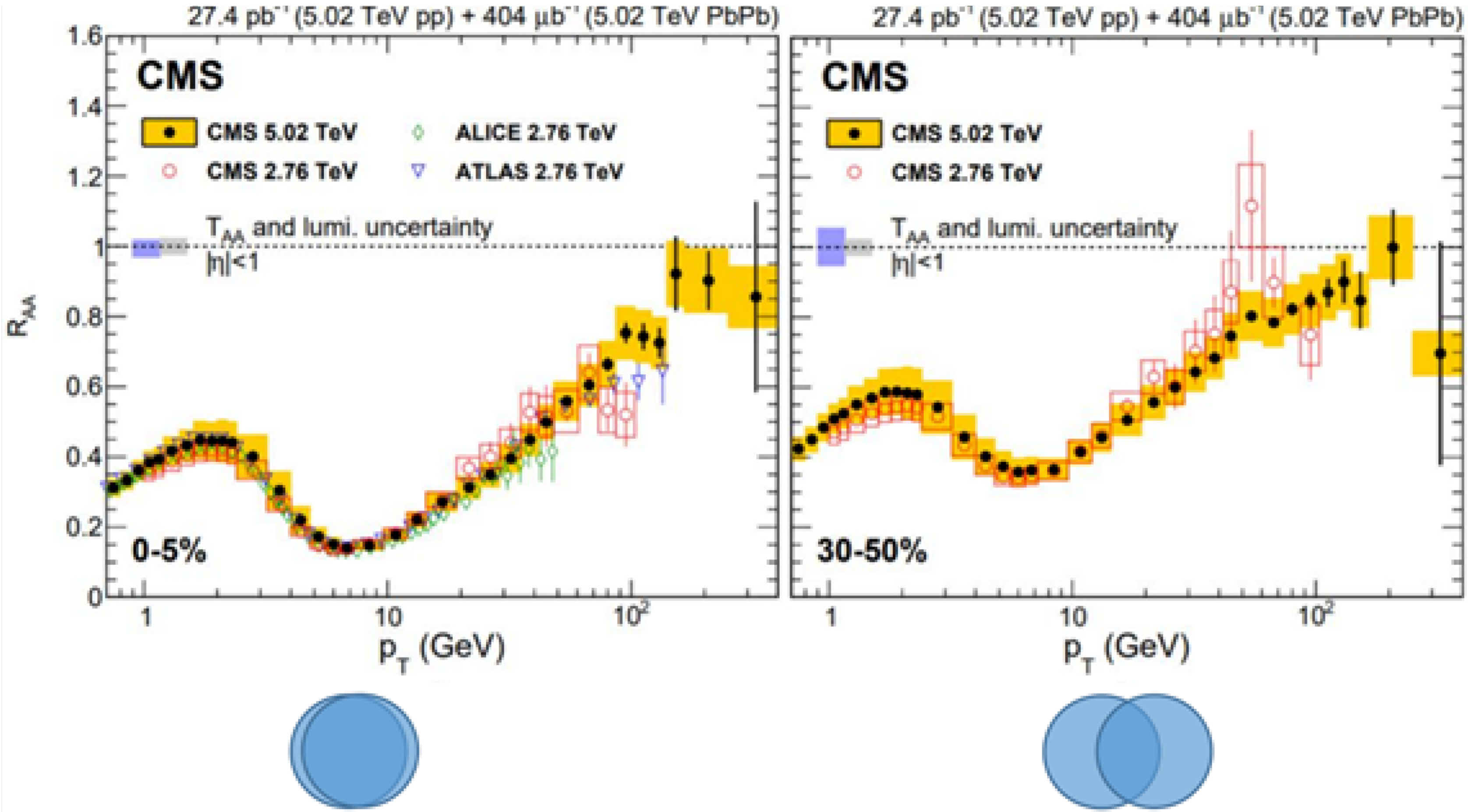
Evidence of jet quenching: hadron R_{AA}<1

Due to final state interaction between hard partons and QGP (i.e., parton energy loss), the production of high p_T hadrons (from fragmentation of hard partons) is suppressed

Nuclear modification factor:

$$R_{AA} = \frac{\sigma_{pp}}{N_{coll}} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} \approx \frac{QCD\ medium}{QCD\ vacuum} = \begin{cases} R_{AA} > 1 & (enhancement) \\ R_{AA} = 1 & (no\ medium\ effect) \\ R_{AA} < 1 & (suppression) \end{cases}$$

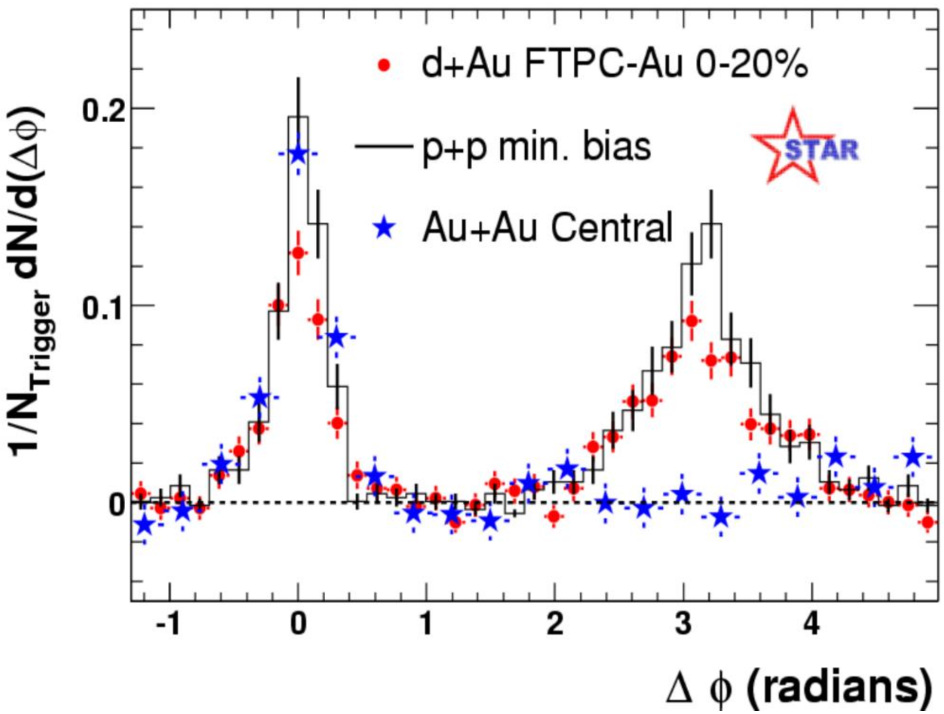
Jet quenching: centrality dependence

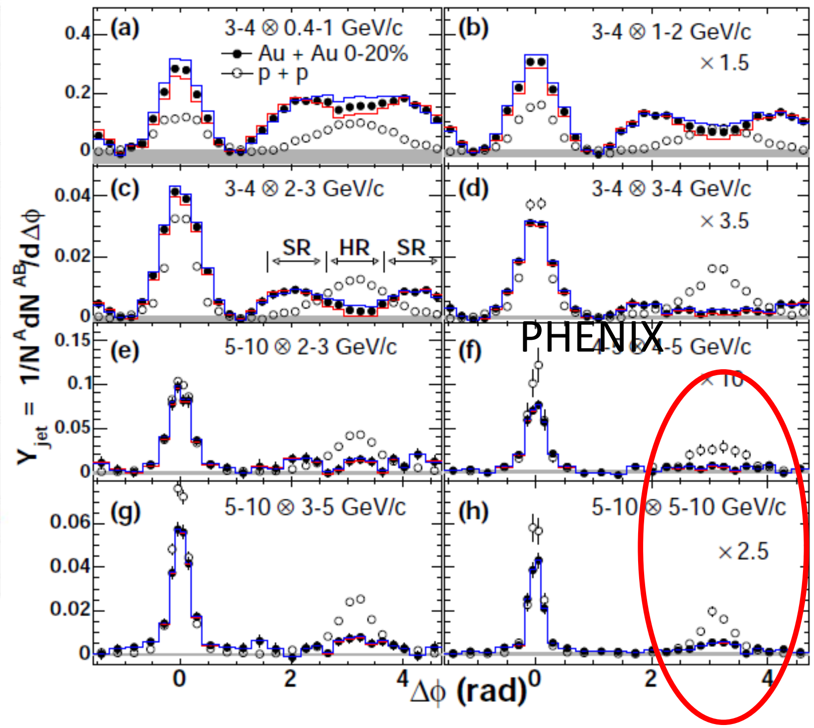


Larger medium => more suppression

smaller medium => less suppression

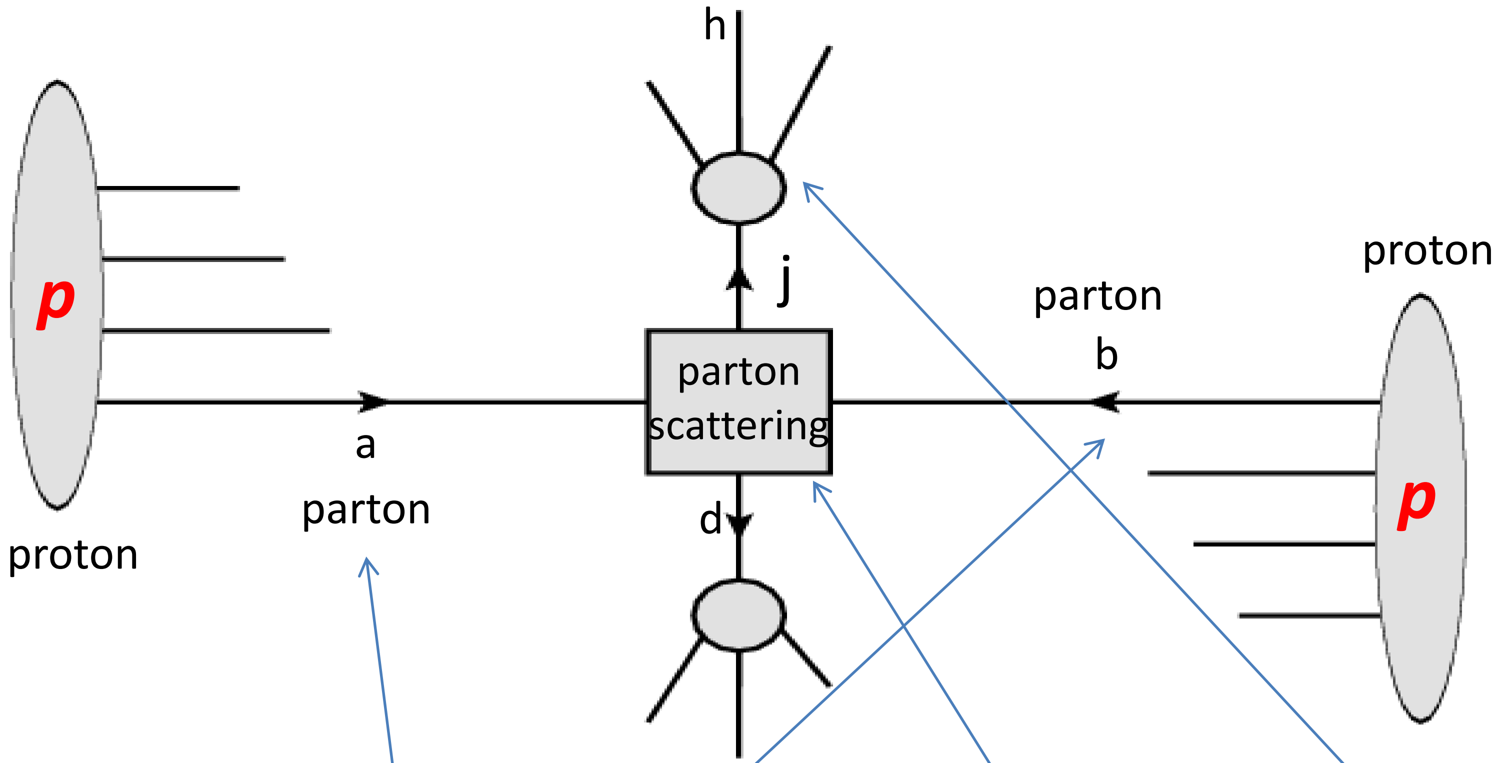
Evidence for jet quenching: dihadron correlation





Both per-trigger yield and the shape of angular distribution are modified by QGP.

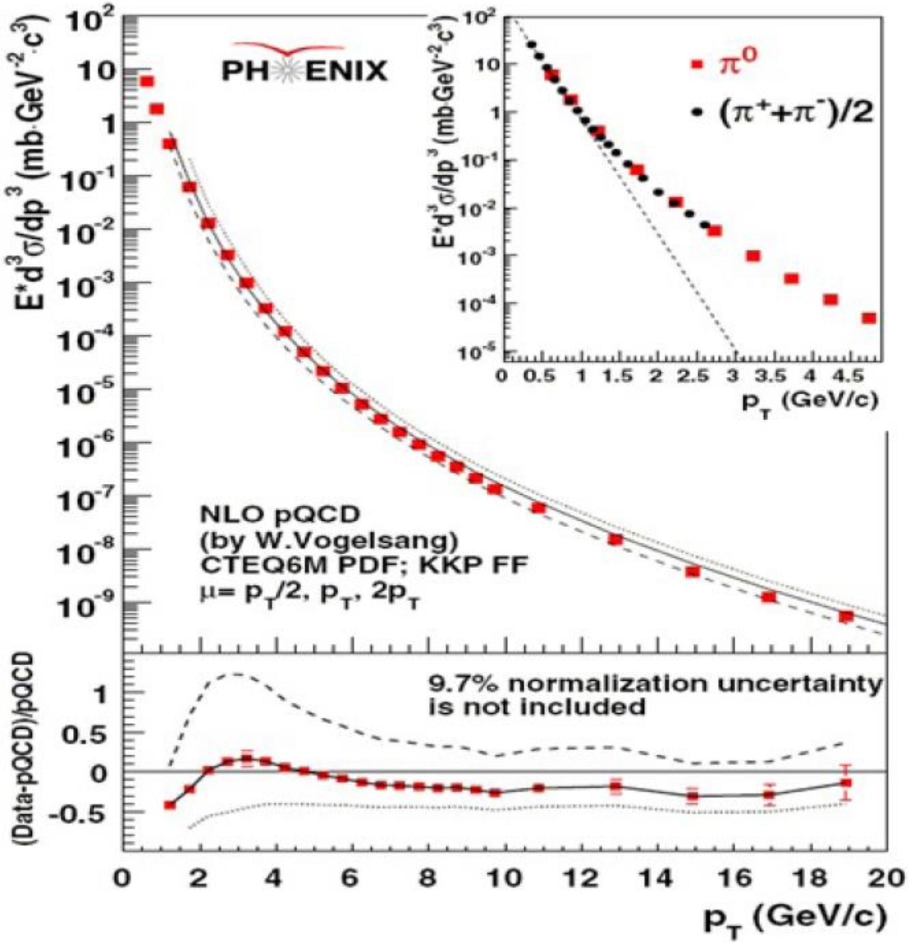
Leading hadron production in pp collisions

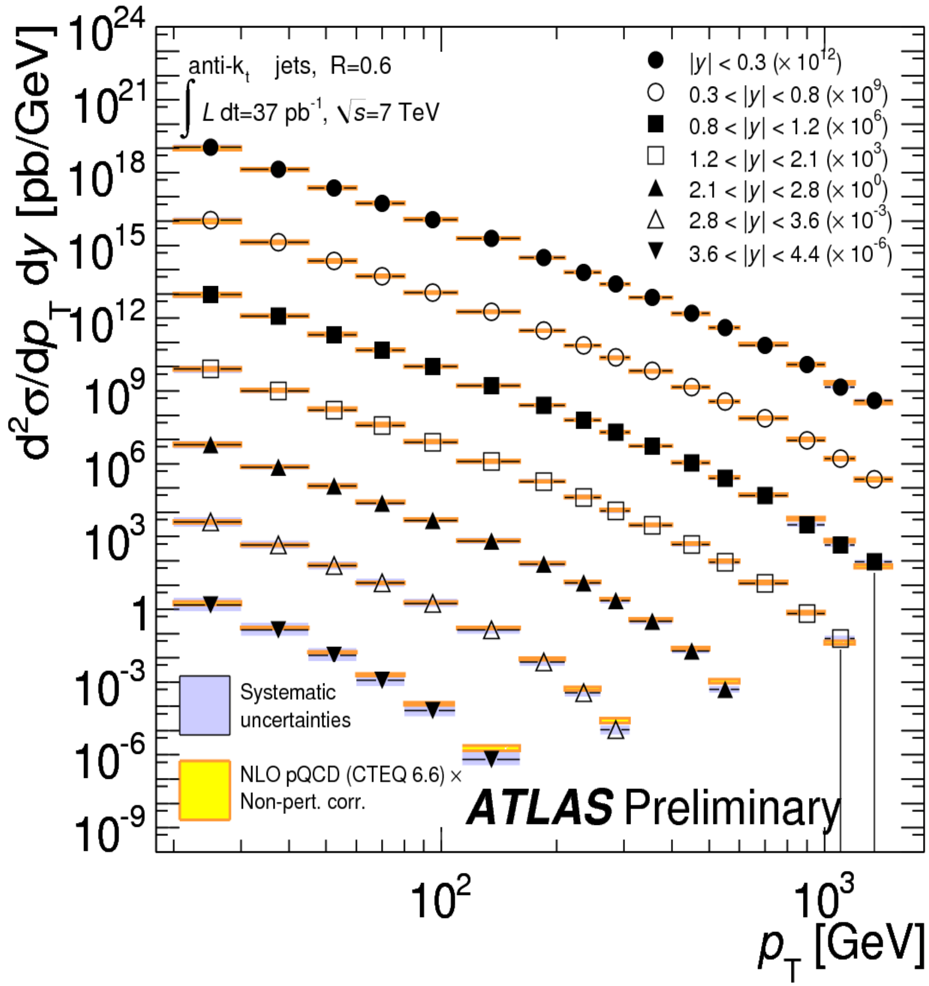


$$d\sigma_h = \sum_{abj} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jX} \otimes D_{h/j}$$

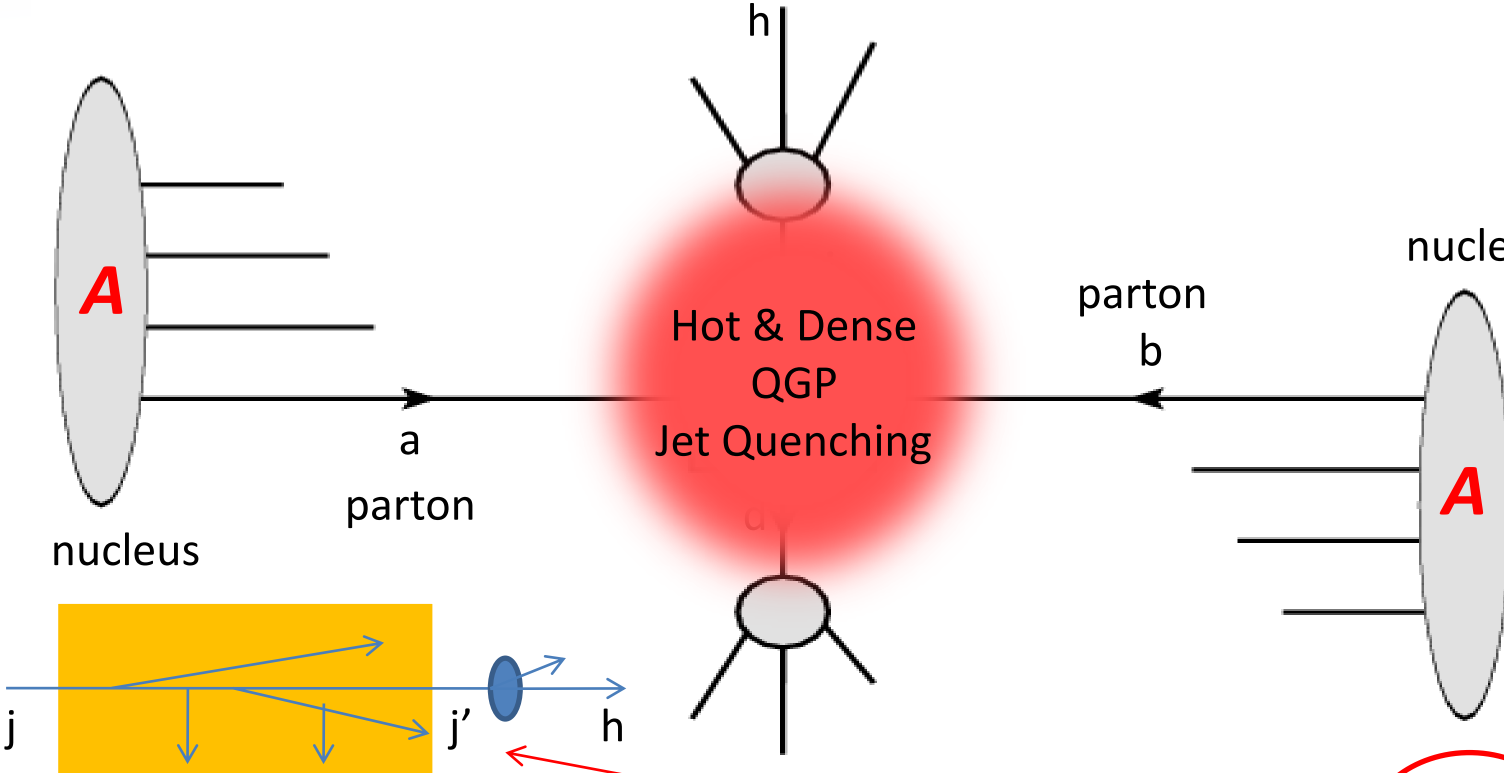
pQCD factorization: Large-p_T processes may be **factorized** into **long-distance pieces** in terms of PDF & FF, and **short-distance parts** describing hard interactions of partons.

Baseline: hadron/jet productions in pp @ NLO





Leading hadron production in AA collisions

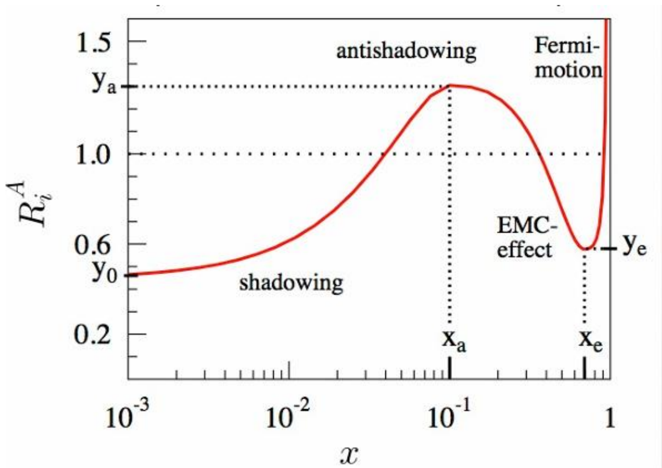


$$d\tilde{\sigma}_h = \sum_{abjX} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jX} \otimes \tilde{D}_{h/j}$$

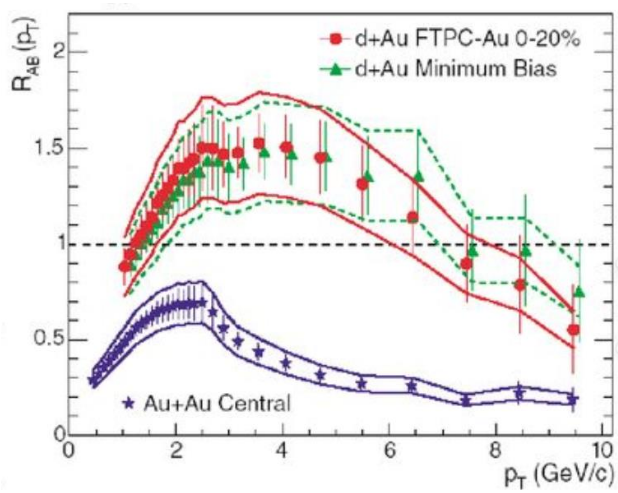
$$d\tilde{\sigma}_h = \sum_{abjj'} f_a \otimes f_b \otimes d\sigma_{ab\to jX} \otimes P_{j\to j'} \otimes D_{h/j'}$$

Cold nuclear matter effect

- Nuclear shadowing effect
  - Nucleons in nucleus are "shadowed" by other nucleons at small x
  - Momentum conservation requires anti-shadowing effect at larger x

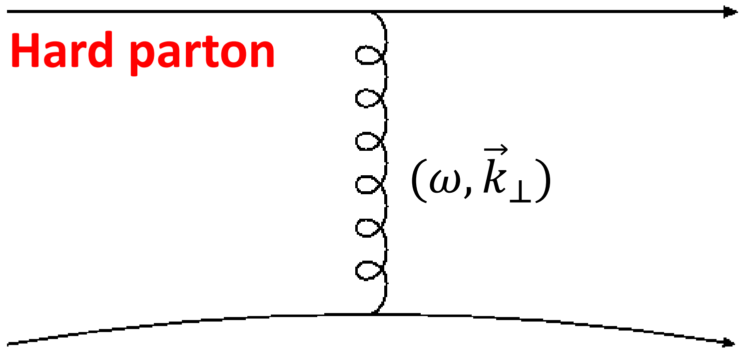


- Cronin effect
  - Momentum broadening of partons before hard scatterings



- CNM effects can be constrained using pA or dA collisions

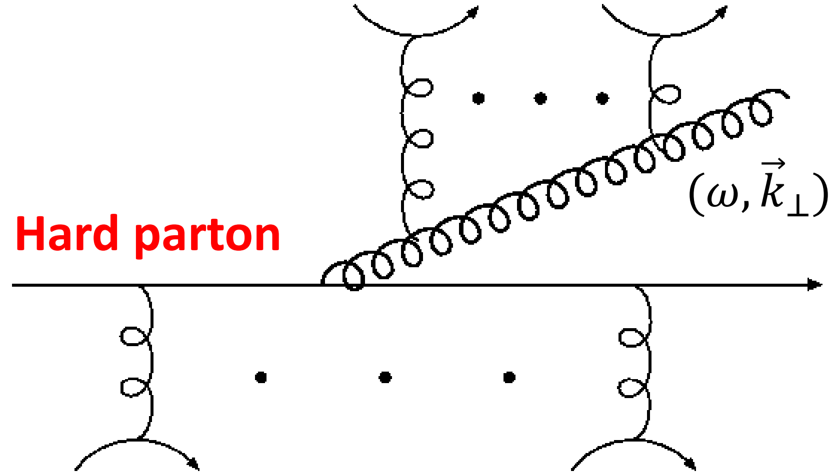
Hot nuclear matter effect



Elastic (collisional)

$$\frac{d\Gamma_{coll}}{d\omega dk_\perp^2 dt}(T, E, \dots) = ?$$

Bjorken 1982; Bratten, Thoma 1991; Thoma, Gyulassy, 1991; Mustafa, Thoma 2005; Peigne, Peshier, 2006; Djordjevic, 2006; Wicks et al (DGLV), 2007; GYQ et al (AMY), 2008; …

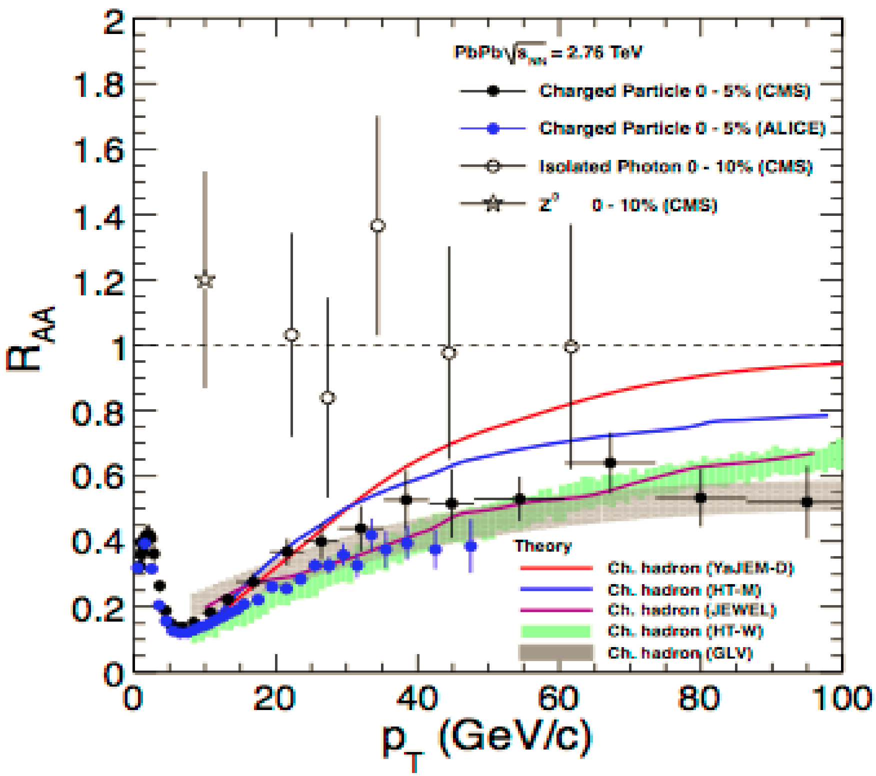


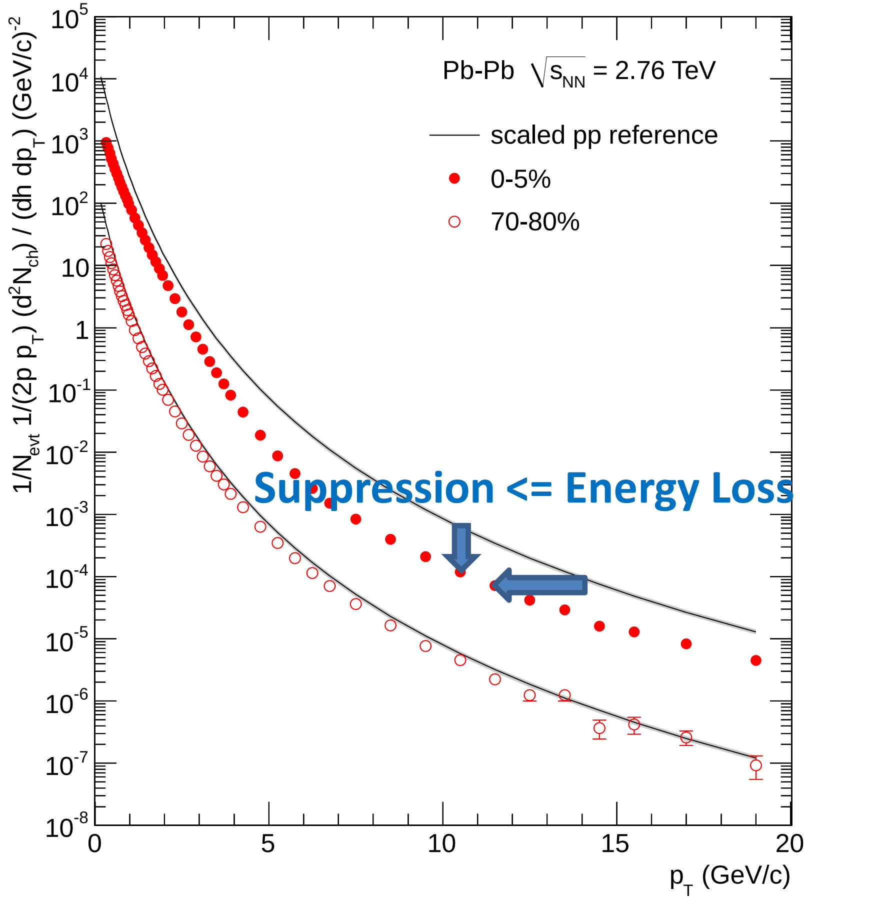
Inelastic (radiative)

$$\frac{d\Gamma_{rad}}{d\omega dk_\perp^2 dt}(T, E, \dots) = ?$$

BDMPS-Z: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov
ASW: Amesto-Salgado-Wiedemann
AMY: Arnold-Moore-Yaffe (& Caron-Huot, Gale)
GLV: Gyulassy-Levai-Vitev (& Djordjevic, Heinz)
HT: Wang-Guo (& Zhang, Wang, Majumder)

Jet quenching is the result of energy loss





Nuclear modification factor:

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{N_{coll}dN_{pp}/dp_T} = \frac{dN_{pp}(p_T+\Delta p_T)/dp_T}{dN_{pp}(p_T)/dp_T}$$

A simple analysis

- For a power law distribution, $\frac{\mathrm{d}N}{dp_{Ti}} = \frac{A}{p_{Ti}^n}$,

  where n is larger at RHIC than the LHC.

- Given energy loss fraction $\epsilon = 1 - \frac{p_{Tf}}{p_{Ti}}$,

$$\frac{dN}{dp_{Tf}} = \int dp_{Ti} \frac{dN}{dp_{Ti}} \delta\left(p_{Tf} - (1-\epsilon)p_{Ti}\right)$$

$$= \frac{1}{(1-\epsilon)} \left(\frac{\mathrm{d}N}{dp_{Ti}}\right)_{p_{Ti}=\frac{p_{Tf}}{1-\epsilon}} = (1-\epsilon)^{n-1} \frac{A}{p_{Tf}^n}$$

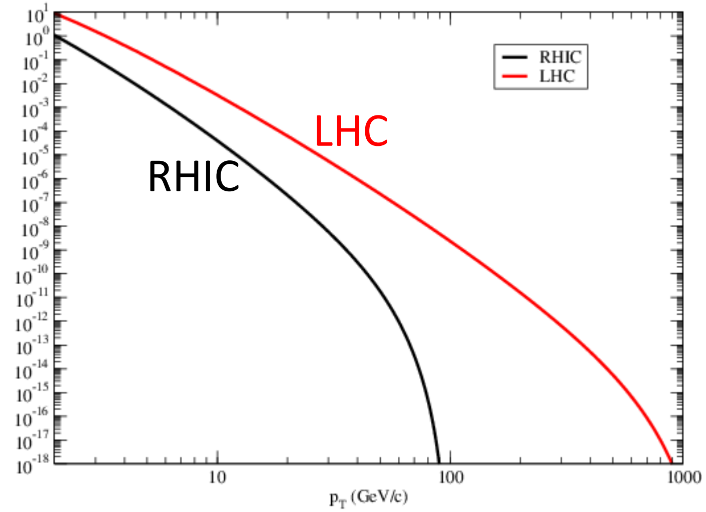
$$R_{AA} = (1-\epsilon)^{n-1}$$

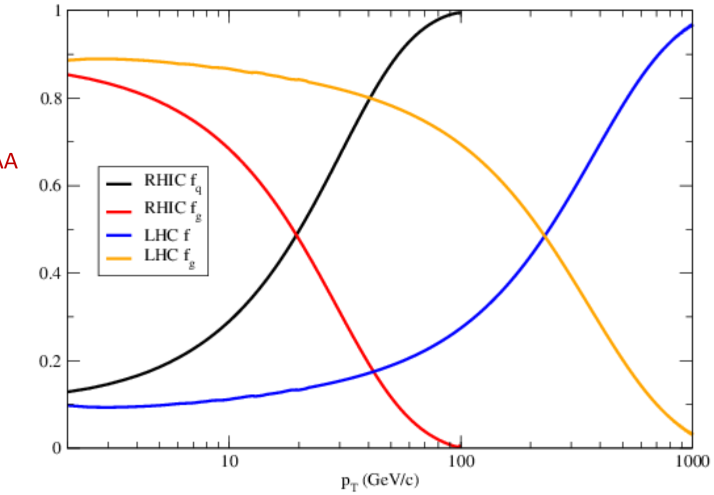
- If ϵ and n are independent of p_T, then R_{AA} is constant.
- Usually, n increases with p_T while ϵ decreases with p_T , so R_{AA} first increases then decreases with p_T (if no other effects).
- For energy loss fraction distribution $P(\epsilon)$,

$$\frac{dN}{dp_{Tf}} = \int dp_{Ti} \frac{dN}{dp_{Ti}} \int d\epsilon P(\epsilon) \delta\left(p_{Tf} - (1-\epsilon)p_{Ti}\right)$$

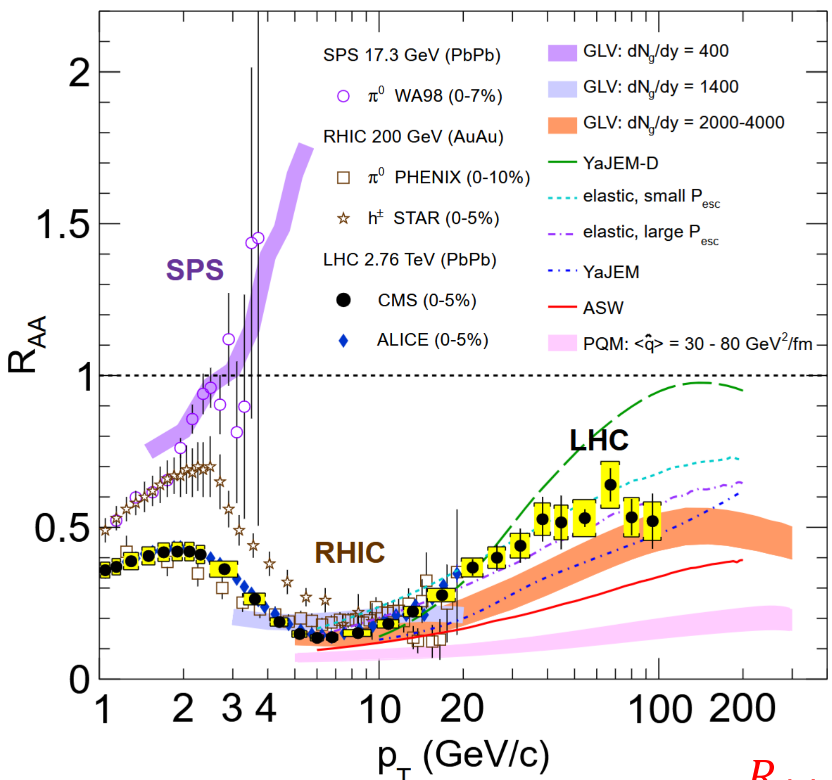
$$= \int \frac{d\epsilon}{(1-\epsilon)} P(\epsilon) \left(\frac{\mathrm{d}N}{dp_{Ti}}\right)_{p_{Ti}=\frac{p_{Tf}}{1-\epsilon}} = \int d\epsilon (1-\epsilon)^{n-1} P(\epsilon) \frac{A}{p_{Tf}^n}$$

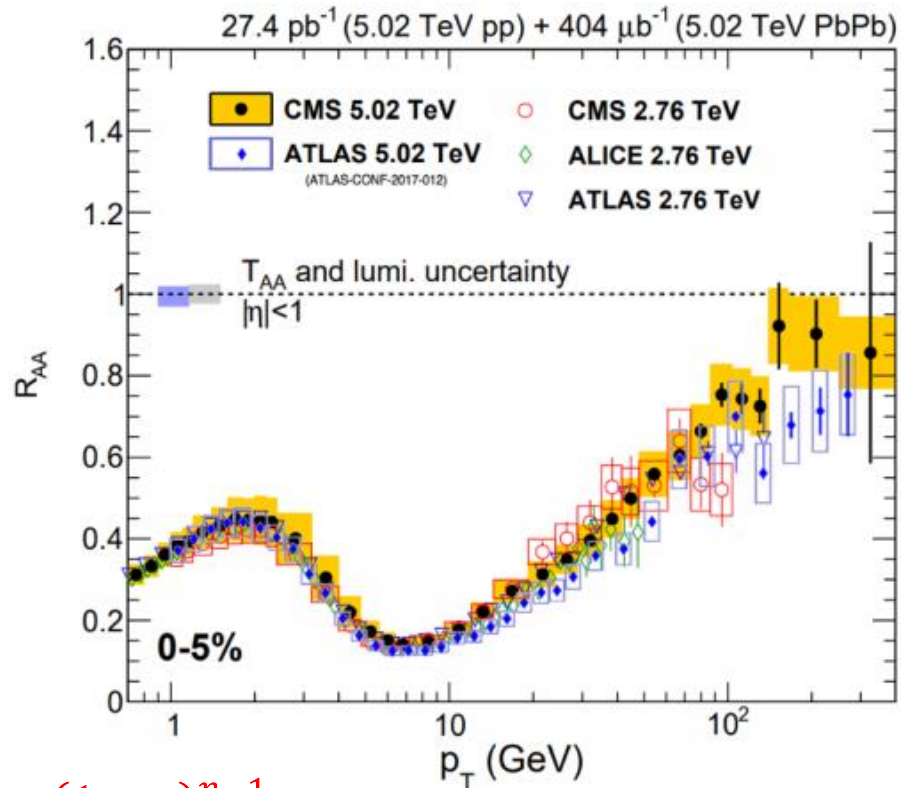
$$R_{AA} = \int d\epsilon (1-\epsilon)^{n-1} P(\epsilon)$$





Similar quenching at RHIC and the LHC





$R_{AA} \sim (1-\epsilon)^{n-1}$

Similar R_{AA} in different colliding energies: larger QGP & energy loss at higher colliding energies.

Smaller R_{AA} at higher p_T: parton energy loss and power n of parton spectrum depend on energy/momentum.

Where does the leading hadron come from?

- For a power law distribution of jet spectrum, $\frac{dN}{dp_{Tj}} = \frac{A}{p_{Tj}^n}$, where n is large number, the leading hadron spectrum is given by

$$\frac{dN}{dp_{Th}} = \int dz D(z) \int dp_{Tj} \frac{dN}{dp_{Tj}} \delta(p_{Th} - z p_{Tj})$$

$$= \int \frac{dz}{z} D(z) \left(\frac{dN}{dp_{Tj}}\right)_{p_{Tj}=\frac{p_{Th}}{z}} = \int dz z^{n-1} D(z) \frac{A}{p_{Th}^n}$$

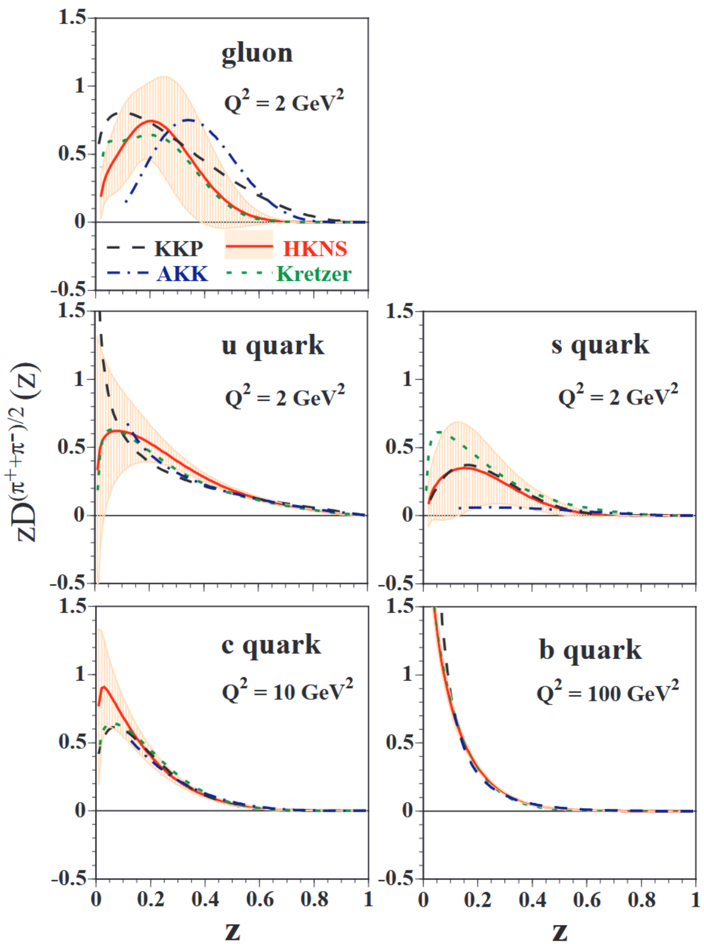
- While D(z) is usually a deep-falling function, the leading hadron is actually produced from the large z region of D(z), i.e., the leading fragment of the jet.
- Putting energy loss and fragmentation together

$$\frac{dN}{dp_{Th}} = \int dp_{Tj} \frac{dN}{dp_{Tj}} \int d\epsilon P(\epsilon) \int dz D(z) \delta\big(p_{Th} - z(1-\epsilon) p_{Tj}\big)$$

$$= \int \frac{d\epsilon}{(1-\epsilon)} P(\epsilon) \int \frac{dz}{z} D(z) \left(\frac{dN}{dp_{Tj}}\right)_{p_{Tj}=\frac{p_{Th}}{z(1-\epsilon)}}$$

$$= \int dz z^{n-1} D(z) \int d\epsilon (1-\epsilon)^{n-1} P(\epsilon) \frac{A}{p_{Th}^n}$$

$$\Rightarrow \int dz z^{n-1} D(z) \int d\epsilon (1-\epsilon)^{n-1} P\left(\epsilon, \frac{p_{Th}}{z(1-\epsilon)}\right) \frac{A}{p_{Th}^{n\left(\frac{p_{Th}}{z(1-\epsilon)}\right)}}$$

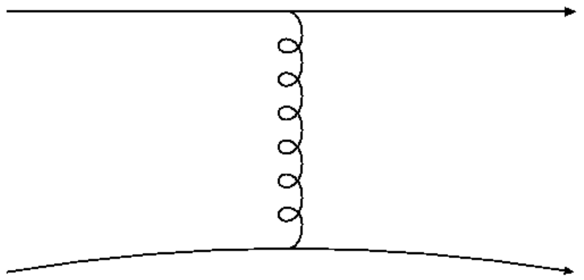


Phys.Rev.D 75 (2007) 094009

Elastic/collisional energy loss

- From kinetic theory, the elastic scattering rate:

$$\Gamma_{ab\to cd}(\vec{p}_a, T) = \frac{\gamma_2}{2E_a}\int \frac{d^3p_b}{(2\pi)^3 2E_b}\frac{d^3p_c}{(2\pi)^3 2E_c}\frac{d^3p_d}{(2\pi)^3 2E_d} \times f_b(\vec{p}_b, T)[1 \pm f_c(\vec{p}_c, T)][1 \pm f_d(\vec{p}_d, T)] \times (2\pi)^4\delta^{(4)}(p_a + p_b - p_c - p_d)|\mathcal{M}_{ab\to cd}|^2$$



- The collisional energy loss rate:

$$\frac{dE}{dt} = \frac{g_k}{2E}\int\frac{d^3k}{(2\pi)^3 2k}\int\frac{d^3p'}{(2\pi)^3 2E'}\int\frac{d^3k'}{(2\pi)^3 2k'} (2\pi)^4\delta^4(P + K - P' - K')(E - E')|\bar{M}|^2 f(k)[1 \pm f(k')]$$

$$\left.\frac{dE}{dt}\right|_{qq} = \frac{2}{9}n_f\pi\alpha_s^2T^2\left[\ln\frac{ET}{m_g^2} + c_f + \frac{23}{12} + c_s\right]$$

$$\left.\frac{dE}{dt}\right|_{qg} = \frac{4}{3}\pi\alpha_s^2T^2\left[\ln\frac{ET}{m_g^2} + c_b + \frac{13}{6} + c_s\right]$$

$$\left.\frac{dE}{dt}\right|_{gq} = \frac{1}{2}n_f\pi\alpha_s^2T^2\left[\ln\frac{ET}{m_g^2} + c_f + \frac{13}{6} + c_s\right]$$

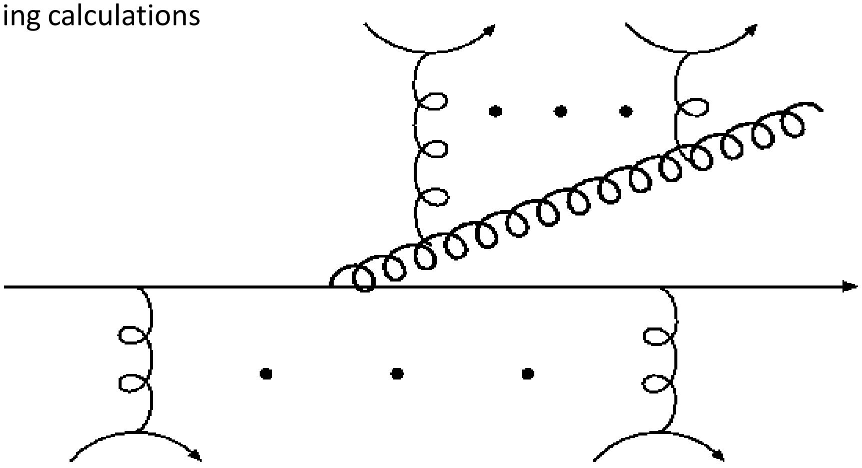
$$\left.\frac{dE}{dt}\right|_{gg} = 3\pi\alpha_s^2T^2\left[\ln\frac{ET}{m_g^2} + c_b + \frac{131}{48} + c_s\right]$$

- It is infrared logarithmic divergent, screened by plasma effects which are incorporated by including HTL corrections for soft momenta of order gT

Bjorken 1982; Bratten, Thoma 1991; Thoma, Gyulassy, 1991; Mustafa, Thoma 2005; Peigne, Peshier, 2006; Djordjevic (GLV), 2006; Wicks et al (DGLV), 2007; GYQ et al (AMY), 2008

Medium-induced radiation

- **Single gluon emission kernel:**
  - The starting point or central goal in most jet quenching calculations



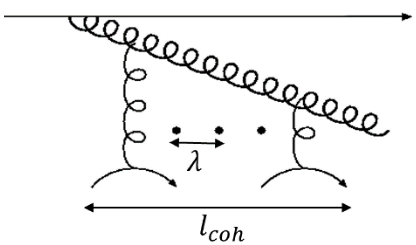
- **PQCD-based formalisms:**
  - Multiple soft scatterings (BDMPS-Z, ASW, AMY)
  - Few hard scatterings (GLV, ASW, HT)
  - **BDMPS-Z:** Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov
  - **ASW:** Amesto-Salgado-Wiedemann
  - **AMY:** Arnold-Moore-Yaffe
  - **DGLV:** Djordjevic-Gyulassy-Levai-Vitev
  - **HT:** Wang-Guo-Majumder

- **Some later developments:**
  - AMY: finite L (Caron-Huot, Gale 2010)
  - GLV: finite dynamical medium (Djordjevic, Heinz, 2008)
  - DGLV: non-zero magnetic mass (Djordjevic, Djordjevic, 2012)
  - Higher Twist (HT): multiple scatterings (Majumder, 2012)

- **Various approximations:**
  - High energy & eikonal approximations; soft gluon emission approximation (ASW, GLV); collinear expansion (BDMPS-Z, HT); gluon emission induced by transverse scatterings

- **More recent improvements:**
  - Include non-eikonal corrections within path integral formalism (Apolinrio, Armesto, Milhano, Salgado, arXiv:1407.0599)
  - Reinvestigate the GLV formalism by relaxing the soft gluon emission approximation (Blagojevic, Djordjevic, Djordjevic, arXiv:1804.07593; Sievert, Vitev, arXiv:1807.03799)
  - Generalize HT formalism by going beyond collinear expansion and soft gluon emission approximation, including both transverse and longitudinal scatterings, for massless and massive quarks (Zhang, Hou, GYQ, PRC 2018 arXiv:1804.00470; PRC 2019, arXiv:1812.11048; Zhang, GYQ, Wang, PRD 2019, arXiv:1905.12699)

Medium-induced radiation: heuristic discussion



- Neglect logarithmic and numerical factors of O(1) [hep-ph/0002198]
- (1) Mean free path λ for soft scatterings
- (2) Coherence length l_{coh} for induced radiation
- (3) Size L of the medium
- Consider a gluon with energy ω is emitted by a jet parton after N_{coh} coherent soft scatterings. Assuming each soft scattering contributes a momentum kick μ, then the total transverse momentum squared μ_{coh}^2 after N_{coh} coherent scatterings is

$$\mu_{coh}^2 = N_{coh}\mu^2$$

- In the mean time, the distance travelled by the jet parton is given by

$$l_{coh} = N_{coh}\lambda \Rightarrow \mu_{coh}^2 = \frac{l_{coh}}{\lambda}\mu^2$$

- This is also the formation time of the gluon radiation

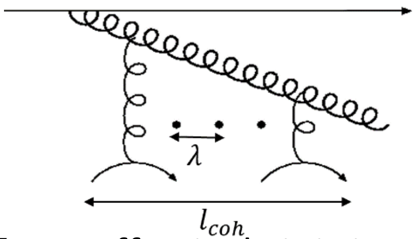
$$l_{coh} = t_{form} = \frac{\omega}{\mu_{coh}^2} = \frac{\lambda\omega}{l_{coh}\mu^2}$$

- Therefore, the coherence time can be obtained

$$l_{coh} = t_{form} = \sqrt{\frac{\lambda\omega}{\mu^2}}$$

Medium-induced radiation: heuristic discussion

- (1) When $l_{coh} \ll \lambda$, i.e., $\omega \ll \lambda\mu^2 = E_{LPM}$, the multiple scatterings are incoherent (independent). This is Bethe-Heitler regime:



$$\omega \frac{dP}{d\omega dL} = \frac{\alpha_s}{\pi} N_c \frac{1}{\lambda}$$

- (2) When $l_{coh} \gg L$, i.e., $\omega \gg \frac{L^2\mu^2}{\lambda} = \left(\frac{L}{\lambda}\right)^2 \lambda\mu^2 = \left(\frac{L}{\lambda}\right)^2 E_{LPM} = E_{fact}$, effectively it is just a single scattering. This is also Bethe-Heitler regime:

$$\omega \frac{dP}{d\omega dL} = \frac{\alpha_s}{\pi} N_c \frac{1}{L}$$

- (3) When $\lambda \ll l_{coh} \ll L$, i.e., $E_{LPM} \ll \omega \ll E_{fact}$, the multiple scatterings are coherent. This is the LPM regime:

$$\omega \frac{dP}{d\omega dL} = \frac{\alpha_s}{\pi} N_c \frac{1}{l_{coh}} = \frac{\alpha_s}{\pi} N_c \sqrt{\frac{\mu^2}{\lambda\omega}}$$

  - RHIC: $L \sim 5fm, \mu \sim 0.5GeV, \lambda \sim 1fm \Rightarrow E_{LPM} \sim 1.25GeV, E_{fact} \sim 30GeV$.
  - LHC: $L \sim 5fm, \mu \sim 1GeV, \lambda \sim 0.5fm \Rightarrow E_{LPM} \sim 2.5GeV, E_{fact} \sim 250GeV$.

Medium-induced radiation: heuristic discussion

- In order to obtain the energy loss per unit distance in the LPM region, one integrate one integrates the gluon spectrum over ω. For $E > E_{fact}$,

$$\frac{dE}{dL} = \int_{E_{LPM}}^{E_{fact}} \omega \frac{dP}{d\omega dL} d\omega \approx \frac{2\alpha_s}{\pi} N_c \sqrt{\frac{\mu^2}{\lambda} E_{fact}} = \frac{2\alpha_s}{\pi} N_c \frac{\mu^2}{\lambda} L$$

- Given that the accumulated transverse momentum broadening due to successive scatterings:

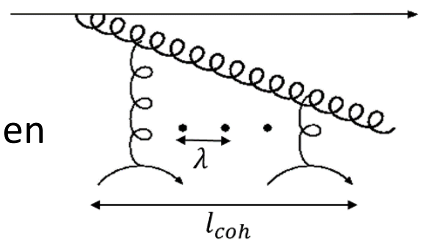
$$\langle k_\perp^2 \rangle_L = \frac{L}{\lambda}\mu^2$$

- One can see that the medium-induced radiative energy loss is controlled by jet broadening:

$$\frac{dE}{dL} = \frac{2\alpha_s}{\pi} N_c \langle k_\perp^2 \rangle_L$$

- Define jet quenching (transport) parameter $\hat{q} = \frac{\langle k_\perp^2 \rangle_L}{L} = \frac{\mu^2}{\lambda} = \frac{\mu_{coh}^2}{l_{coh}}$, then

$$\frac{dE}{dL} = \frac{2\alpha_s}{\pi} N_c \hat{q} L$$

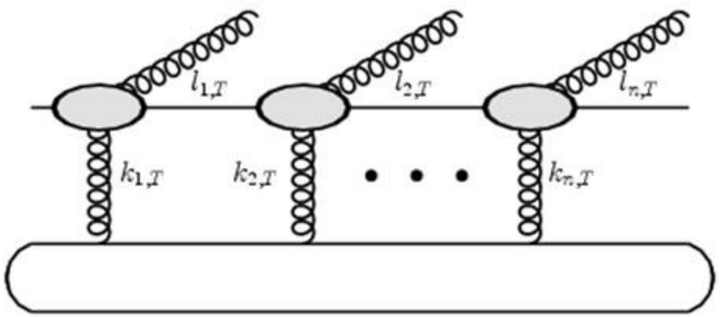


- Integrating over length, one obtains the total energy loss growing as L^2 [hep-ph/0002198],

$$\Delta E = \frac{\alpha_s}{\pi} N_c \hat{q} L^2$$

Multiple gluon emissions

- **Multiple gluon emissions**
  - Full calculations of multiple parton final state need to include the interference between different emissions
  - Common practice: repeat the application of the single gluon emission kernel



- **Poisson convolution (BDMPS/ASW/DGLV)**

$$\mathrm{P}(\Delta E) = \sum_{n=0}^{\infty} \frac{e^{-\langle N_g \rangle}}{n!} \left[\prod_{i=1}^{n} \int d\omega \frac{dI(\omega)}{d\omega} \right] \delta\left(\Delta E - \sum_{i=1}^{n} \omega_i \right)$$

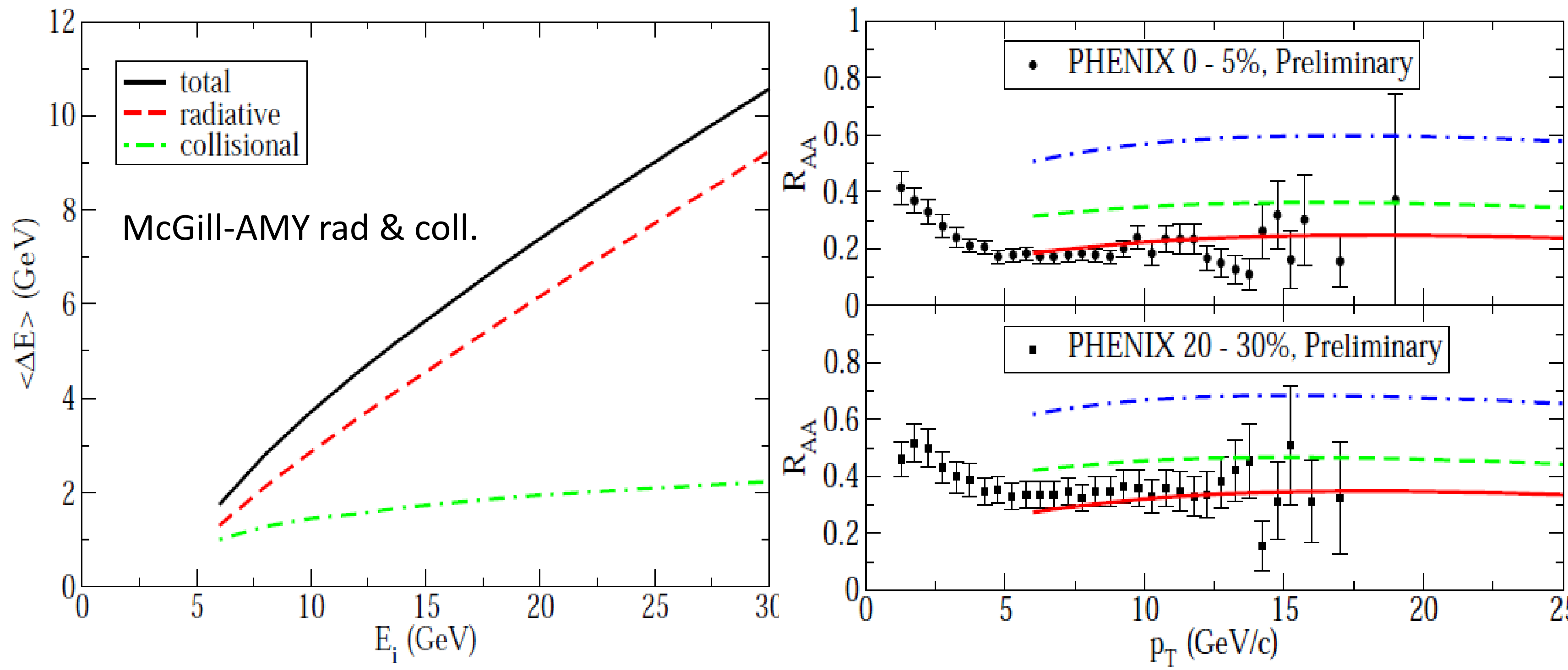
- **Transport approach (AMY)**

$$\frac{df(p,t)}{dt} = \int dk f(p+k,t) \frac{d\Gamma(p+k,k)}{dkdt} - \int dk f(p,t) \frac{d\Gamma(p,k)}{dkdt}$$

- **Meddium-modified DGLAP evolution (HT)**

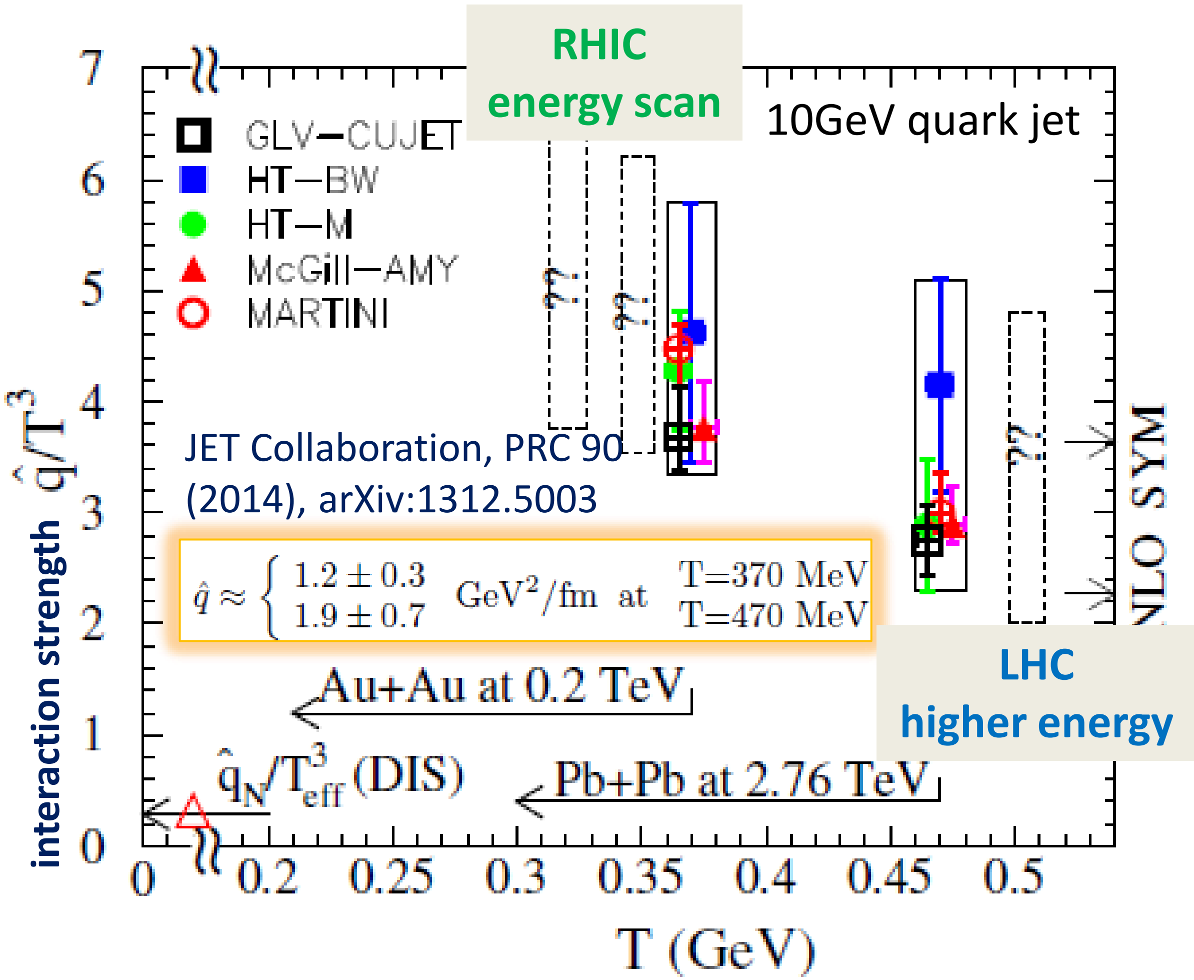
$$\frac{\partial \tilde{D}(z,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi} \int \frac{dy}{y} P(y) \int d\zeta^- K(\zeta^-, q^-, y, Q^2) \tilde{D}(\frac{z}{y}, Q^2)$$

Radiative and collisional energy loss



GYQ, Ruppert, Gale, Jeon, Moore, Mustafa, PRL 2008

Extract $\hat{q}$ by JET collaboration



McGill-AMY:
GYQ, Ruppert, Gale, Jeon, Moore, Mustafa, PRL 2008

HT-BW:
Chen, Hirano, Wang, Wang, Zhang, PRC 2011

HT-M:
Majumder, Chun, PRL 2012

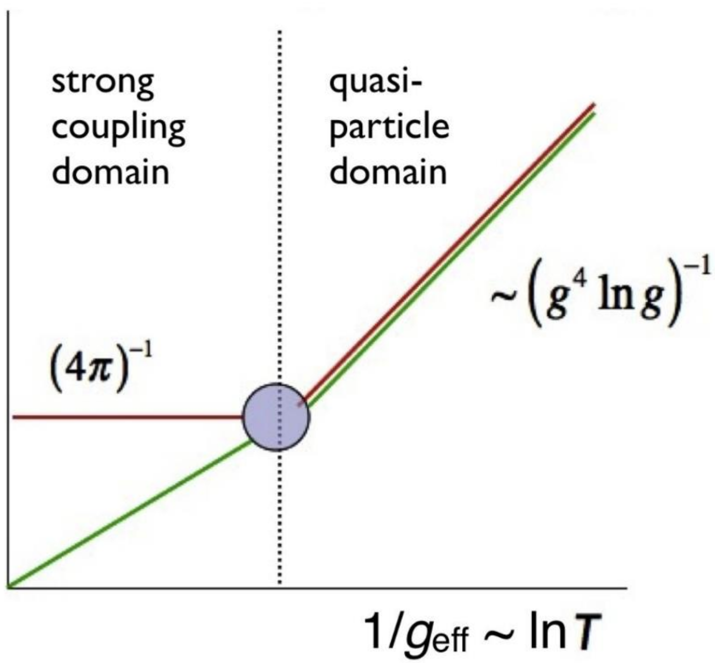
GLV-CUJET:
Xu, Buzzatti, Gyulassy, arXiv: 1402.2956

MARTINI-AMY:
Schenke, Gale, Jeon, PRC 2009

NLO SYM:
Zhang, Hou, Ren, JHEP 2013

$$\Delta E_{rad} = \frac{\alpha_s}{\pi} N_c \hat{q} L^2, \hat{q} = \frac{\langle k_\perp^2 \rangle_L}{L} = \frac{\mu^2}{\lambda}$$

The “perfect” fluid quenches jets almost perfectly



For weak coupling,

$\sigma \sim \frac{4}{\hat{s}} \int dq_\perp^2 q_\perp^2 \frac{d\sigma}{dq_\perp^2} \sim \frac{4\hat{q}}{\hat{s}n}, \eta \sim \frac{1}{3} n\lambda\bar{p} \sim \frac{\bar{p}}{3\sigma} \sim \frac{\bar{p}\hat{s}n}{12\hat{q}},$

$\frac{\eta}{s} \sim \frac{\eta}{3.6n} \sim \frac{\bar{p}\hat{s}}{43.2\hat{q}} \sim \frac{54T^3}{43.2\hat{q}} \sim 1.25\frac{T^3}{\hat{q}}$

$$\frac{\eta}{s} \left\{ \begin{matrix} \approx \\ \gg \end{matrix} \right\} 1.25 \frac{T^3}{\hat{q}} \qquad \left\{ \begin{matrix} \text{for weak coupling,} \\ \text{for strong coupling.} \end{matrix} \right.$$

Figure 4: η/s (upper [red] line) and $1.25\,T^3/\hat{q}$ (lower [green] line) as function of the inverse coupling strength. The two quantities approximately agree in the weak coupling domain, when a quasi-particle picture applies, but not in the strong coupling domain, where $\eta/s > 1.25\,T^3/\hat{q}$.

Reliable determinations of shear viscosity and quenching parameter from RHIC and the LHC can tell a lot about the property of the medium.
How does a weakly-coupled (asymptotic free) QCD medium at extremely high temperature turns into a strongly-interacting QGP at relatively “low” temperature?

A. Majumder, B. Muller, X.-N. Wang, PRL 2007; B. Muller, Prog.Part.Nucl.Phys. 62 (2009) 551

Summary for Lecture II

- Jets are fundamental objects in QCD and collider physics
- High p_T hadron suppression plays an important role for the discovery (and study) of jet quenching, which originates from parton-medium interaction and parton energy loss
- Leading hadron-based observable is sensitive to leading fragment of the jet
- Radiative and collisional energy loss are both important for jet quenching
- Jets (high p_T particles) provide important tools to extract the transport properties of QGP