Physics with Heavy-Ion Beams at SppC

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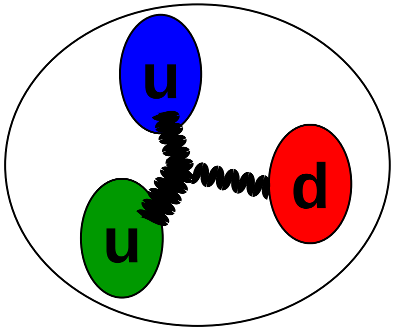
Outline

- QCD and high-energy heavy-ion collisions
- Some main results from RHIC and the LHC
- Selected predictions for heavy-ion collisions at SppC energy
- Summary

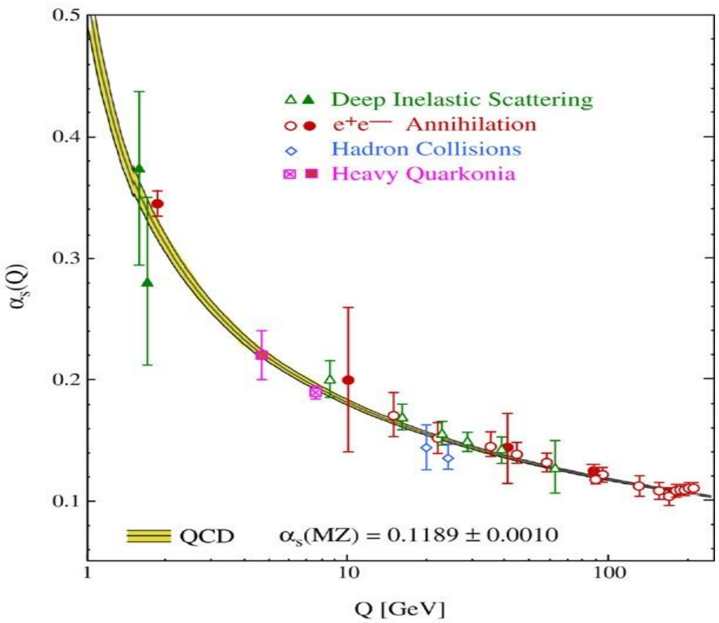
QCD & high-energy heavy-ion collisions

QCD and strong interaction

- QCD is an essential ingredient of Standard Model and the fundamental quantum field theory of the strong interaction
- Elementary fields: quarks and gluons which carry “color” degrees of freedom



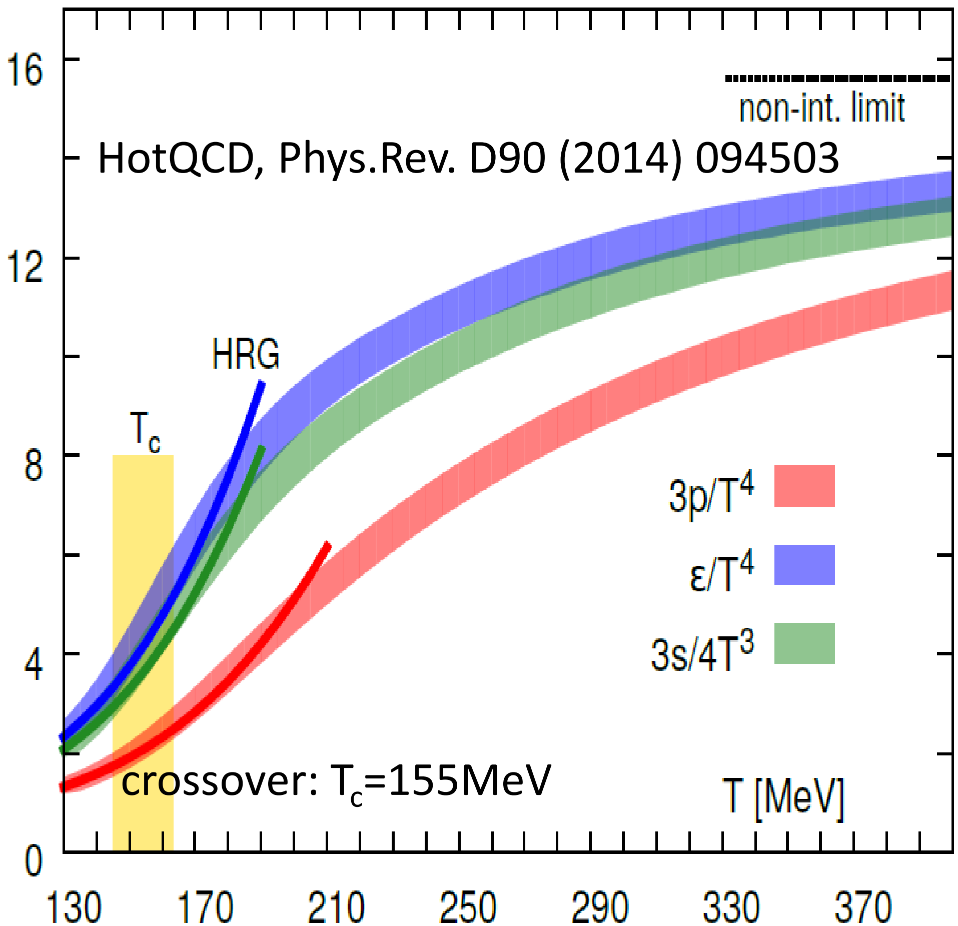
$$\mathcal{L} = \sum_f \overline{\psi}_f (i\gamma^\mu D_\mu - m_f)\psi_f - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu}$$

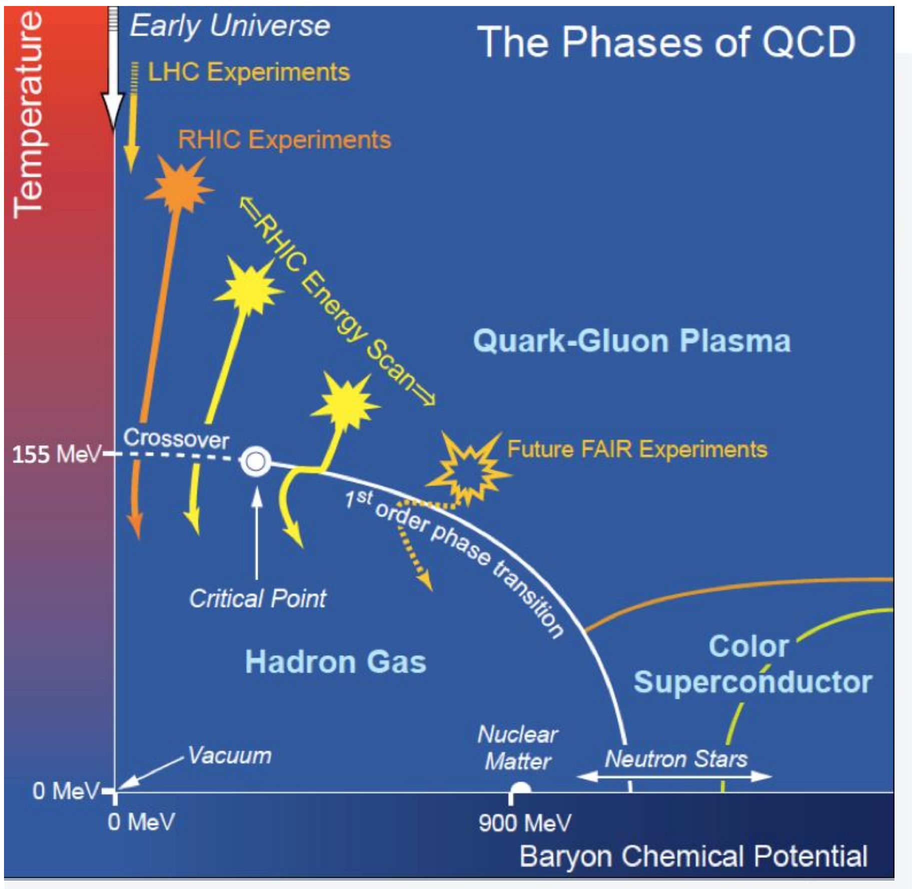


- SU(3) non-Abelian gauge theory
- Asymptotic freedom and confinement
- Approximate chiral symmetry which is spontaneously broken
- Approximate conformal symmetry broken by quantum interaction
- …

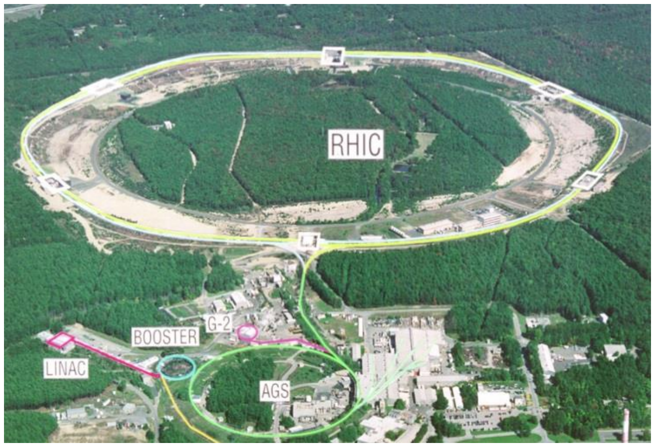
Strong-interaction matter

How QCD behaves at finite/extreme temperatures and densities?



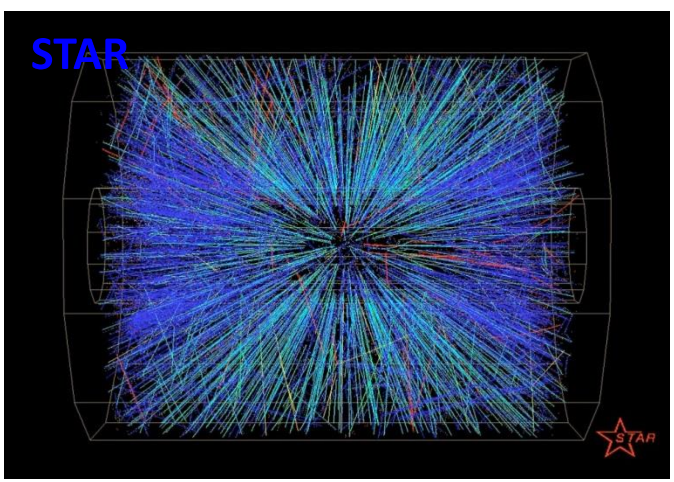


Current two heavy-ion colliders



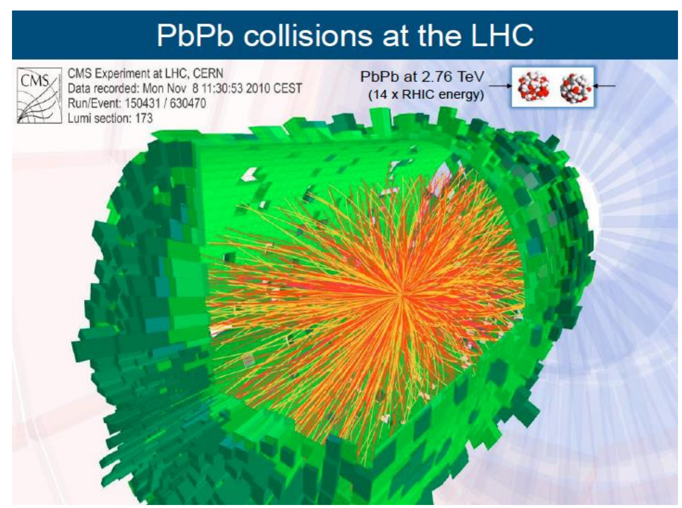
Relativistic Heavy Ion Collider (RHIC)

Au-Au, Cu-Cu,U-U @ $\sqrt{s_{NN}}$=7-200GeV

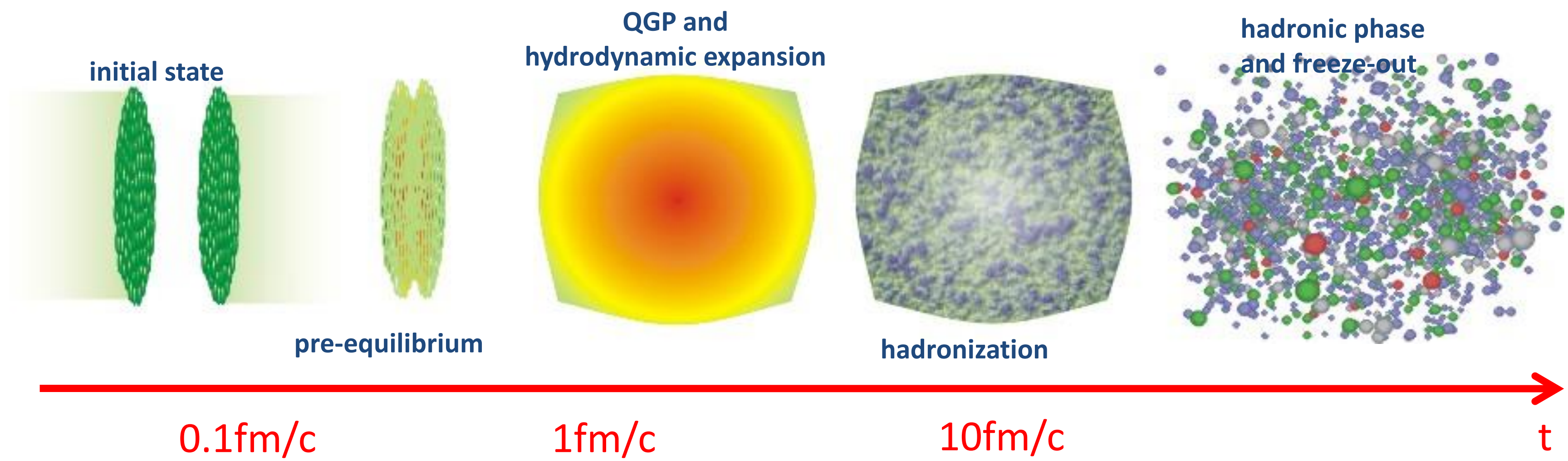


Larger Hadron Collider (LHC)

Pb-Pb @ $\sqrt{s_{NN}}$=2.76-5.5TeV



“Standard Model” of high-energy heavy-ion collisions



Goal: to create QGP (L~10^{-15}m, t~10^{-23}s), and to study the microscopic structure and interaction nature of QCD matter at various conditions (temperature, density, length/momentum scale …)

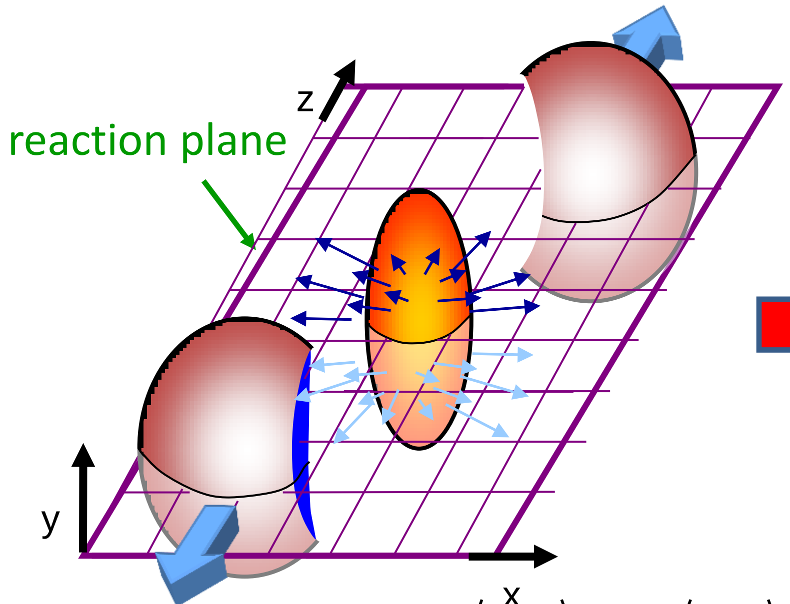
- Soft probes: multiplicity, spectrum, flow, fluctuations, and correlations
- Hard probes: jets, open heavy flavors and heavy quarkonia
- Electromagnetic probes: photons and dileptons
- …

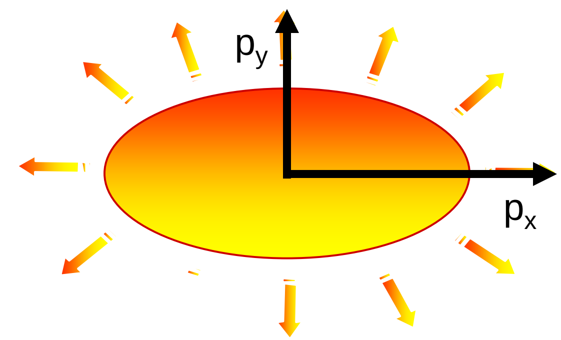
Some important heavy-ion results from RHIC and the LHC

- RHIC
  - Wealthy evidences of the formation of strongly-coupled QGP
    - Strong collective flow
    - Jet quenching
  - Bonus
    - First observation of anti-hypertriton in 2010 & anti-Alpha in 2011 in Au-Au collisions (by STAR Collaboration)

- LHC
  - Confirmed all experimental evidences of QGP, obtained semi-quantitative understanding of QGP
    - Flow: larger specific shear viscosity
    - Jets: smaller jet-medium interaction strength, full jets up to hundreds of GeV, mass ordering for jet quenching (D and non-prompt J/ψ)
  - Surprise
    - Evidence for the collectivity in p-Pb collisions

Anisotropic collective flow





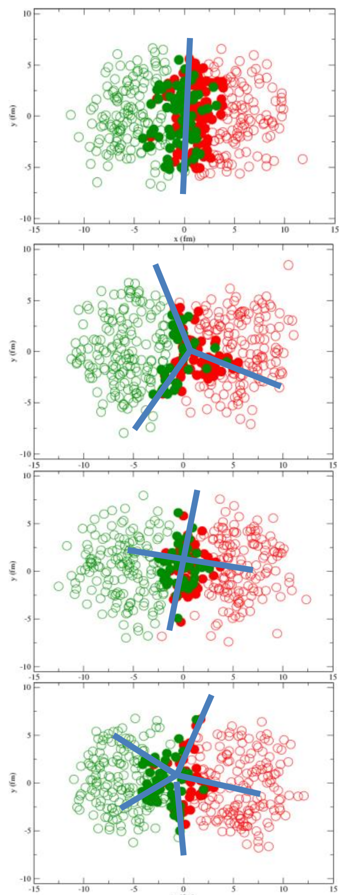
eccentricity $\varepsilon_2 = \dfrac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$ elliptic flow $v_2 = \dfrac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$

The interaction among QGP constituents translates initial state geometric anisotropy to final state momentum anisotropy (particle correlations)

Relativistic hydrodynamics gives nice description of flow => strongly-coupled QGP

Initial state fluctuations and final state correlations

lumpy IC



The lumpiness of the initial conditions leads to anisotropy and inhomogeneity of QGP (e_1, e_2, e_3, e_4, e_5 …)

$$\varepsilon_n e^{in\Phi_n} = \frac{\left\{r^m e^{in(\phi-\Phi_n)}\right\}}{\left\{r^m\right\}} = \frac{\int d^2 r_\perp \rho(r_\perp) r^m e^{in(\phi-\Phi_n)}}{\int d^2 r_\perp \rho(r_\perp) r^m}$$

Initial state fluctuations affect the system evolution and manifest in final state flow and correlations (v_1, v_2, v_3, v_4, v_5 …)

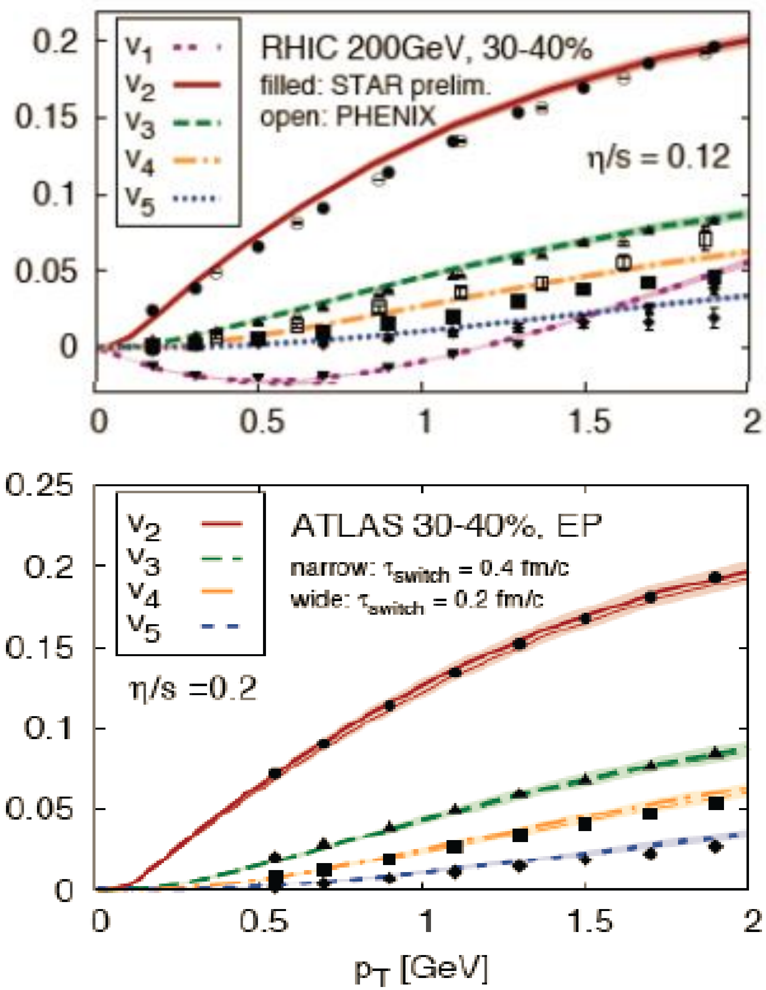
$$\frac{dN}{d\psi} \propto 1 + \sum_n 2v_n \cos[n(\psi - \psi_n)] \qquad v_n e^{in\Psi_n} = \left\{e^{in(\psi-\Psi_n)}\right\}$$

The joint distribution of flow magnitudes and phases:

$$p(v_n, v_m, \ldots, \psi_n, \psi_m, \ldots) = \frac{1}{N_{evt}} \frac{dN_{evt}}{dv_n dv_m \ldots d\psi_n d\psi_m \ldots}$$

Alver and Roland, PRC 2010; GYQ, Petersen, Bass, Muller, PRC 2010; Teaney, Yan, PRC 2011; etc.

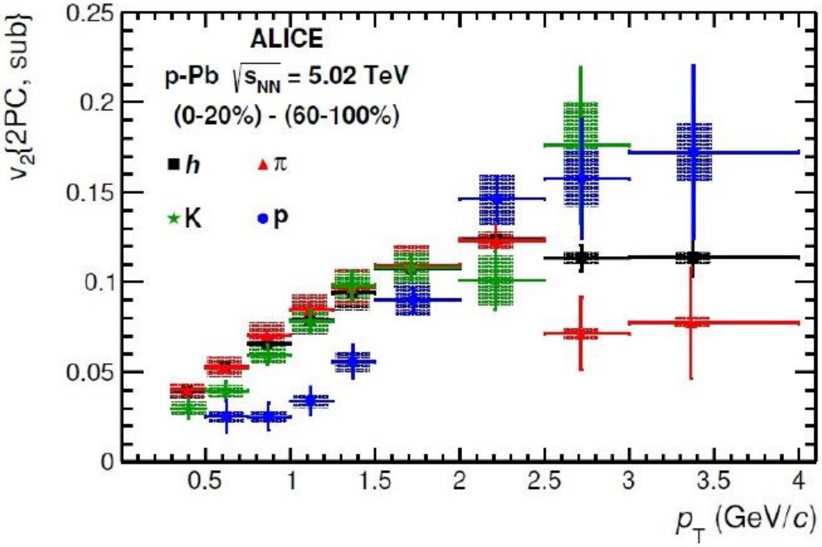
Collective flow at RHIC and the LHC

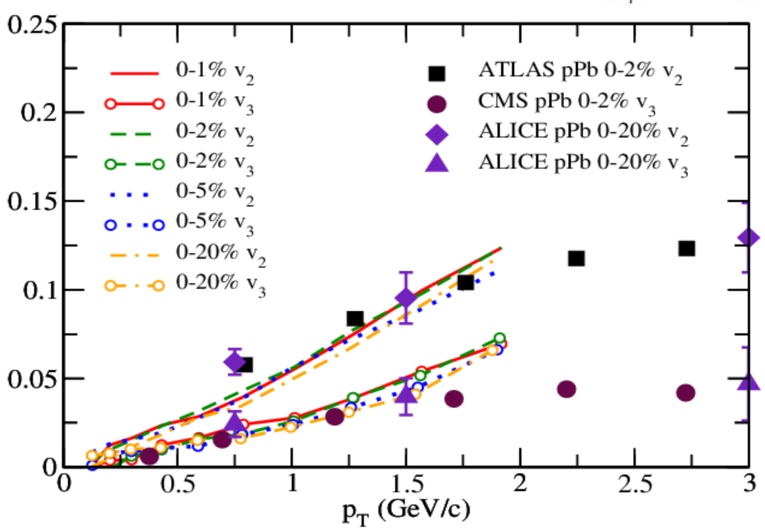


- Initial temperature T_0>T_c => QGP is created
  - 360MeV @RHIC
  - 470MeV @LHC
- Thermalization time: τ_0=0.6fm/c
- Strong collective flow & small specific shear viscosity η/s obtained => strongly-coupled QGP, a relativistic fluid
  - ~0.12 @RHIC
  - ~0.2 @LHC
- One of the largest uncertainties is the incomplete knowledge of initial state (fluctuations)

Gale, Jeon, Schenke, Tribedy, Venugopalan, PRL 2012; etc.

Collectivity in small collision systems

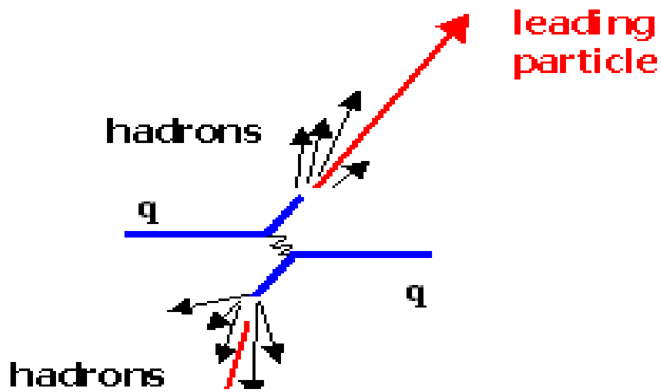


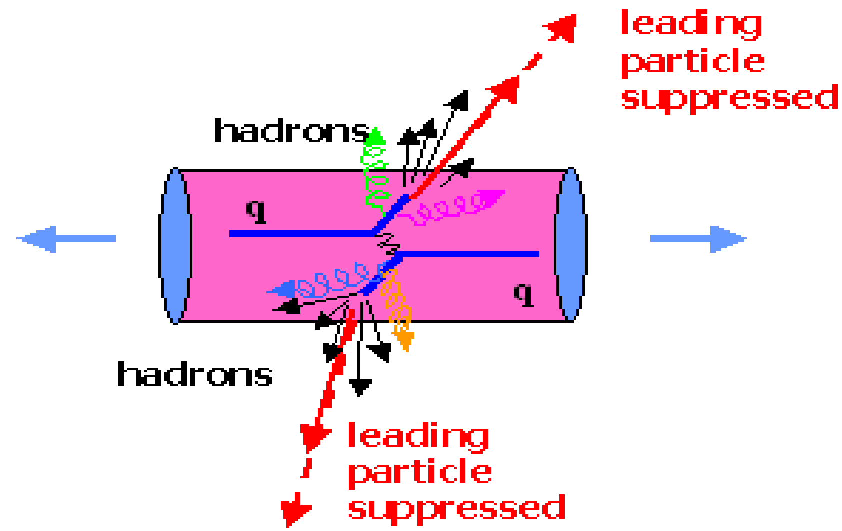


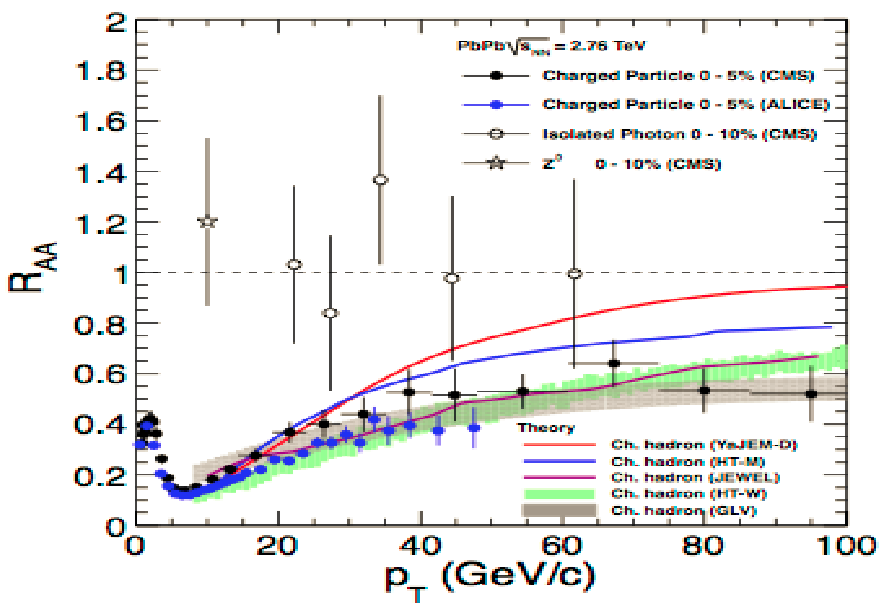
- Collectivity should diminish for smaller system size, so was not expected in p-p and p-A collisions
- But at the LHC, similar long range correlations have been observed in p-A and high multiplicity p-p collisions
- Hydrodynamics provides a natural explanation (so a mini-QGP has been created?), but is also challenged by its applicability in such small systems and the assumption of rapid thermalization
- Initial state quark and gluon correlations?
- How to disentangle initial and final state correlation effects?

Bozek, Broniowski, Torrieri, PRL 2013; GYQ, Muller, PRC 2014; Bzdak, Ma, PRL 2014; etc.

Hard probes of QGP





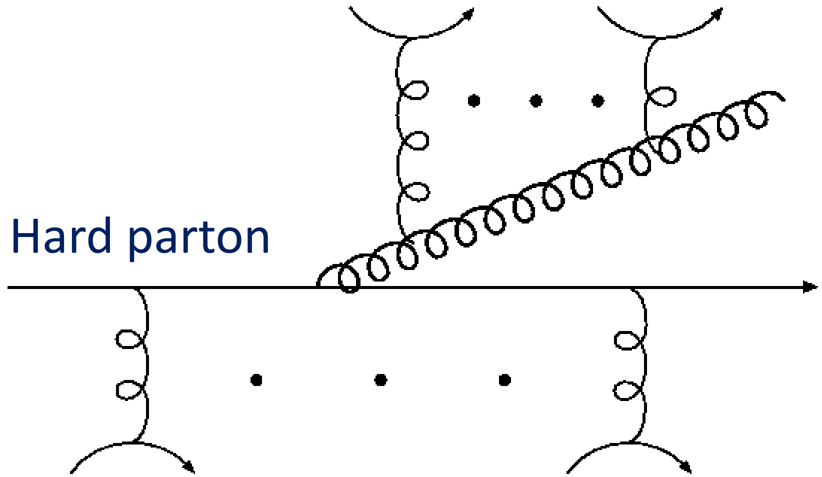


Nuclear modification factor:

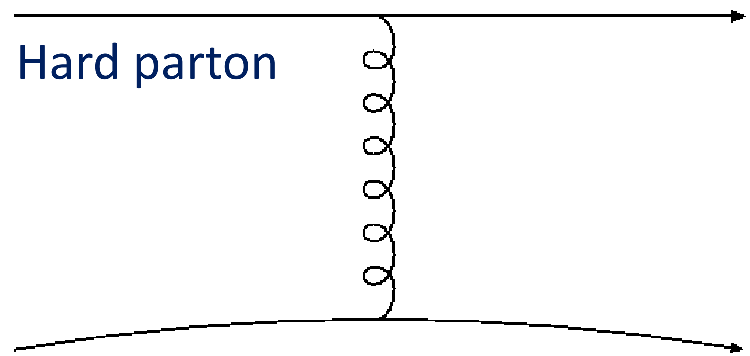
$$R_{AA} = \frac{dN^{AA} / d^2 p_T dy}{N_{\mathrm{coll}} dN^{pp} / d^2 p_T dy}$$

Jet quenching mainly originates from parton energy loss in hot QGP

Parton energy loss and jet transport parameter



Inelastic (radiative)



Elastic (collisional)

Higher-Twist (Wang-Guo-Majumder)

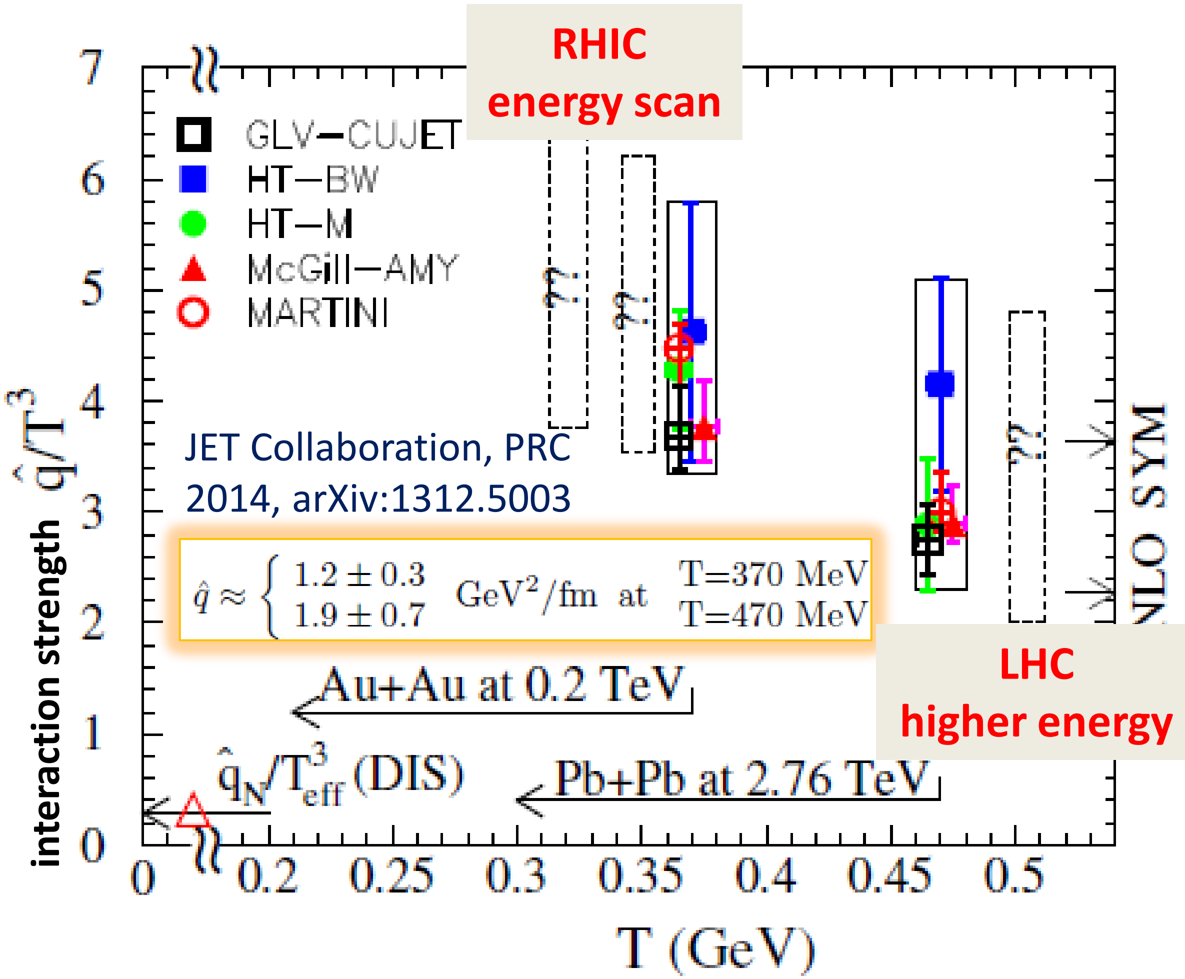
$$\frac{dN_g}{dx dk_\perp^2 dt} \approx \frac{2\alpha_s}{\pi} P(x) \frac{\hat{q}}{k_\perp^4} \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

BDMPS-Z: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov
ASW: Amesto-Salgado-Wiedemann
AMY: Arnold-Moore-Yaffe
DGLV: Djordjevic-Gyulassy-Levai-Vitev

Jet transport coefficient:

$$\hat{q} = \frac{d\langle \Delta p_\perp^2 \rangle}{dt} \approx \frac{4\pi^2\alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle F^{\mu +}(0) F_\mu^+(y^-) \right\rangle = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \rho_A x G_N(x) \Big|_{x\to 0}$$

Jet transport parameter at RHIC and the LHC



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

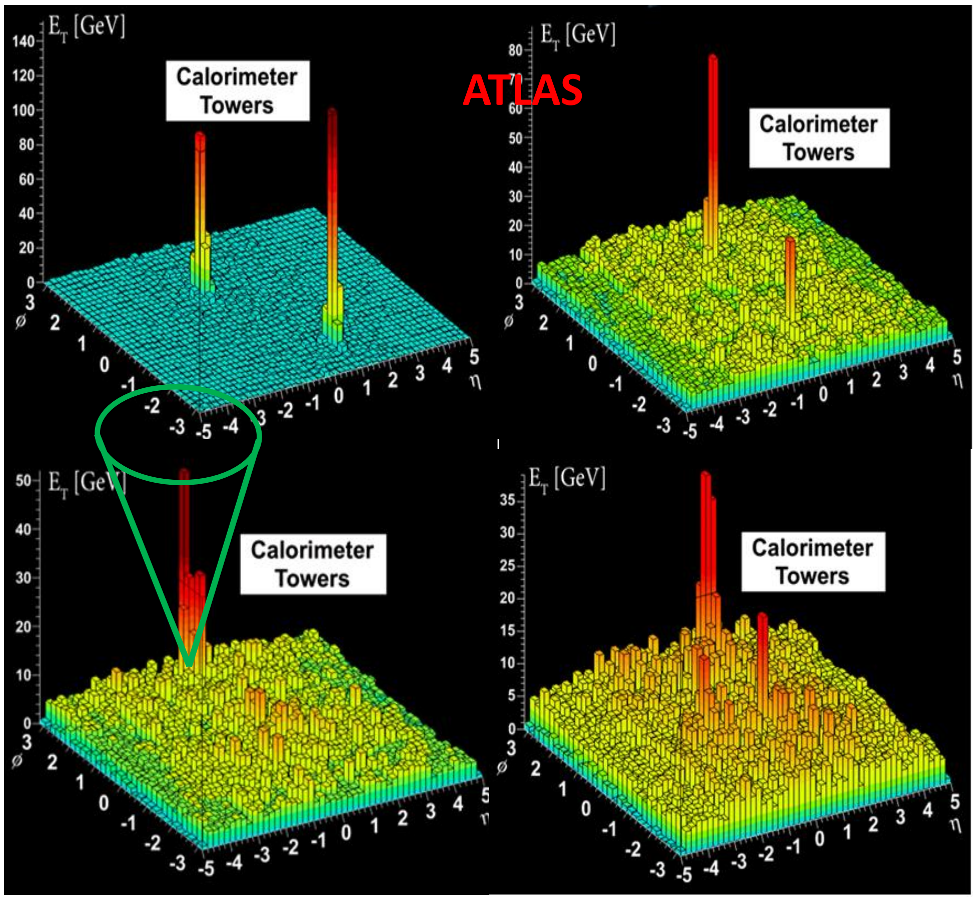
MARTINI-AMY:
Schenke, Gale, Jeon, PRC 2009

NLO SYM:
Zhang, Hou, Ren, JHEP 2013

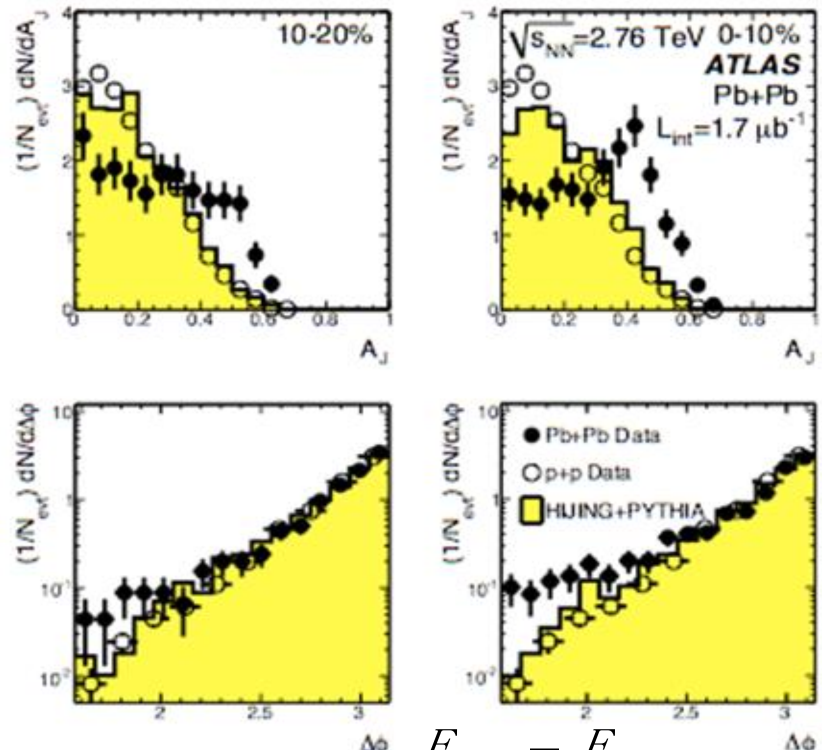
Future: precise determination of T (& E) dependence of jet transport parameters

Full jets in heavy-ion collisions

Full jets are expected to provide more detailed information than single hadron observables



Dijet momentum imbalance

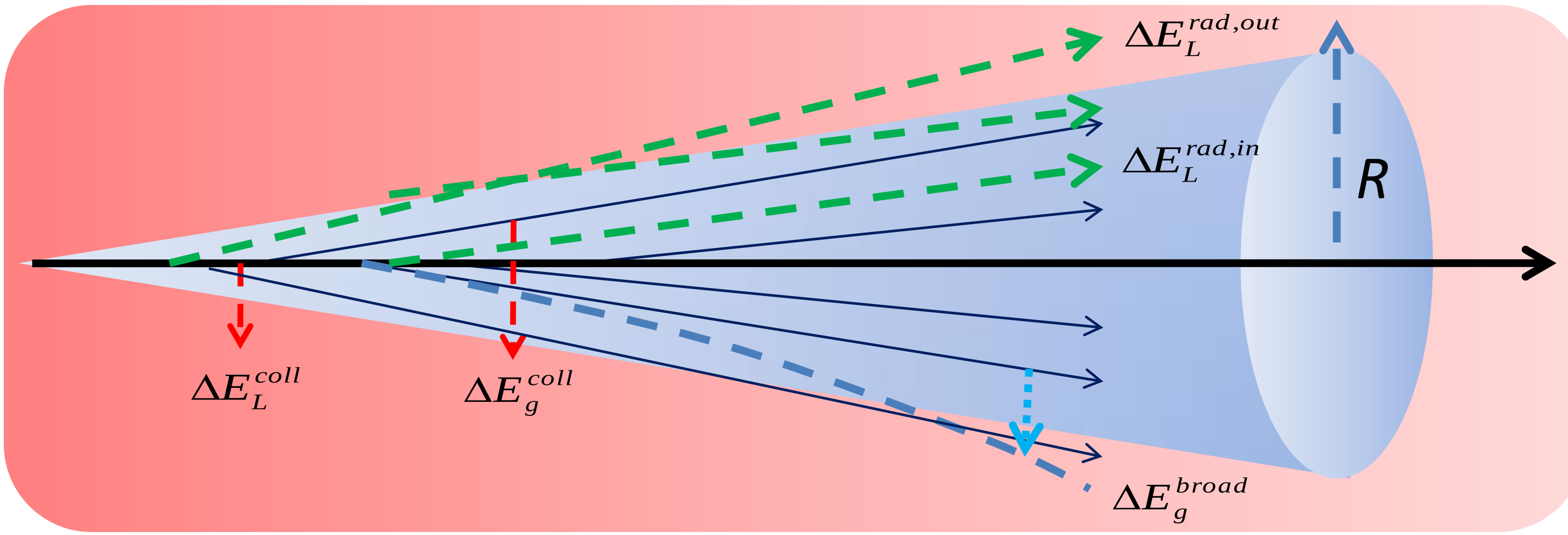


$$A_J = \frac{E_{J,1} - E_{J,2}}{E_{J,1} + E_{J,2}}$$

1. Strong modification of dijet imbalance distribution
2. Largely-unchanged angular distribution

Significant energy loss for the away-sidesubleading jets

Full jet shower evolution in medium



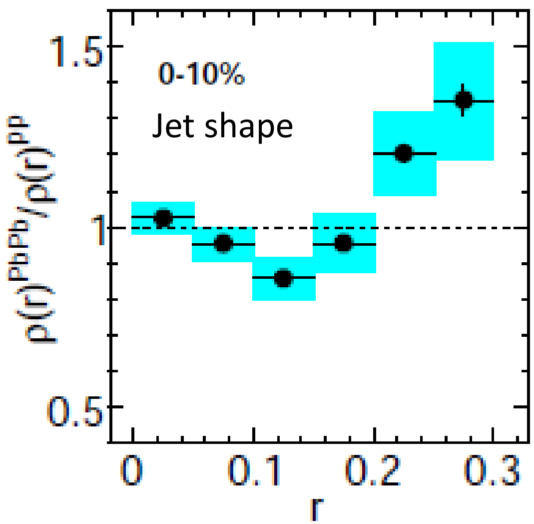
Not only the interaction of the leading hard parton with the medium constituents, but also the fate of radiated shower partons as well

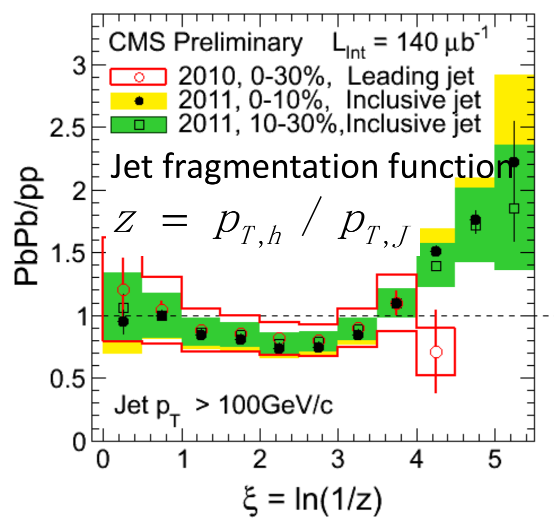
$E_{jet} = E_{in} + E_{lost}$

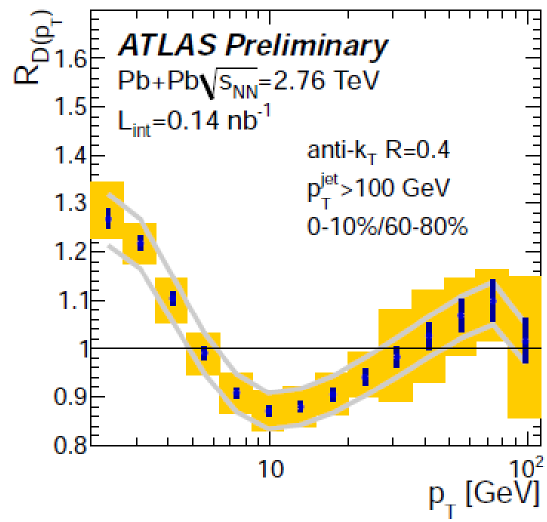
$\quad = E_{in} + E_{out}(\text{radiation}) + E_{out}(\text{broadening}) + E_{th}(\text{collision})$

GYQ, Muller, PRL, 2011; Young, Schenke, Jeon, Gale, PRC, 2011; Dai, Vitev, Zhang, PRL 2013; Wang, Zhu, PRL 2013; Blaizot, Iancu, Mehtar-Tani, PRL 2013; etc.

Full jet structure



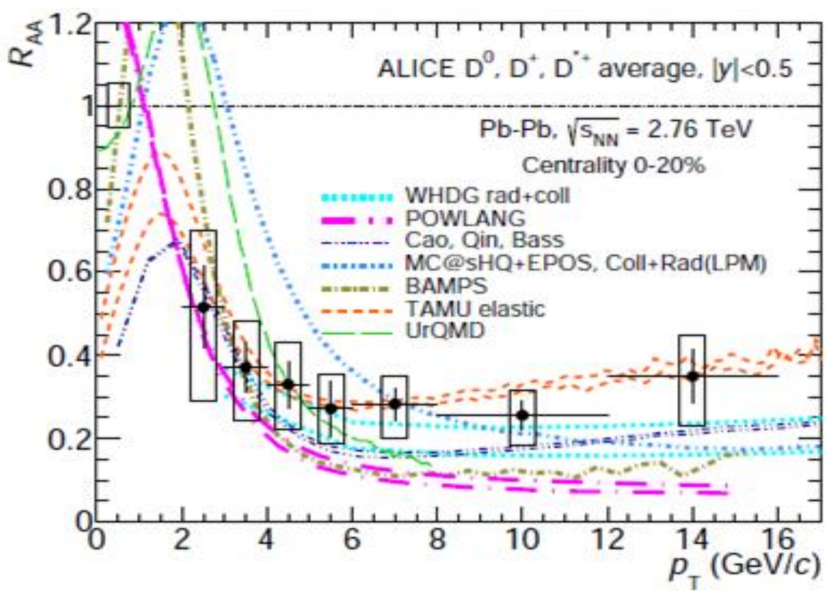


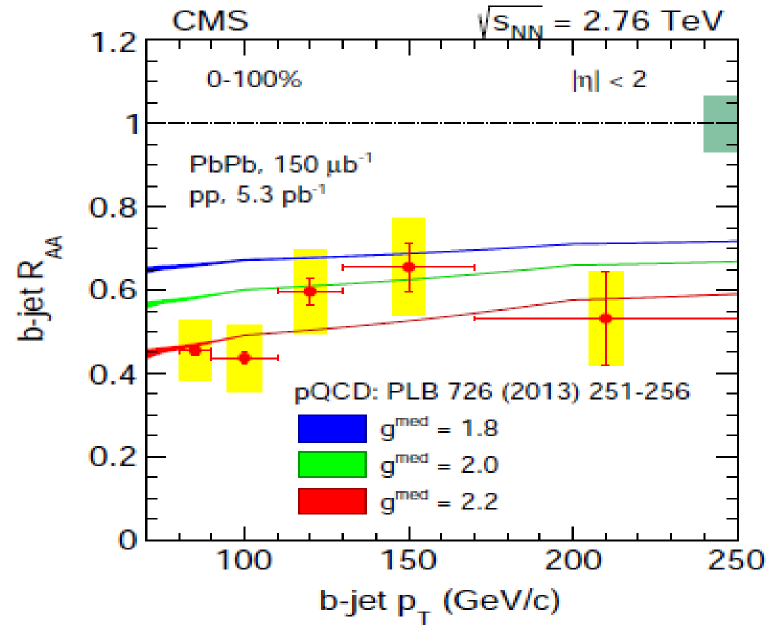


Medium modification of jet fragment (shape) profiles

- Little change at small r; depletion at intermediate r, z; excess at large r, low & high z
- The soft outer part of jets is easier to be modified (some absorbed by medium), while the modification of the inner hard cone is more difficult; the enhancement at large r is consistent with the broadening
- The enhancement at low z is expected from medium-induced radiation; the enhancement at large z can be understood since the inner hard core does not change much while the outer soft part flows to the medium

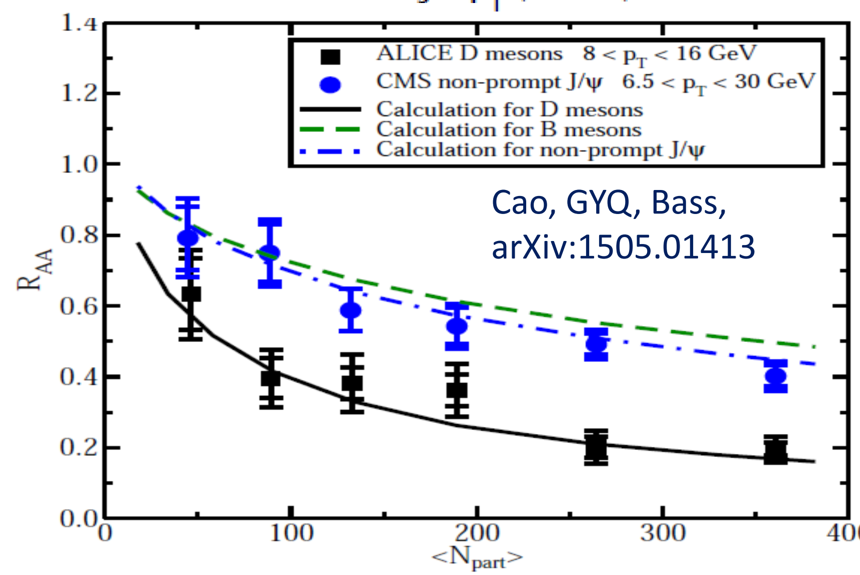
Open heavy flavors



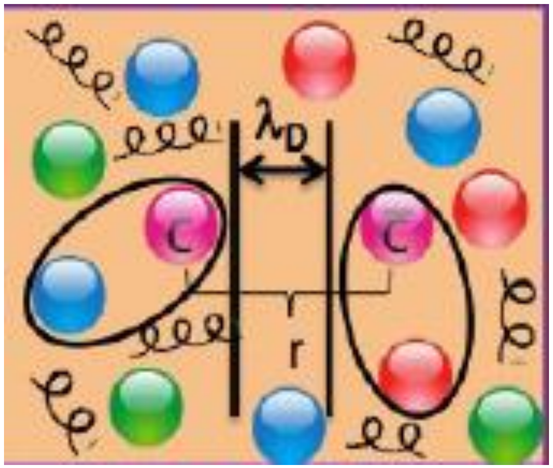


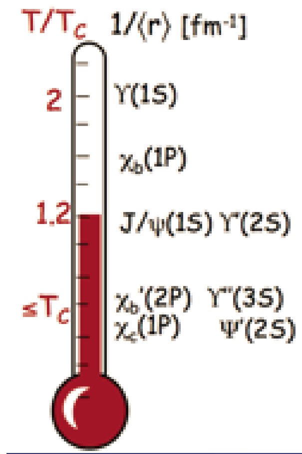
$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b ?$$

- D-mesons show similar suppression to light flavor mesons
- High-p_T b-quark jets show similar suppression to inclusive jets
- Comparison of D-meson production and non-prompt J/ψ from B decays indicates the mass ordering



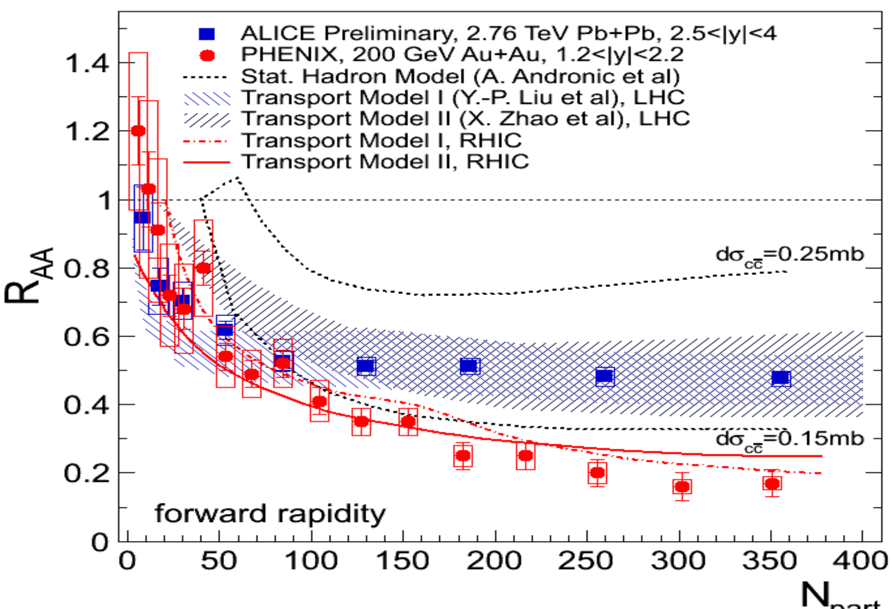
Heavy quarkonia





- J/ψ suppression has been proposed as a signature of QGP
- At high T, when the color screening length λ_D becomes smaller than quarkonium radius r_{QQ}, the bound states melt (dissociate)
- Sequential melting may be used to determine T & λ_D

Matsui, H.Satz, PLB 1986; Karsch, Satz, ZPC , 1991; Karsch, Kharzeev, Satz, PLB 2006



- Less suppression in central collisions at the LHC than at RHIC can be explained well by regeneration mechanism
- Higher temperature at the LHC means: more effective melting, but also much more frequent recombination of heavy quark pairs into quarkonia

What have we learned so far from RHIC & LHC

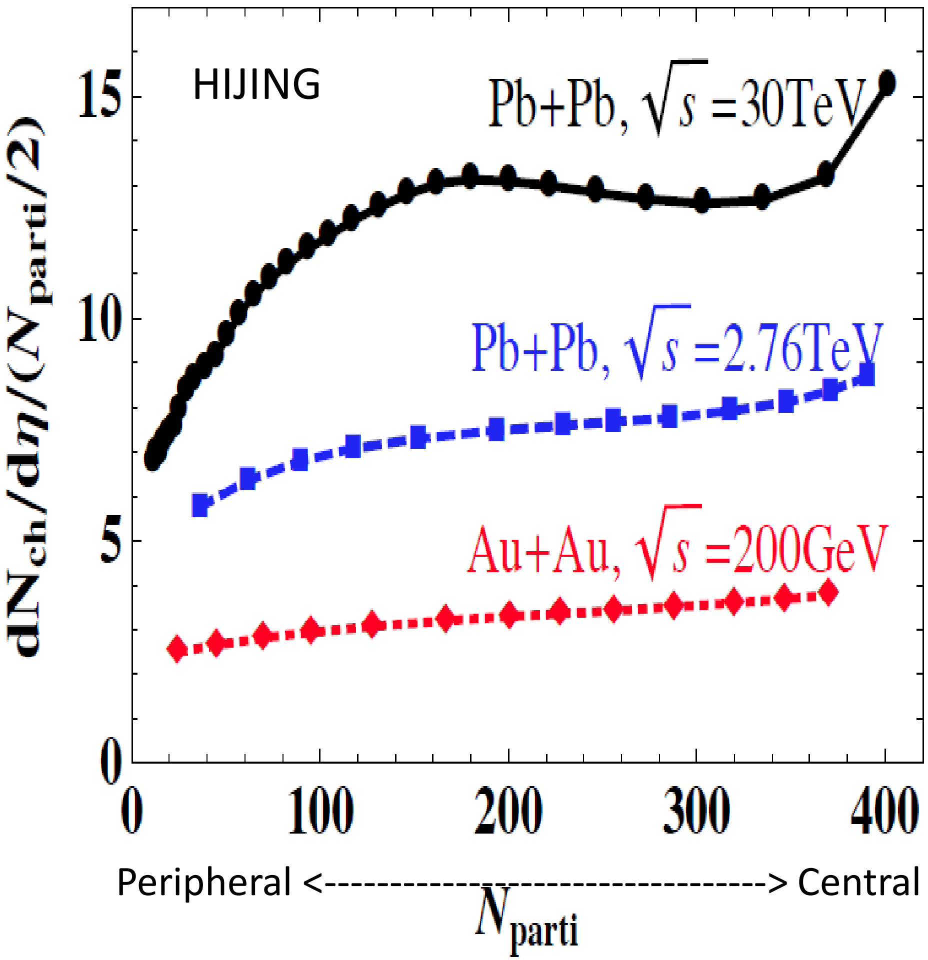
- Lattice QCD gives Tc~155MeV (the transition is a smooth crossover)
- We have created the hottest matter in Universe since it was a few μs old
- The QGP is a strongly-coupled liquid (η/s is larger at the LHC than at RHIC)
- Quantum fluctuations of initial states persist and manifest in the final states (the knowledge of initial states is the largest uncertainties in determining η/s)
- The QGP is highly opaque to colored probes (hard partons are more weakly coupled at the LHC than at RHIC)
- The temperature of the QGP is high enough to melt heavy quarkonia (but the recombination of heavy quark pairs into quarkonia is more frequent at the LHC than at RHIC)
- Evidences for collective behaviors in small collision systems
- …

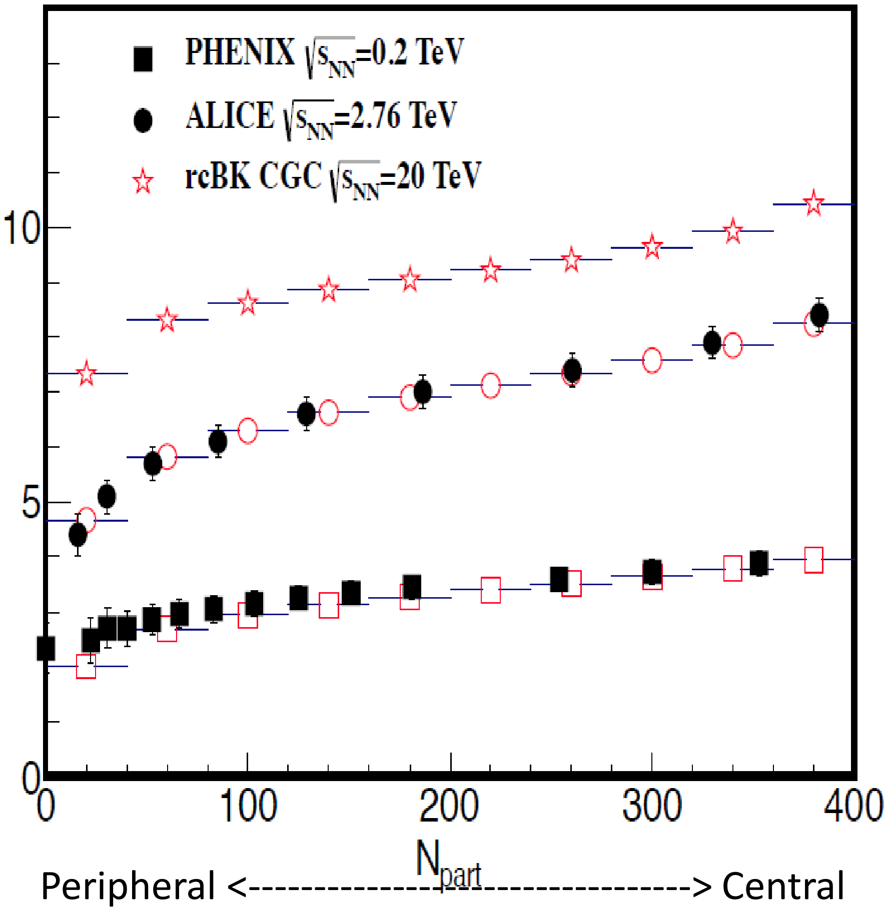
What is still not very clear?

- What is the microscopic origin of the collective properties of QGP?
- What is the nature of the initial state?
  - How to image the high-density gluon fields of incoming nuclei and their fluctuations? How exactly does QCD become a classical high-density gluon system?
- How is QGP formed in heavy-ion collisions?
  - What is the thermalization mechanism? How does the thermalization time depend on collision energy?
- How does QCD matter behaves over a wide range of length/momentum scales?
  - What are the precise values of η/s and jet transport coefficients at various temperatures (scales)?
- What is the smallest QGP that we can create?
- …

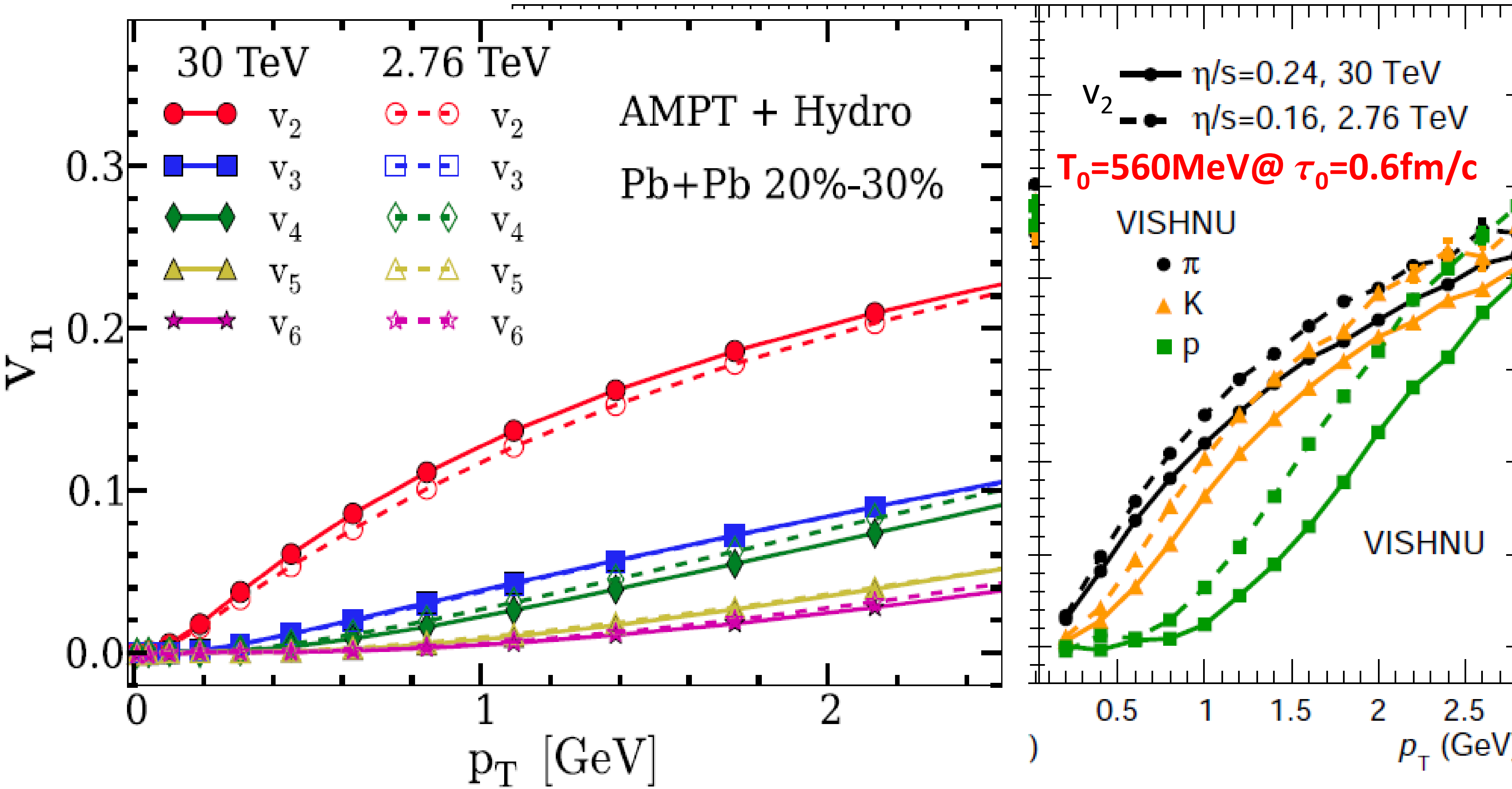
Selected predictions
for heavy-ion beams at SppC

Multiplicity in A-A collisions



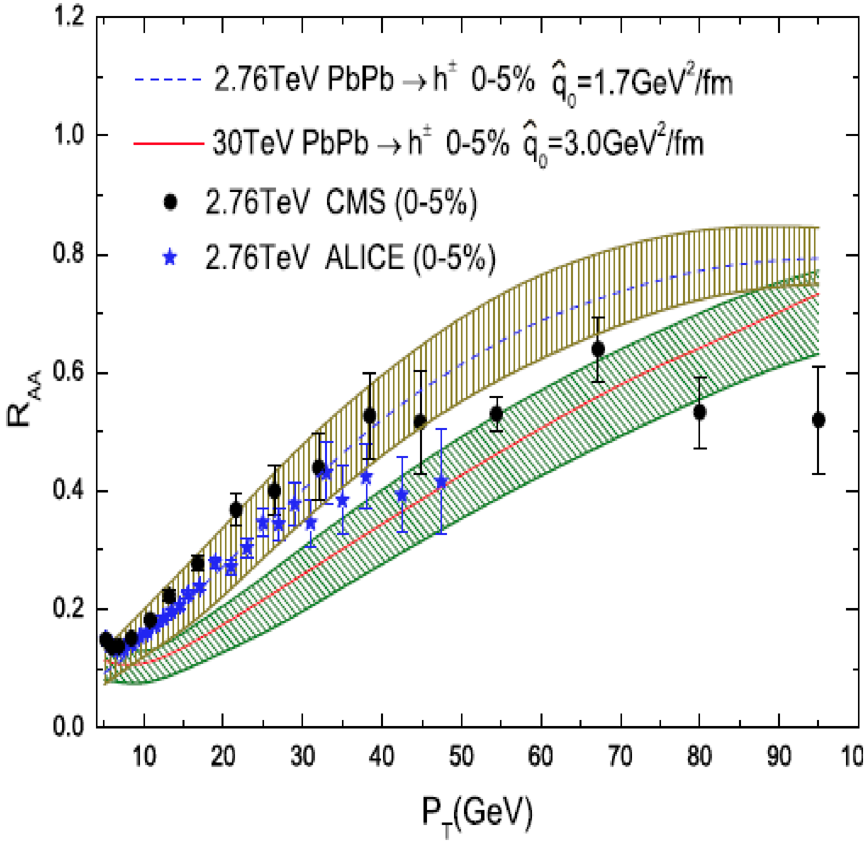


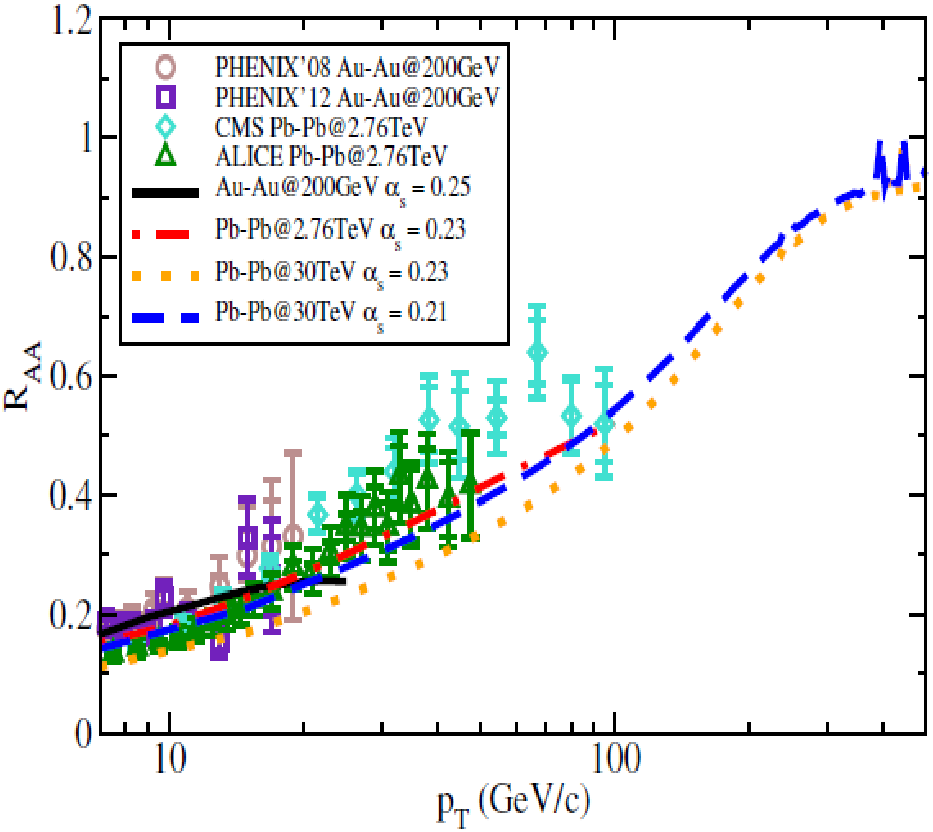
Flow in A-A collisions



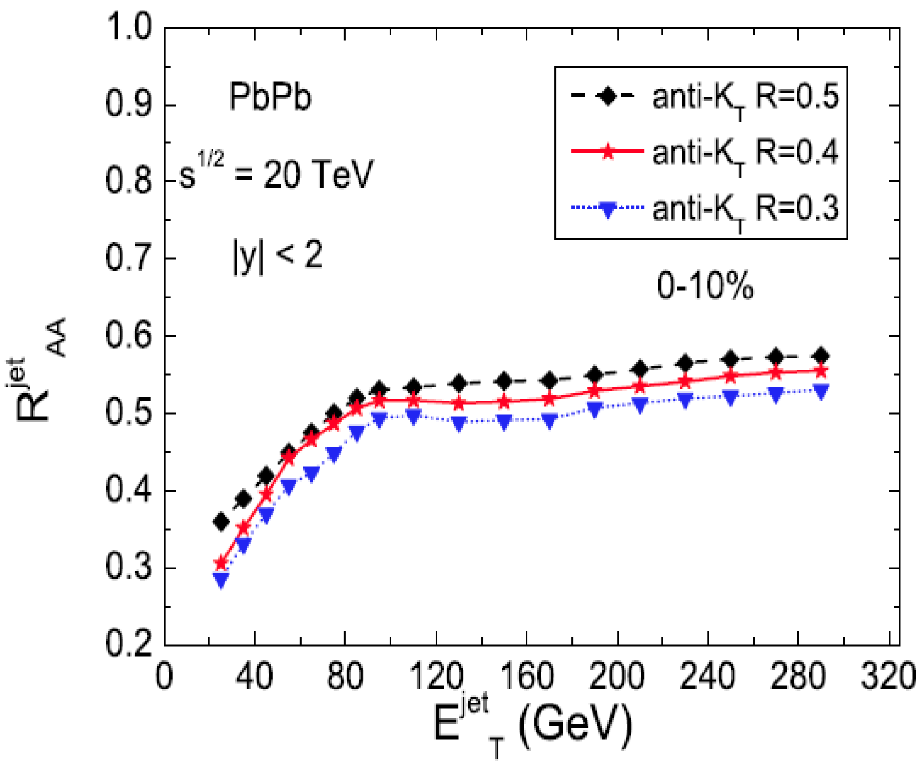
The same η/s gives roughly the same v_n gives at 30TeV, while larger η/s leads to smaller v_n

Jet quenching

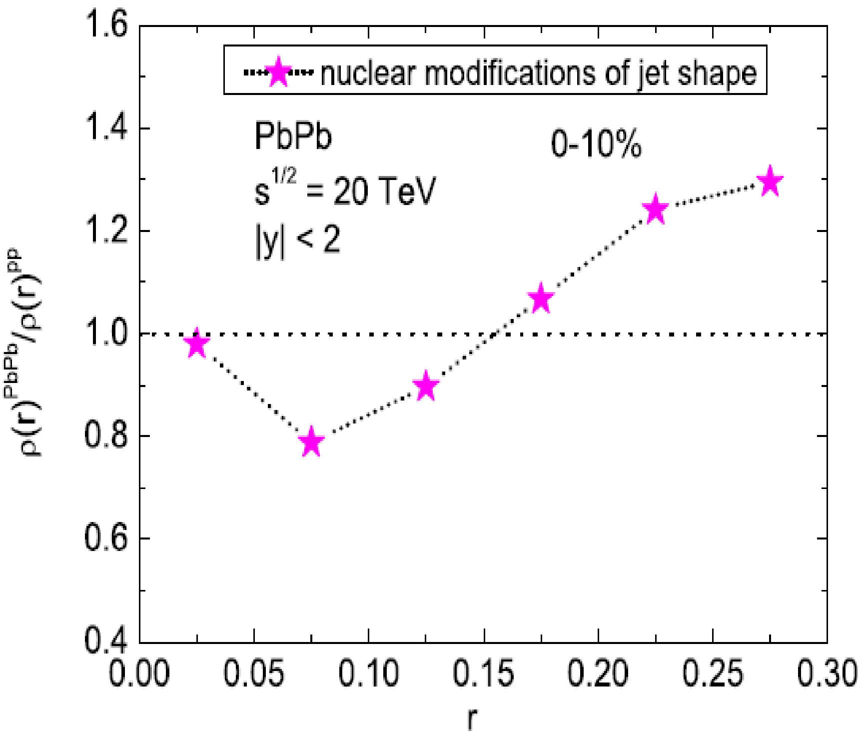




Full jets

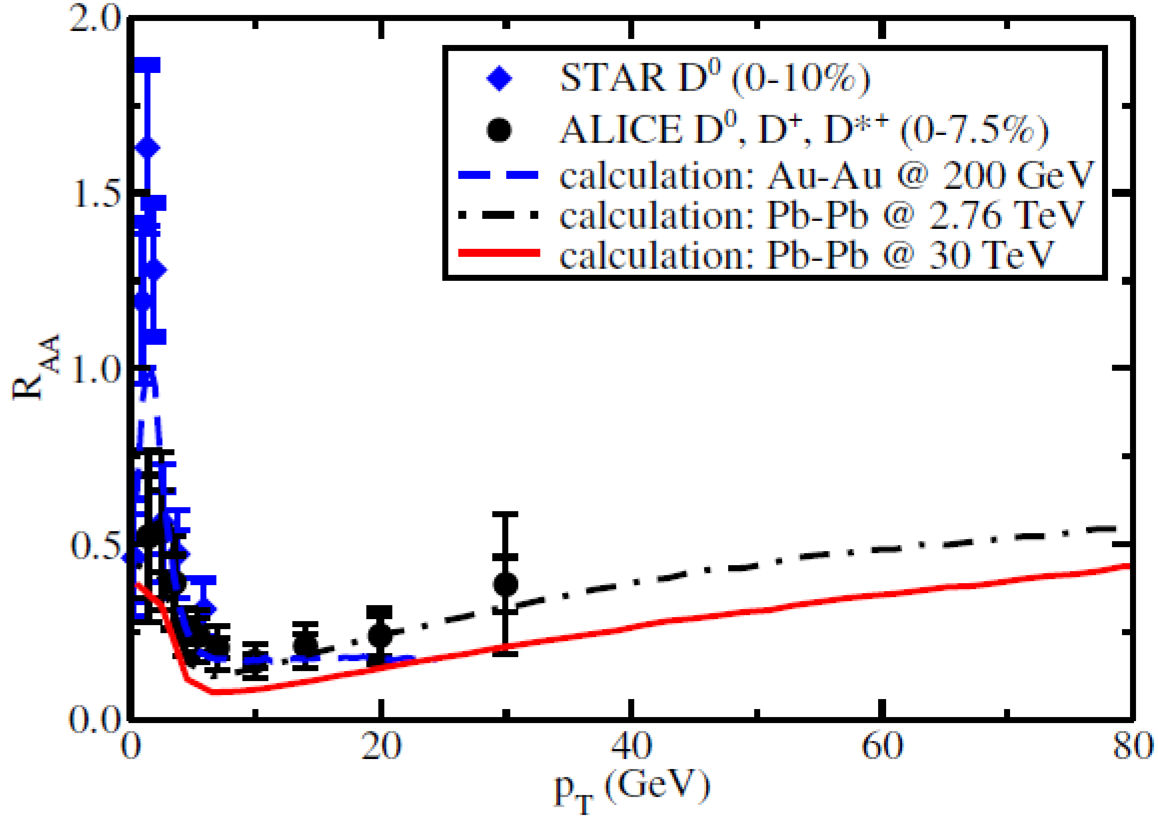


PbPb
s^1/2 = 20 TeV
|y| < 2
0-10%
anti-K_T R=0.5
anti-K_T R=0.4
anti-K_T R=0.3
R^jet_AA
E^jet_T (GeV)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
40
80
120
160
200
240
280
320



nuclear modifications of jet shape
PbPb
s^1/2 = 20 TeV
|y| < 2
0-10%
ρ(r)^PbPb/ρ(r)^pp
r
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.00
0.05
0.10
0.15
0.20
0.25
0.30

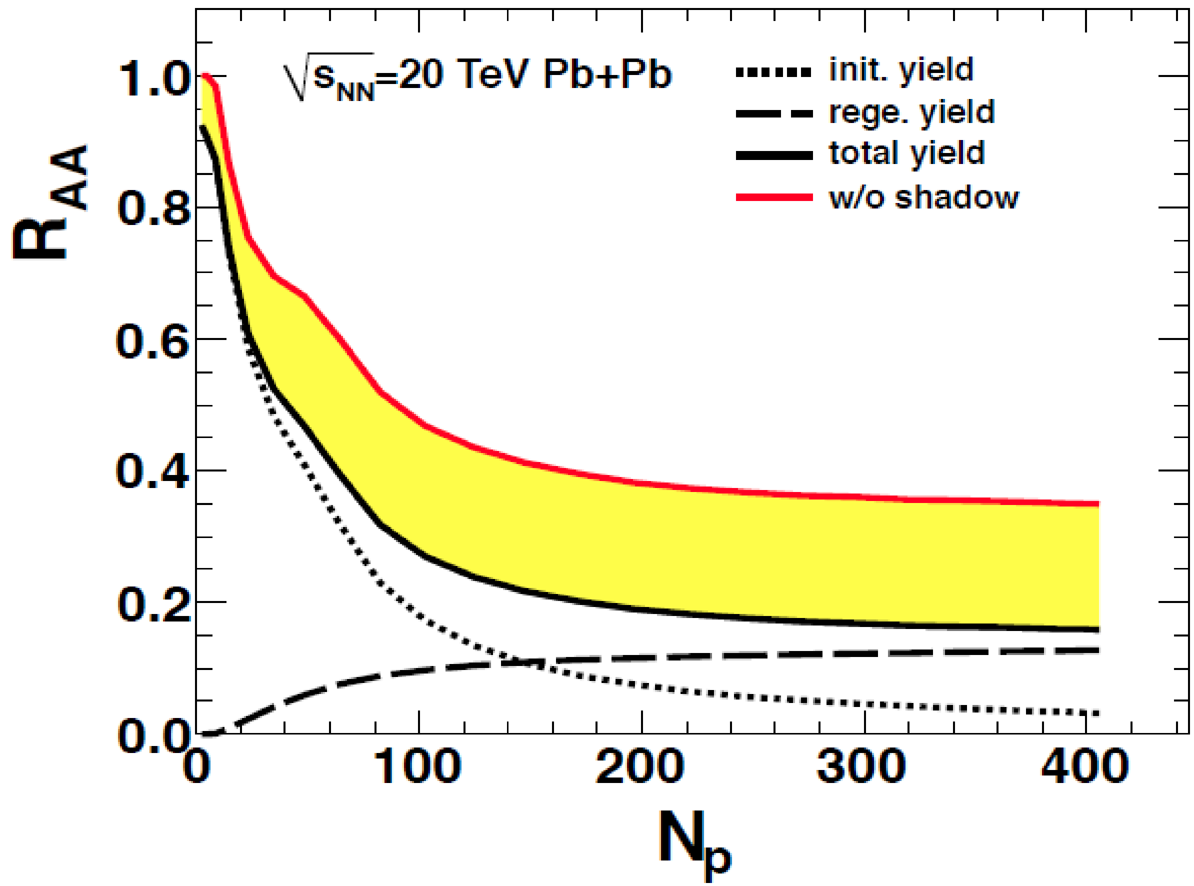
Open heavy flavors



At low p_T, larger gluon shadowing effect

At high p_T, higher temperature and longer lifetime of QGP lead to more suppression

Heavy quarkonia



Initial produced J/ψ are largely melted due to higher temperature
Significant nuclear shadowing effect suppresses the contribution from regeneration

Summary

- **At RHIC, QGP was discovered**
  - It is strongly-interacting, and its collective behavior is similar a perfect fluid
  - It shows strong opaqueness to the colored probes

- **At the LHC, semi-quantitative picture of QGP has been obtained**
  - The temperature dependence of the QGP properties have been investigated/measured
  - Larger specific shear viscosity & smaller jet-medium interaction strength at the LHC than at RHIC
  - Strong evidence of collectivity in small collision systems

– **Future heavy-ion collisions at SppC energies will help to obtain much more precise determination of the properties and the microscopic structures of QGP at a wide range of length/momentum scales**
  - Initial states (and their fluctuations)? How QGP is formed?
  - Temperature dependence of QGP properties (η/s and jet transport coefficients, etc.)
  - How a strongly-interacting QGP fluid at RHIC & LHC emerges from a weakly-coupled gaseous phase at high temperature?
  - QGP might be easily produced in p-A and even p-p collisions. How mini a thermal QGP can be?
  - Other bonuses/surprises?

Pre-proposal for future heavy-ion and electron-ion collision program

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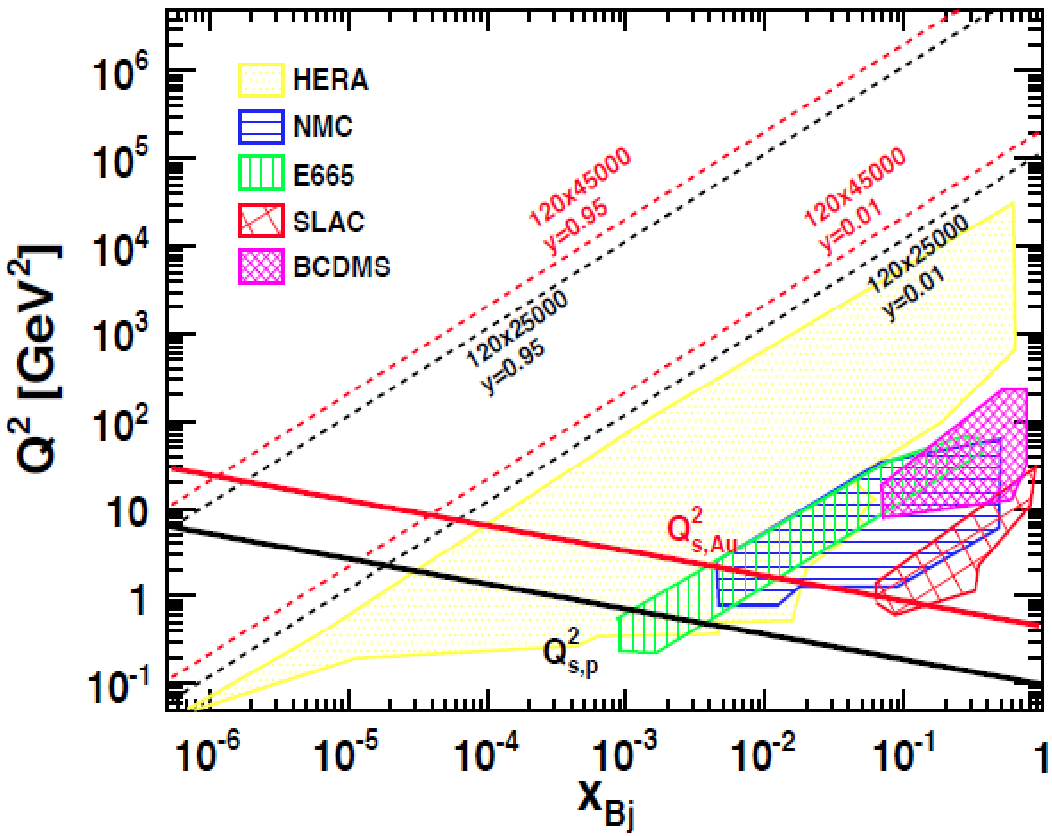
Only a few selected topics are presented.
More comprehensive results
need much more dedicated efforts.

Thank you!

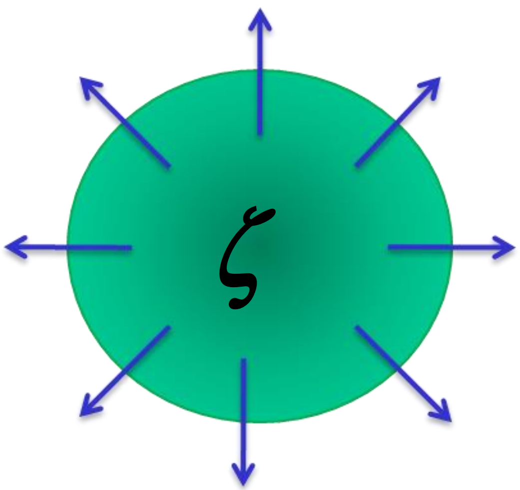
ep & eA collisions

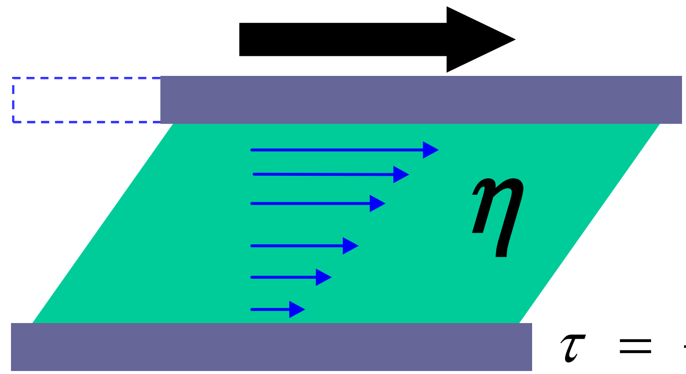
- 120GeV electron + 25-50GeV proton(nucleus), most powerful electron-hadron collider in the near future
- 3D (longitudinal and transverse) image of internal structure of protons and nuclei
- Precise measurement of PDFs (Q^2~10^6GeV^2, x~10^{-7}) is important for hadron-hadron collider and the search for new physics
- Low-x physics: non-linear gluon dynamics, gluon saturation and nuclear structure at extremely high density



Viscosity

- Bulk viscosity: the resistance to expansion
- Shear viscosity: the resistance to flow





$$\tau = \frac{F}{A} = \eta \frac{\partial u}{\partial y}$$

- Shear viscosity measures the ability of momentum transport between different parts of the system (thus the interaction strength)

$$\eta \approx \tfrac{1}{3} n\bar{p}\lambda_f = \frac{\bar{p}}{3\sigma_{tr}}$$

Relativistic hydrodynamics

- **Energy-momentum conservation law:**

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

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

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

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

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

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

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

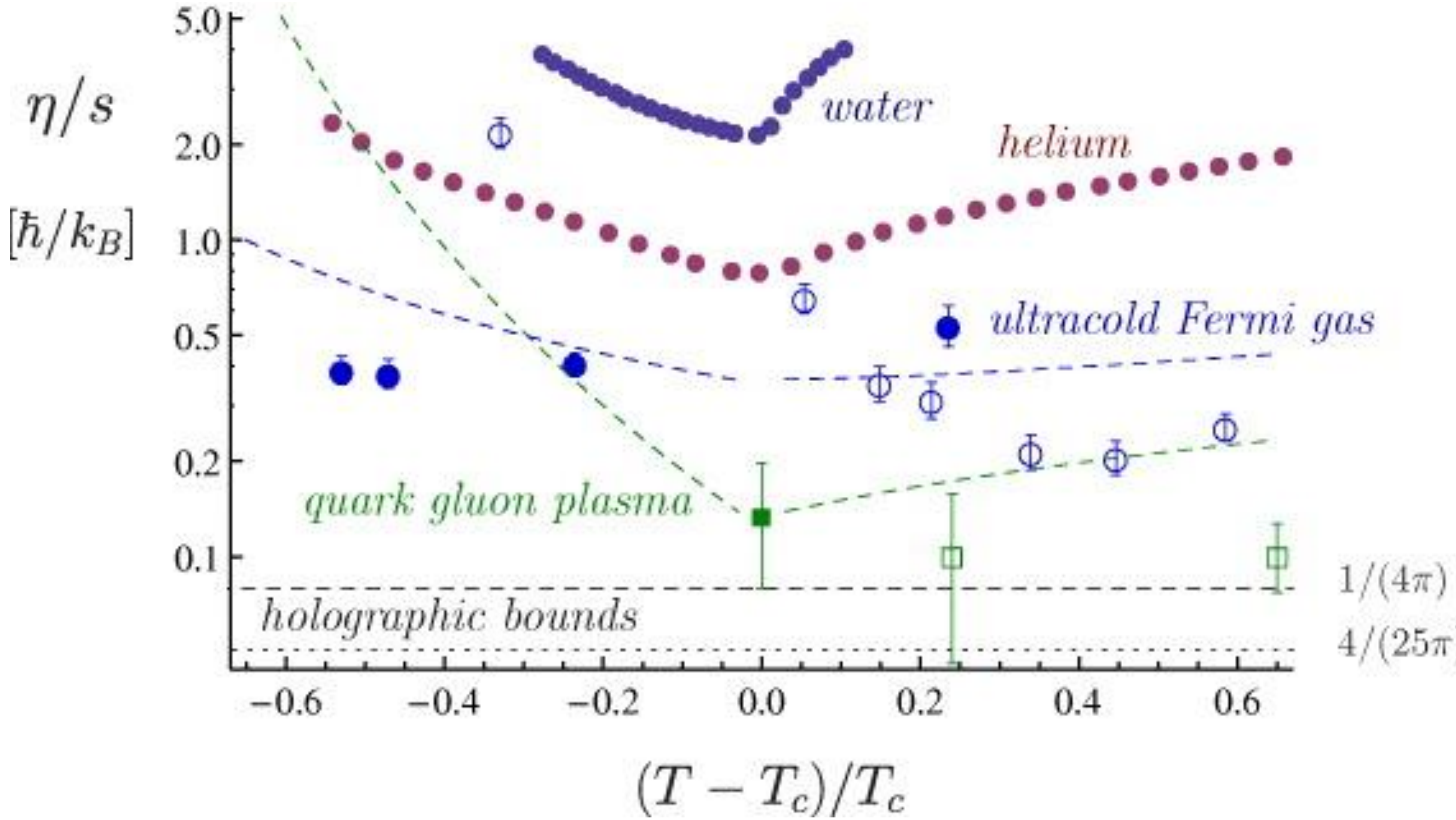
- **Hadron spectra from Cooper-Fry formula:**

$$E\frac{dN_i}{d^3p} = \frac{g_i}{(2\pi)^3}\int_\Sigma p \cdot d^3\sigma f(p \cdot U, T)$$

- **Hadron rescattering and decay**

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

Specific shear viscosity for strongly-correlated fluids



Adams, Carr, Schafer, Steinberg, Thomas, New J.Phys. 14 (2012) 115009, arXiv: 1205.5180