Jets and flow in heavy-ion collisions

Guang-You Qin

Central China Normal University (CCNU)

@

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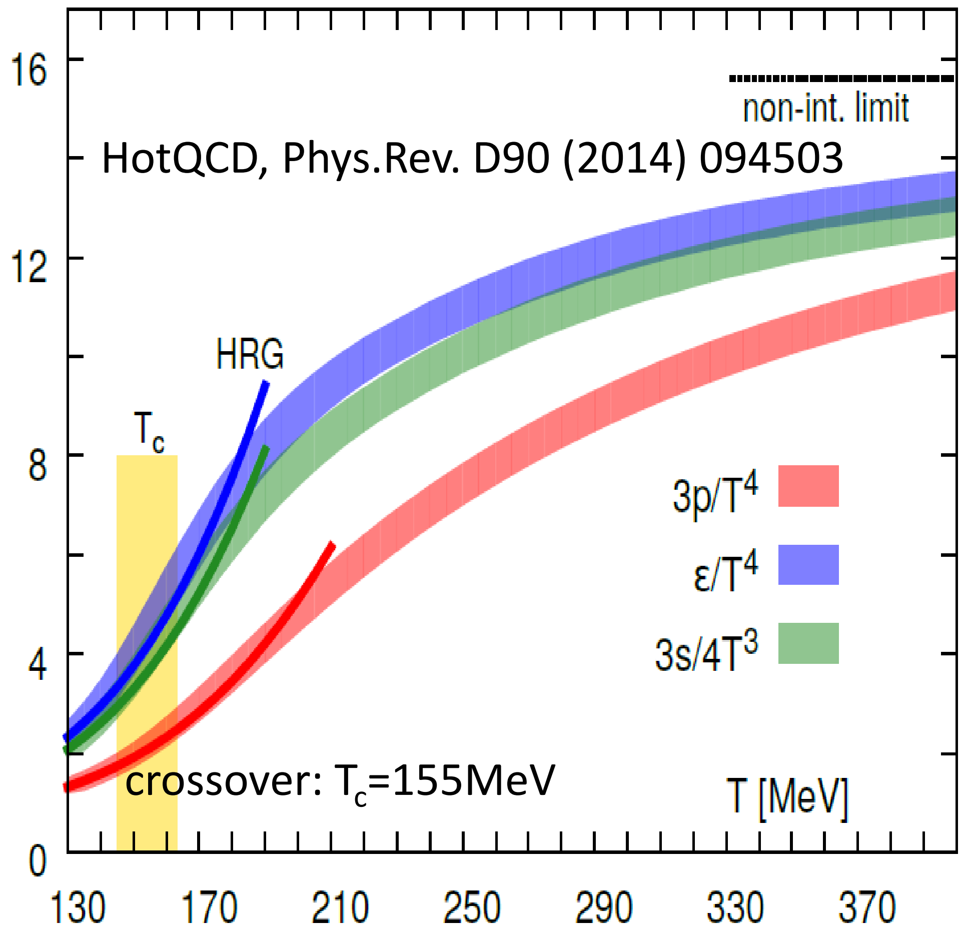
Outline

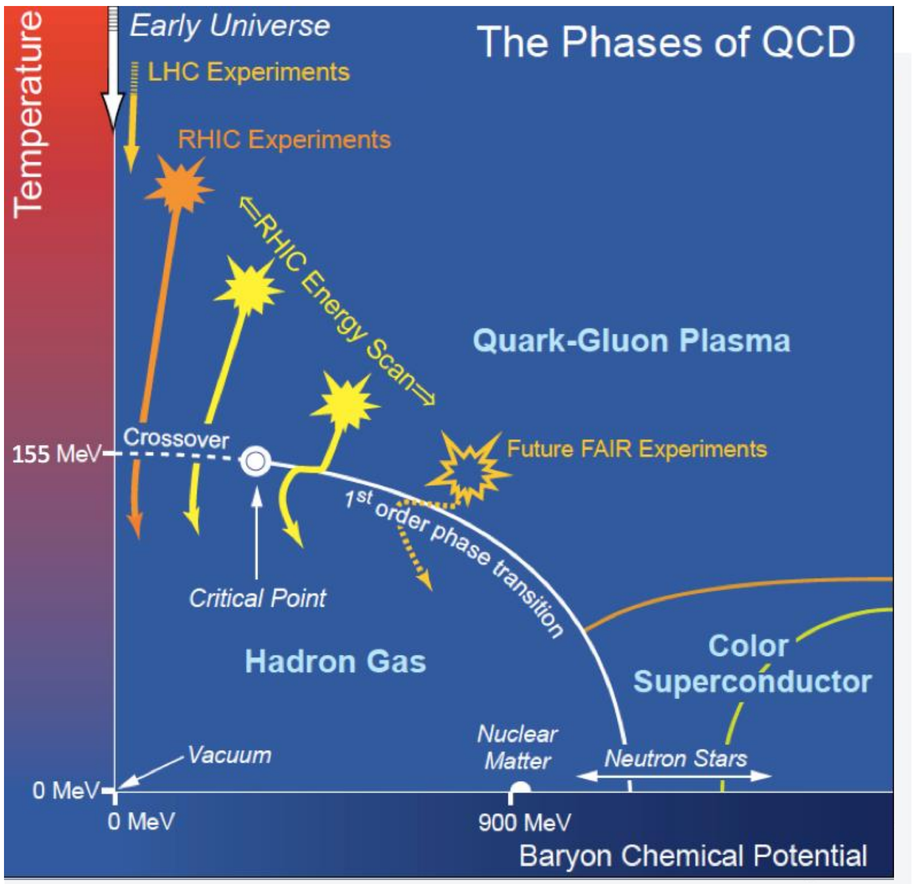
- Introduction: QCD matter and relativistic heavy-ion collisions
- Some main results from RHIC and the LHC
  - Soft bulk matter (flow)
  - Hard probes (light and heavy flavor jet quenching)
- Summary

QCD matter & heavy-ion collisions

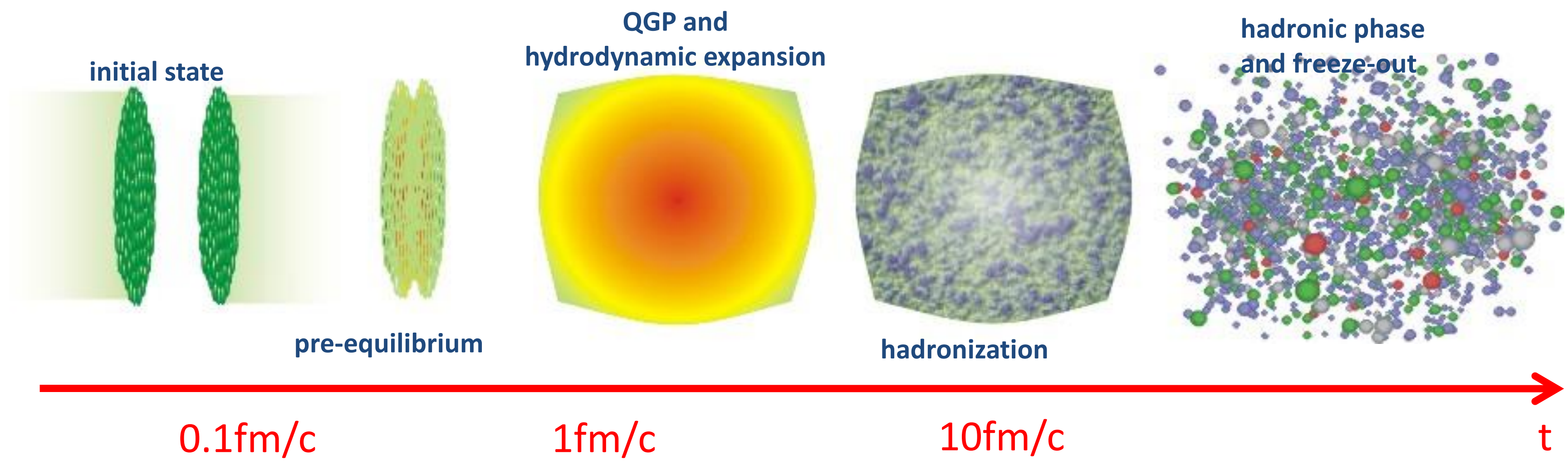
Strong-interaction matter

How QCD behaves at finite/extreme temperatures and densities?





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



Goal: to create QGP in the lab, 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, correlations
- Hard probes: light and heavy flavor jet quenching, heavy quarkonia
- Electromagnetic probes: photons, dileptons
- …

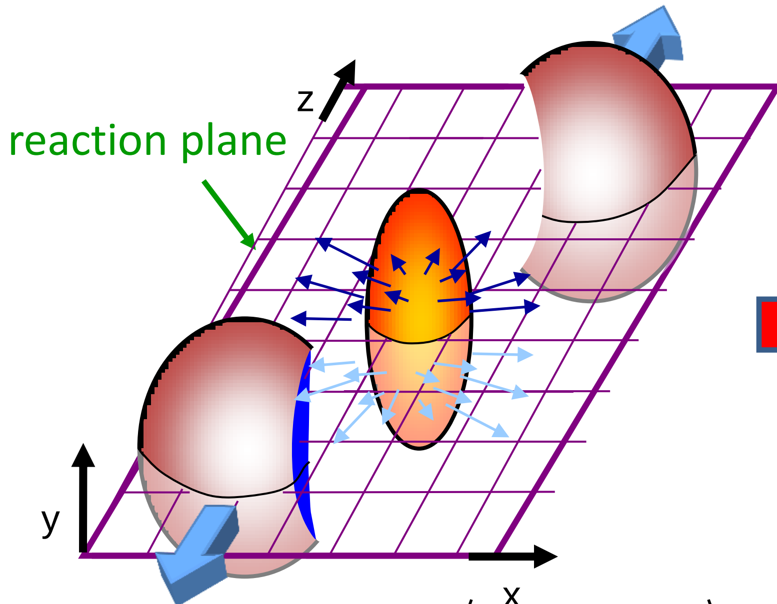
Some important heavy-ion results from RHIC and the LHC

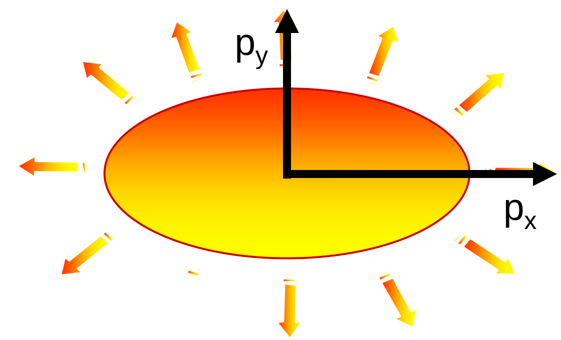
- RHIC
  - Wealthy evidences of the formation of strongly-coupled QGP
    - Soft bulk matter: strong collective flow
    - Hard probes: jet quenching

- LHC
  - Confirmed all experimental evidences of QGP at RHIC, obtained semi-quantitative understanding of QGP
    - Flow: larger specific shear viscosity
    - Jets: smaller jet-medium interaction strength, nuclear modification of full jets up to hundreds of GeV, mass ordering for heavy-flavor jet quenching (e.g., D and non-prompt J/ψ)
  - Surprise
    - Evidence for the collectivity in small collision systems (e.g., p-Pb)

Anisotropic flow of soft bulk matter

Anisotropic collective flow





eccentricity $\varepsilon_2 = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$

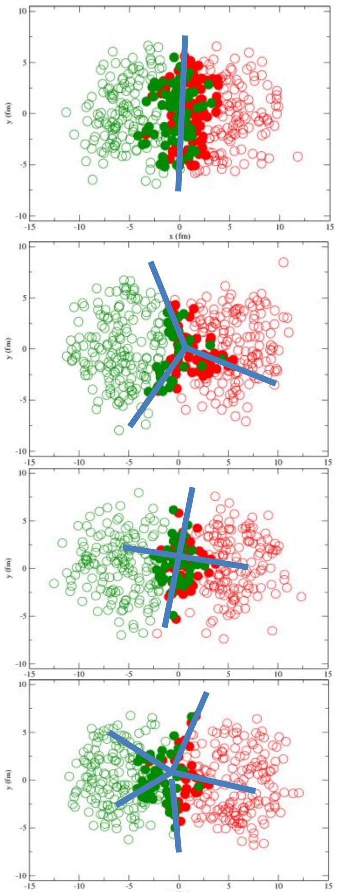
elliptic flow $v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$

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

Relativistic hydrodynamics gives nice explanation 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 …)

$$\varepsilon_{\rm n} e^{in\Phi_{\rm n}} = \frac{\left\{ r^m e^{in(\phi-\Phi_{\rm n})} \right\}}{\left\{ {\rm r}^{\rm m} \right\}} = \frac{\int d^2 r_\perp \rho(r_\perp) r^m e^{in(\phi-\Phi_{\rm n})}}{\int d^2 r_\perp \rho(r_\perp) r^m}$$

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 …)

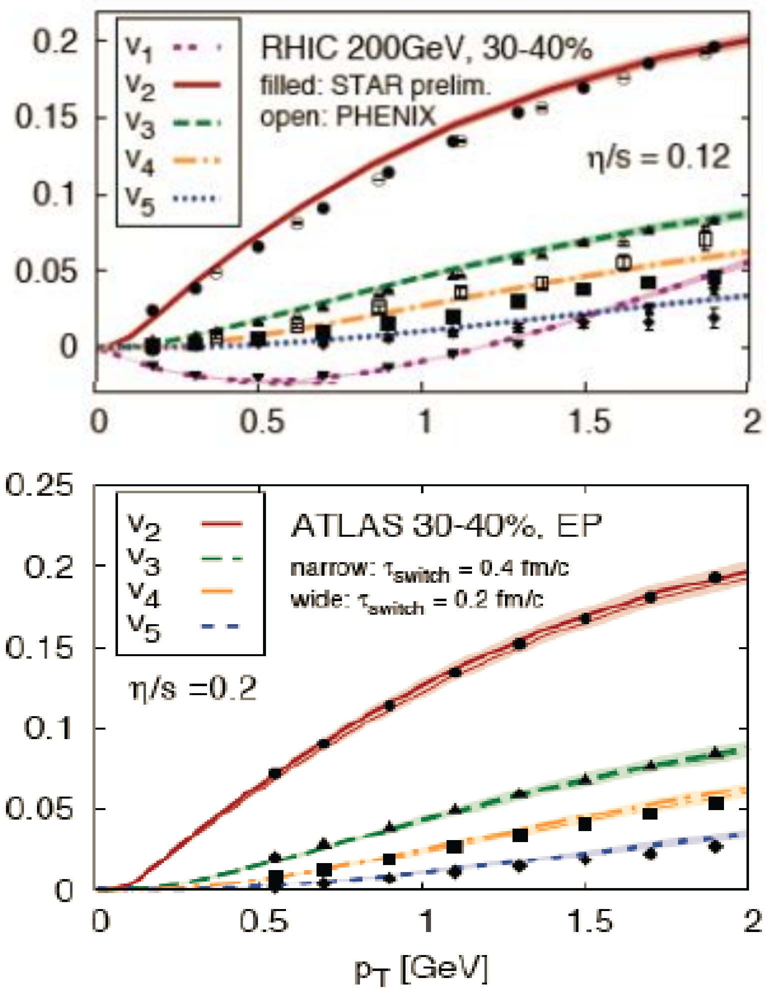
$$\frac{dN}{d\psi} \propto 1 + \sum_n 2v_n \cos[n(\psi - \psi_{\rm n})] \qquad v_{\rm n} e^{in\Psi_{\rm n}} = \left\{ e^{in(\psi-\Psi_{\rm n})} \right\}$$

General observable: the joint probability distribution of the magnitudes and phases of the collective flow:

$$p(v_n, v_m, \ldots, \psi_{\rm n}, \psi_{\rm m}, \ldots) = \frac{1}{N_{evt}} \frac{dN_{evt}}{dv_n dv_m \ldots d\psi_{\rm n} d\psi_{\rm m} \ldots}$$

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

Collective flow at RHIC and the LHC



- **Systematic comparison of hydrodynamics calculation to flow data can give much information about QGP:**

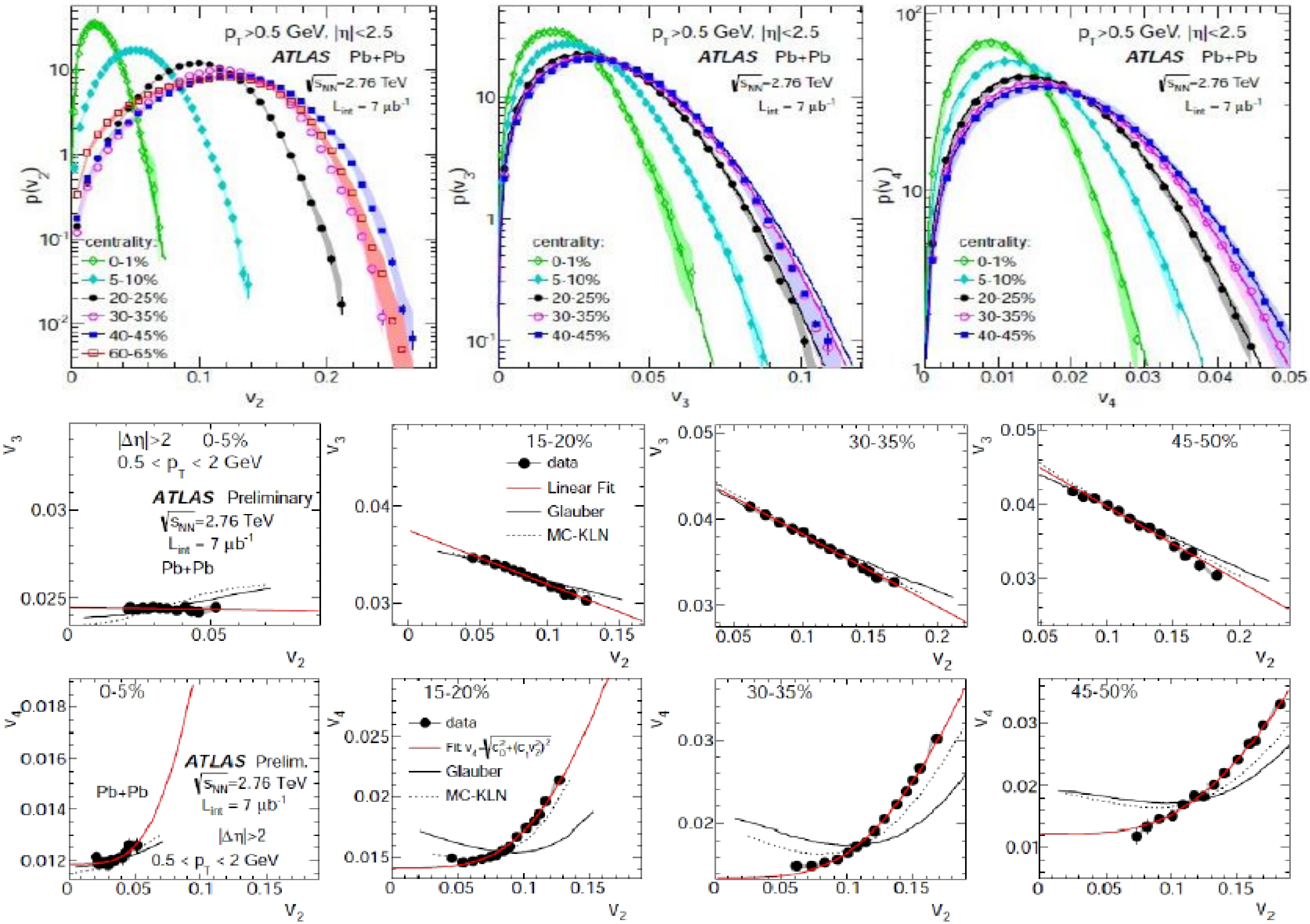
- Initial temperature $T_0 > T_c$ => QGP is created
  - 360MeV @RHIC
  - 470MeV @LHC
  - Thermalization time: τ_0=0.6fm/c

- Strong collective flow & small specific shear viscosity η/s obtained => strongly-coupled QGP
  - ~0.12 @RHIC
  - ~0.2 @LHC

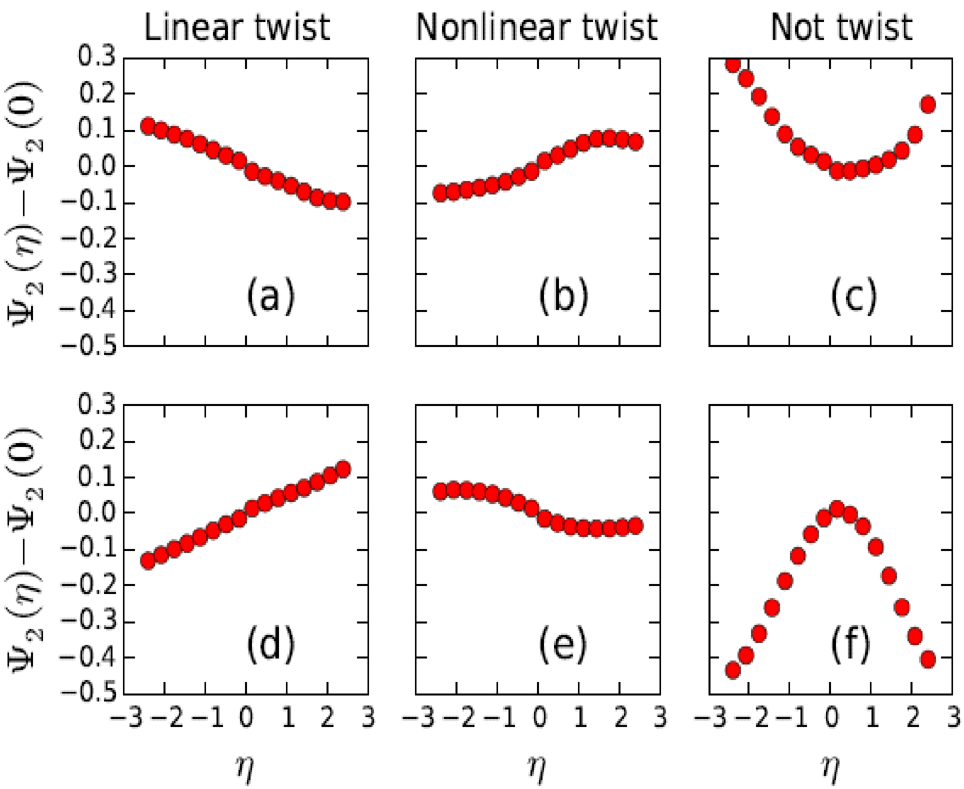
- Large uncertainties in initial state geometry fluctuations

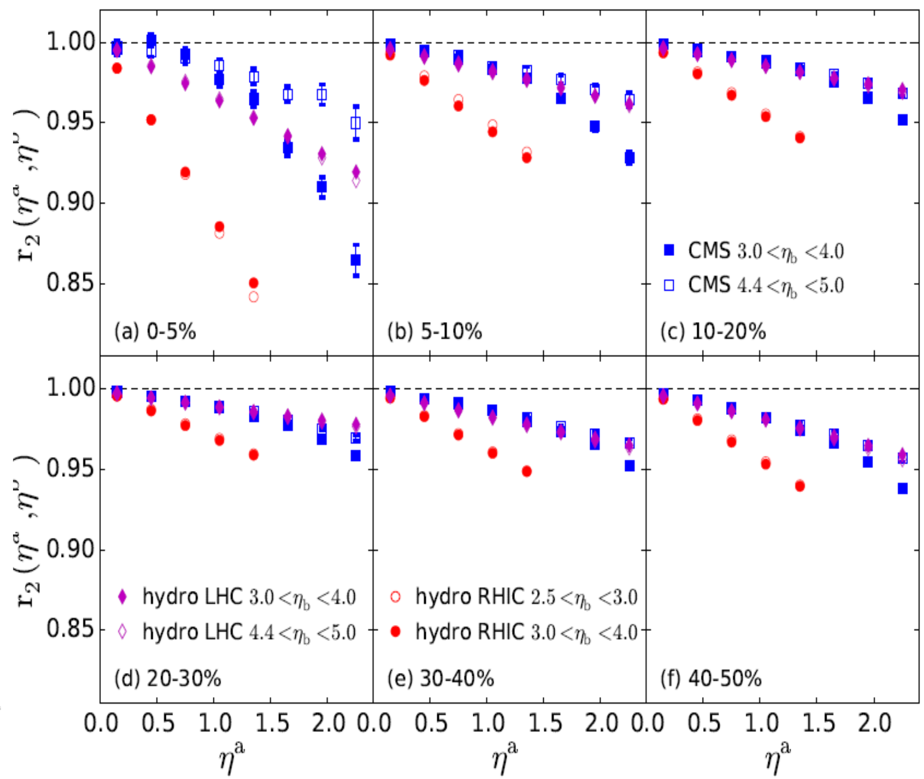
Gale, Jeon, Schenke, Tribedy, Venugopalan, PRL 2012; etc.

Flow fluctuations and correlations



Longitudinal fluctuations and correlations

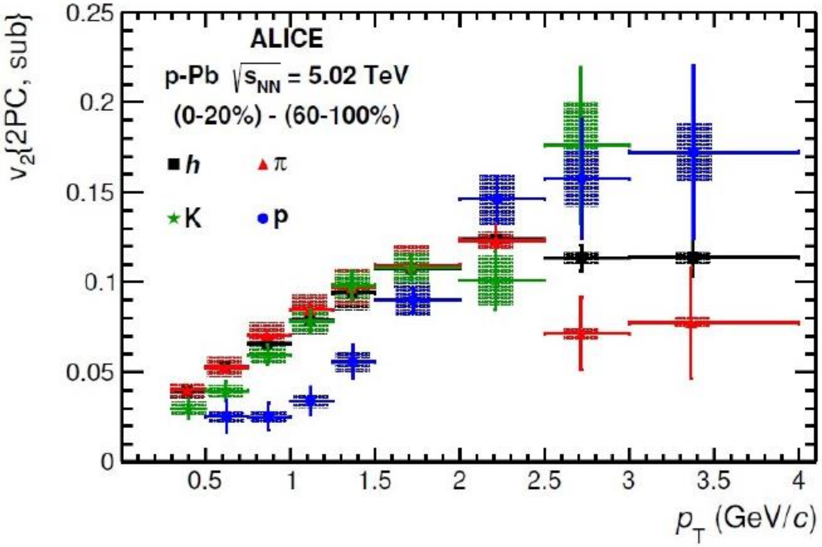


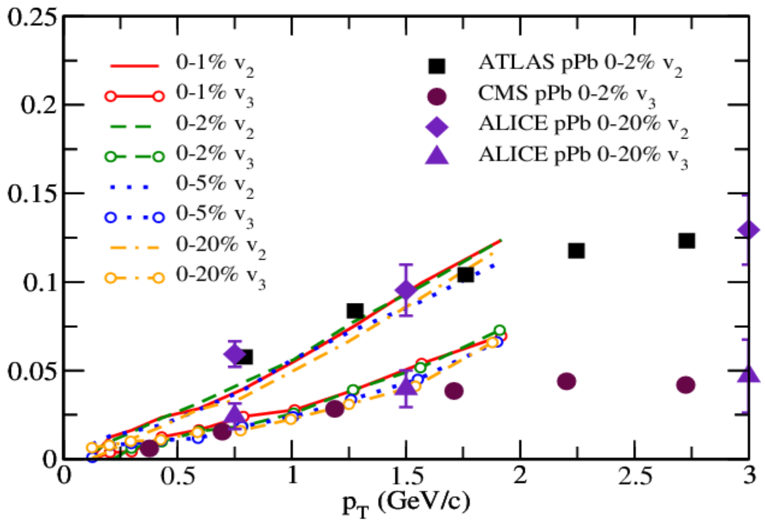


$$r_n(\eta_a,\eta_b) = V_{n\Delta}(-\eta_a,\eta_b)/V_{n\Delta}(\eta_a,\eta_b) = \frac{\langle v_n(-\eta_a)v_n(\eta_b)\cos\left[n\left(\Psi_n(-\eta_a)-\Psi_n(\eta_b)\right)\right]\rangle}{\langle v_n(\eta_a)v_n(\eta_b)\cos\left[n\left(\Psi_n(\eta_a)-\Psi_n(\eta_b)\right)\right]\rangle}$$

Petersen, Bhattacharya, Bass, Greiner, PRC (2011), Xiao, Liu, Wang, PRC (2013), Jia, Huo, PRC (2014), Pang, GYQ, Roy, Wang, Ma, PRC (2015), Bozek, Broniowski, Olszewski, PRC (2015), Pang, Petersen, GYQ, Roy, Wang, arXiv:1511.04131

Collectivity in small collision systems



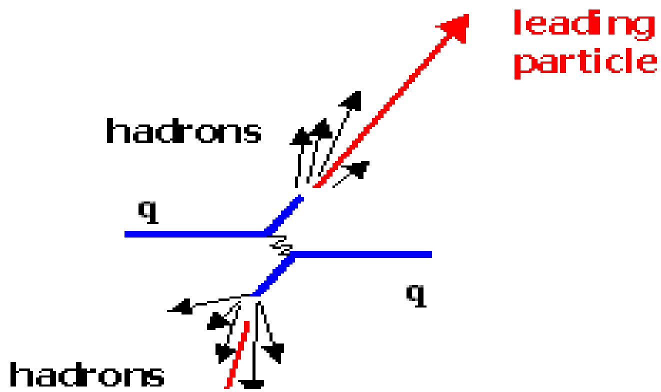


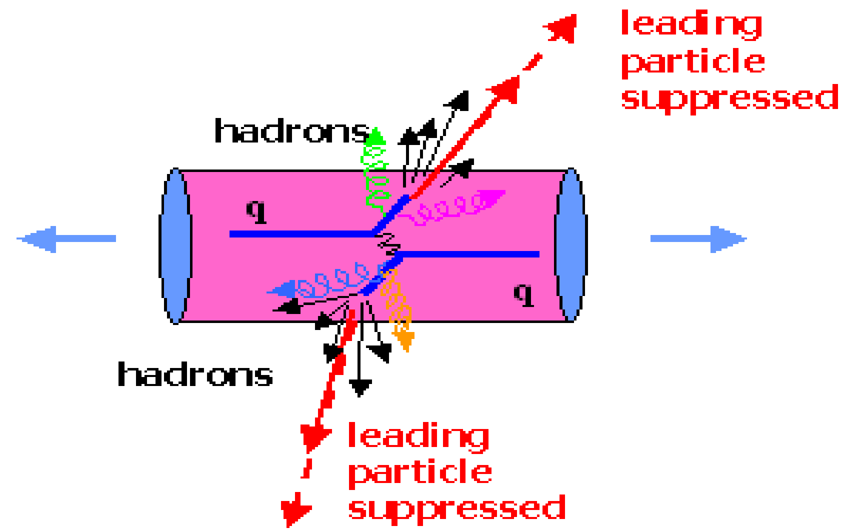
- Collectivity is expected to diminish for smaller system
- Similar long range correlations (collective behaviors) have been observed in p-A and high multiplicity p-p collisions at the LHC
- Hydrodynamics provides a natural explanation, but is also challenged by its applicability in such small systems and the assumption of rapid thermalization
- Initial state correlations (color glass condensate)?
- To disentangle the effects from initial and final state correlations

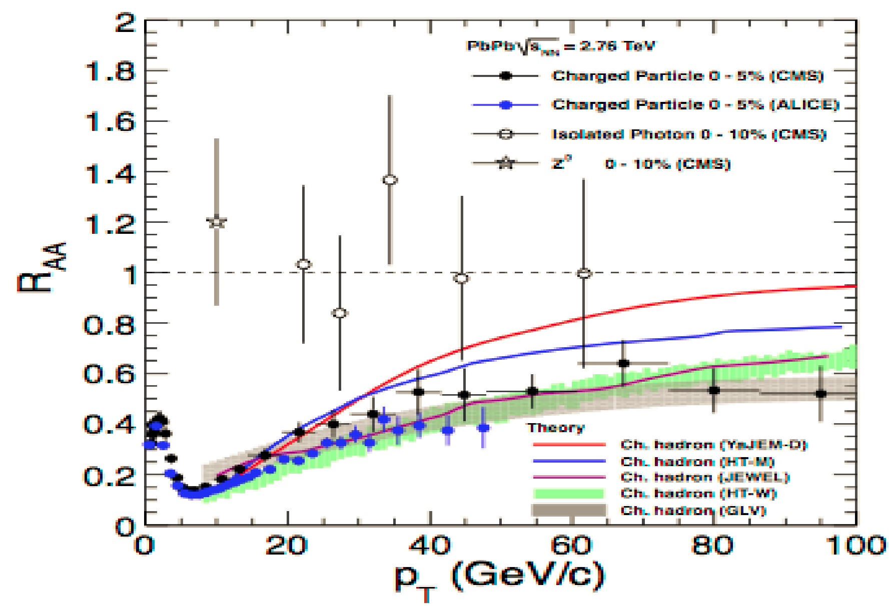
Bozek, Broniowski, Torrieri, PRL 2013; GYQ, Muller, PRC 2014; Bzdak, Ma, PRL 2014; etc.

Hard probes: light and heavy flavor jet quenching

Jets as hard probes of QGP





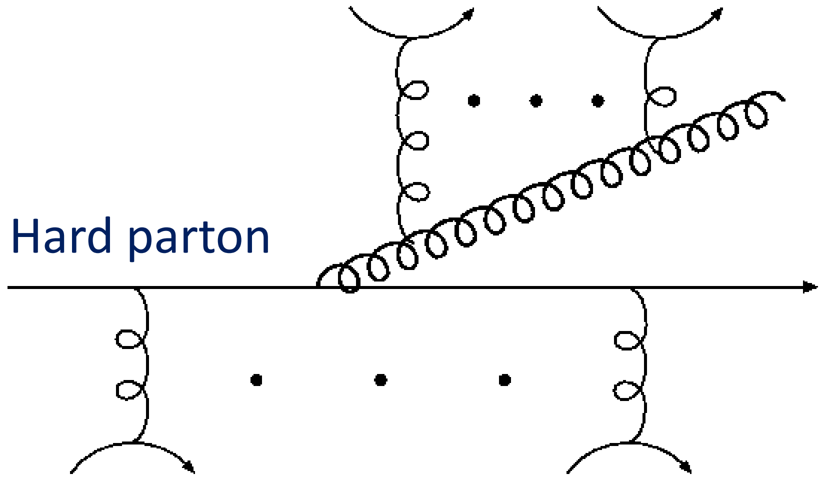


Nuclear modification factor:

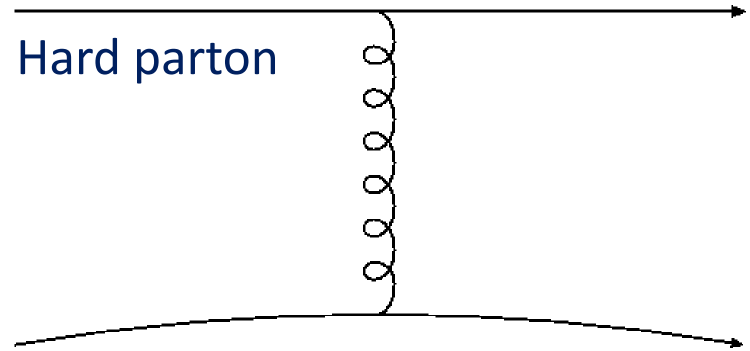
$$R_{AA} = \frac{dN^{AA} \;/\; d^2 p_T dy}{N_{\mathrm{coll}} dN^{pp} \;/\; d^2 p_T dy}$$

=> 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)

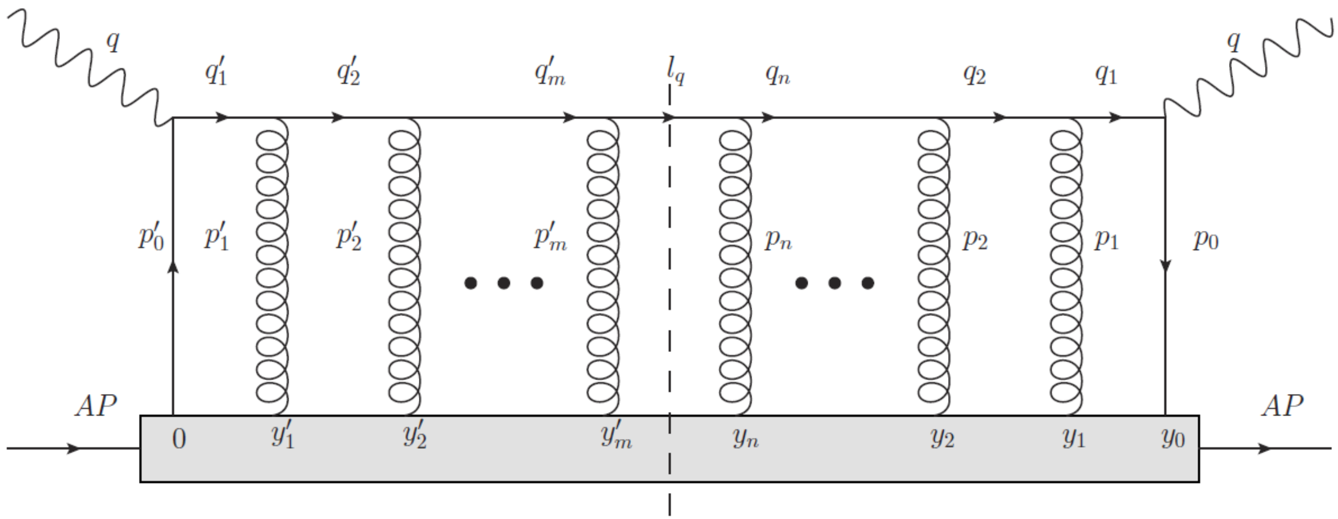
$$\frac{dN_g}{dx dk_\perp^2 dt} \approx \frac{2\alpha_s}{\pi} P(x) \frac{\hat{q}}{k_\perp^4} \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

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

Jet transport coefficient:

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

Elastic collisions & parton transport coefficients



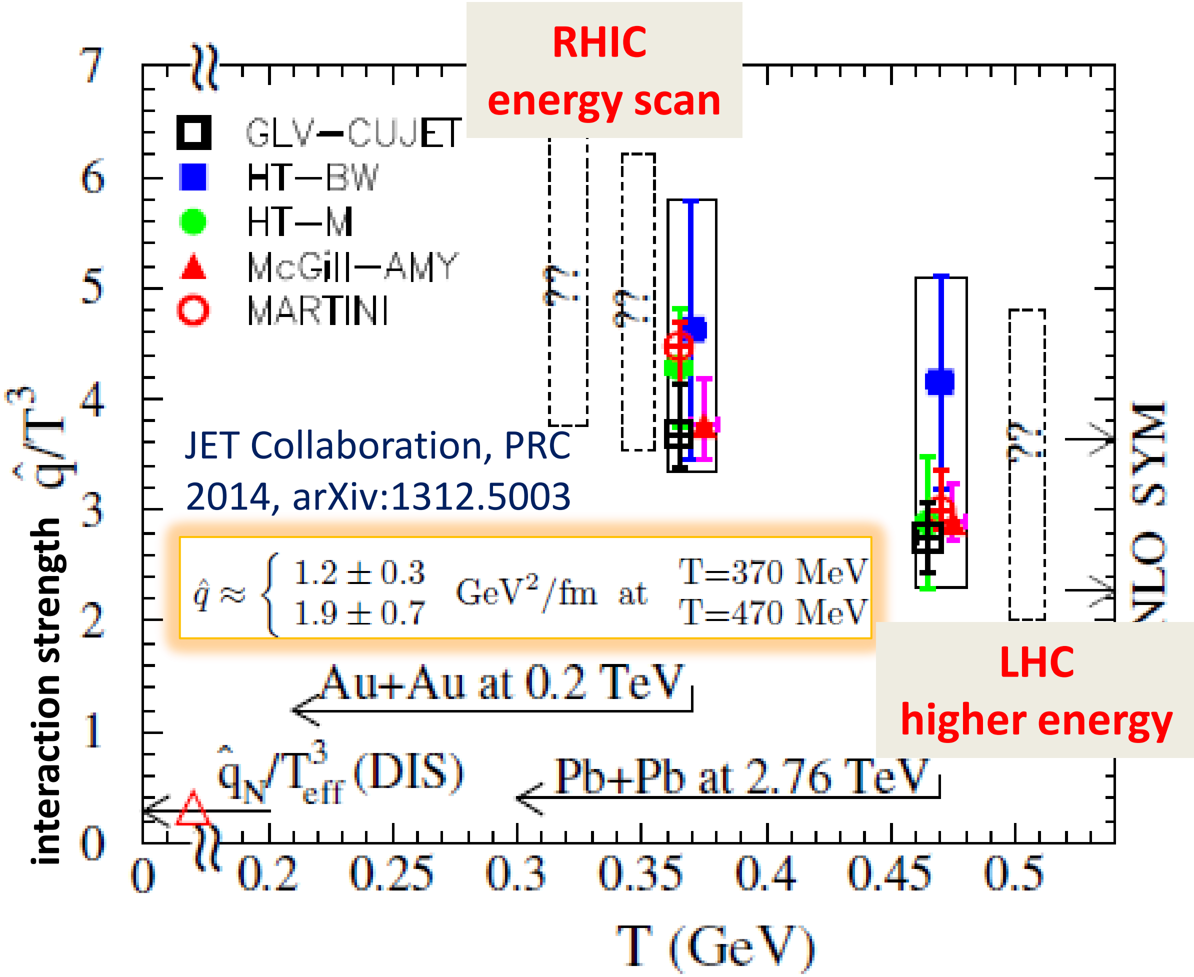
- In the soft scattering limit and keeping up to the second order in a gradient expansion, one obtains **longitudinal drag, longitudinal diffusion & transverse diffusion**

$$\frac{\partial f}{\partial L^-} = \left[D_{L1} \frac{\partial}{\partial l_q^-} + \frac{1}{2} D_{L2} \frac{\partial^2}{\partial^2 l_q^-} + \frac{1}{2} D_{T2} \nabla^2_{\vec{l}_{q\perp}} \right] f(L^-, l_q^-, \vec{l}_{q\perp})$$

$$D_{T2} = \frac{d\left\langle \Delta l^2_{q\perp} \right\rangle}{dL^-} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle F^{\mu+}(0) F^+_\mu(y^-) \right\rangle$$

GYQ, Majumder, PRC 2013; Abir, Kaur, Majumder, PRD 2014

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

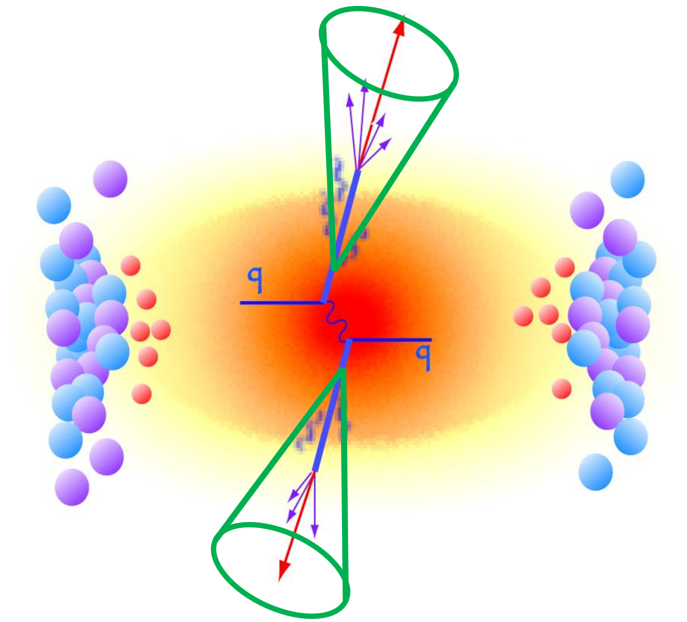
MARTINI-AMY:
Schenke, Gale, Jeon, PRC 2009

NLO SYM:
Zhang, Hou, Ren, JHEP 2013

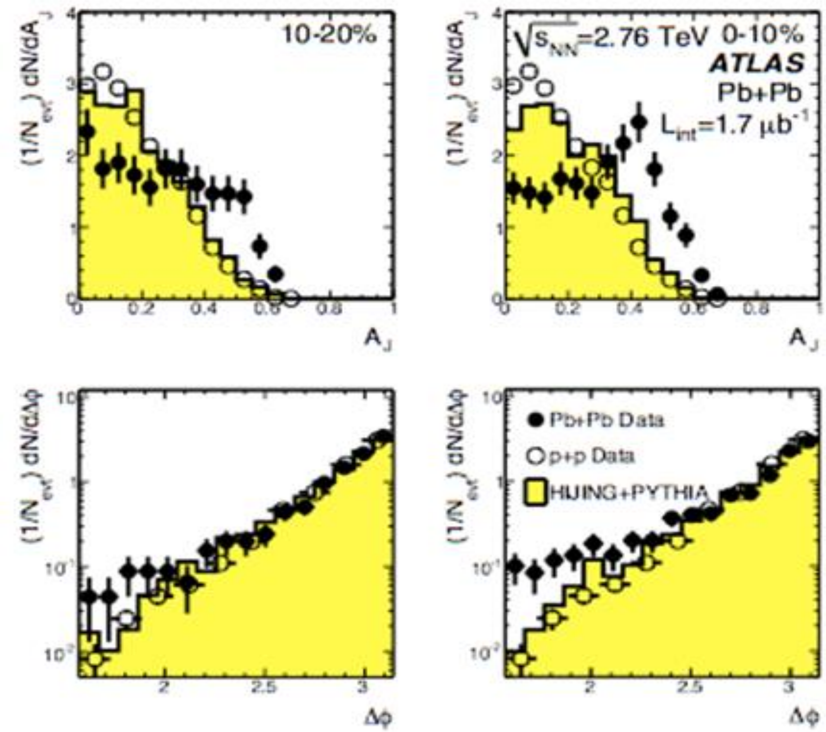
Future: precise determination of T (& E) dependence of jet transport parameters

Full jets in heavy-ion collisions

Fully-reconstructed jets are expected to provide more detailed information than single hadron observables



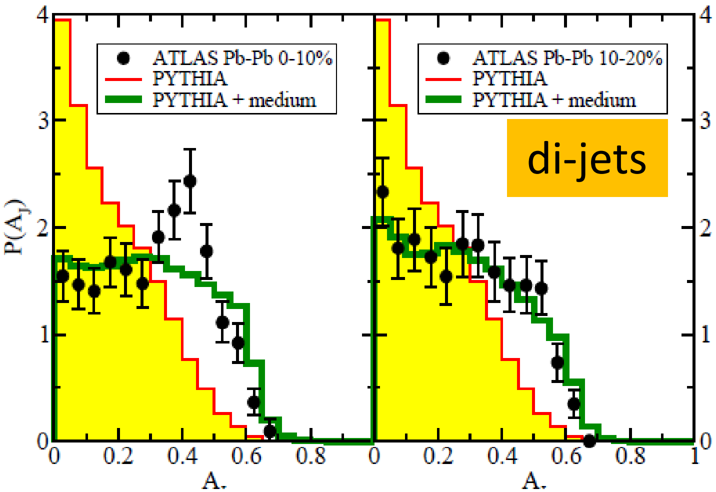
$$A_J = \frac{E_{J,1} - E_{J,2}}{E_{J,1} + E_{J,2}}, \Delta\phi = \left|\phi_1 - \phi_2\right|$$



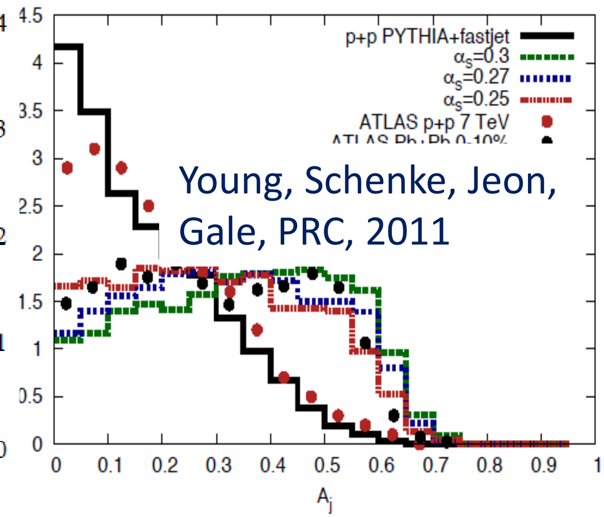
Strong modification of momentum imbalance & largely-unchanged angular distribution
=> significant energy loss experienced by the away-side subleading jets

Energy asymmetry of dijets and γ-jets

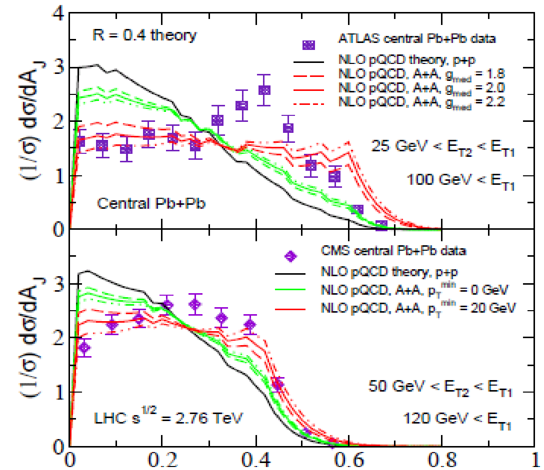
di-jets



GYQ, Muller, PRL, 2011

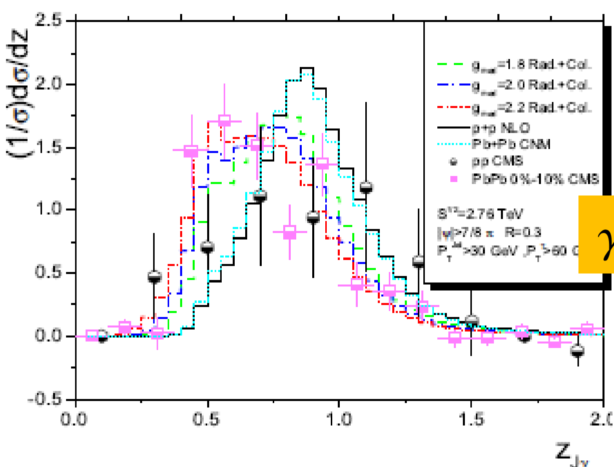


Young, Schenke, Jeon, Gale, PRC, 2011

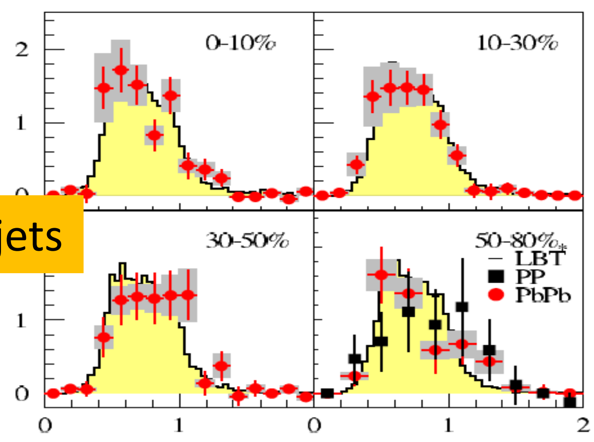


He, Vitev, Zhang, PRC 2011

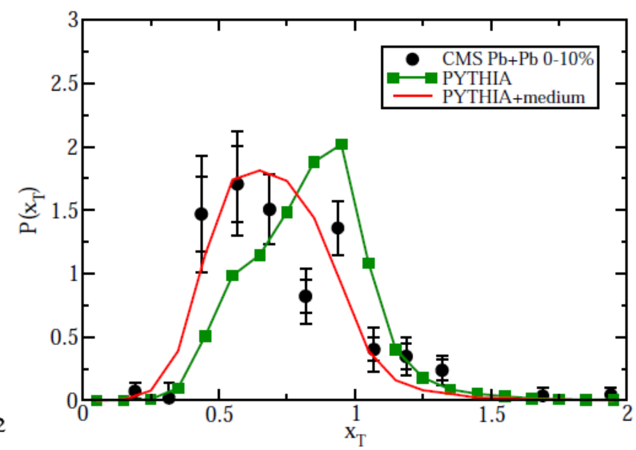
γ-jets



Dai, Vitev, Zhang, PRL 2013



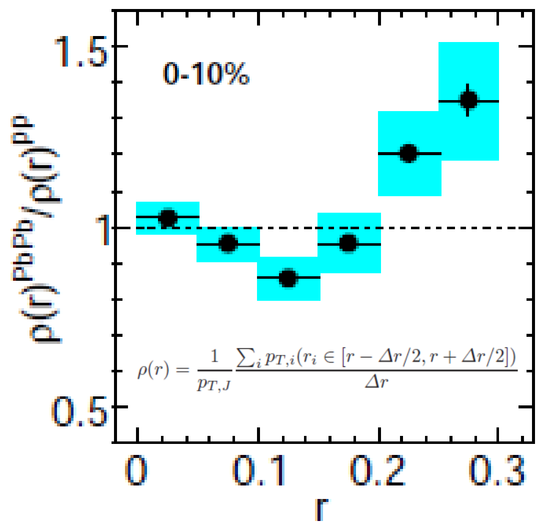
Wang, Zhu, PRL 2013



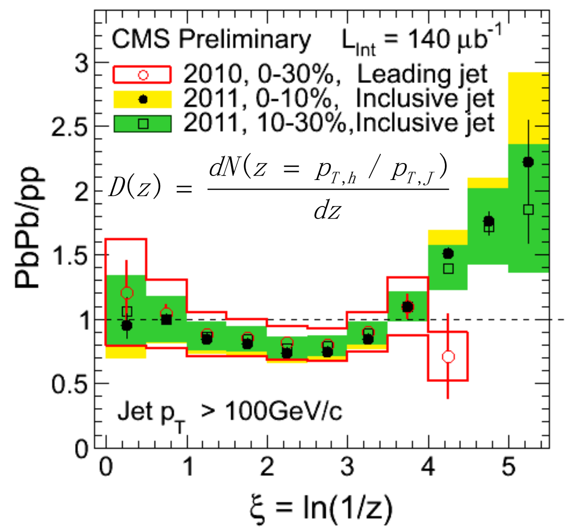
GYQ, EPJC 2014

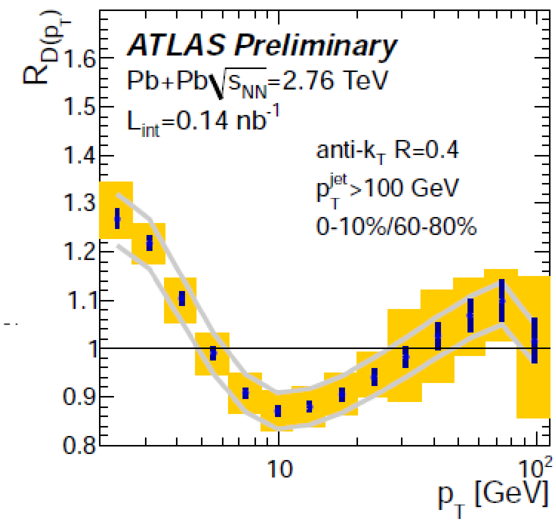
Full jet structure

Jet shape



Jet fragment profile

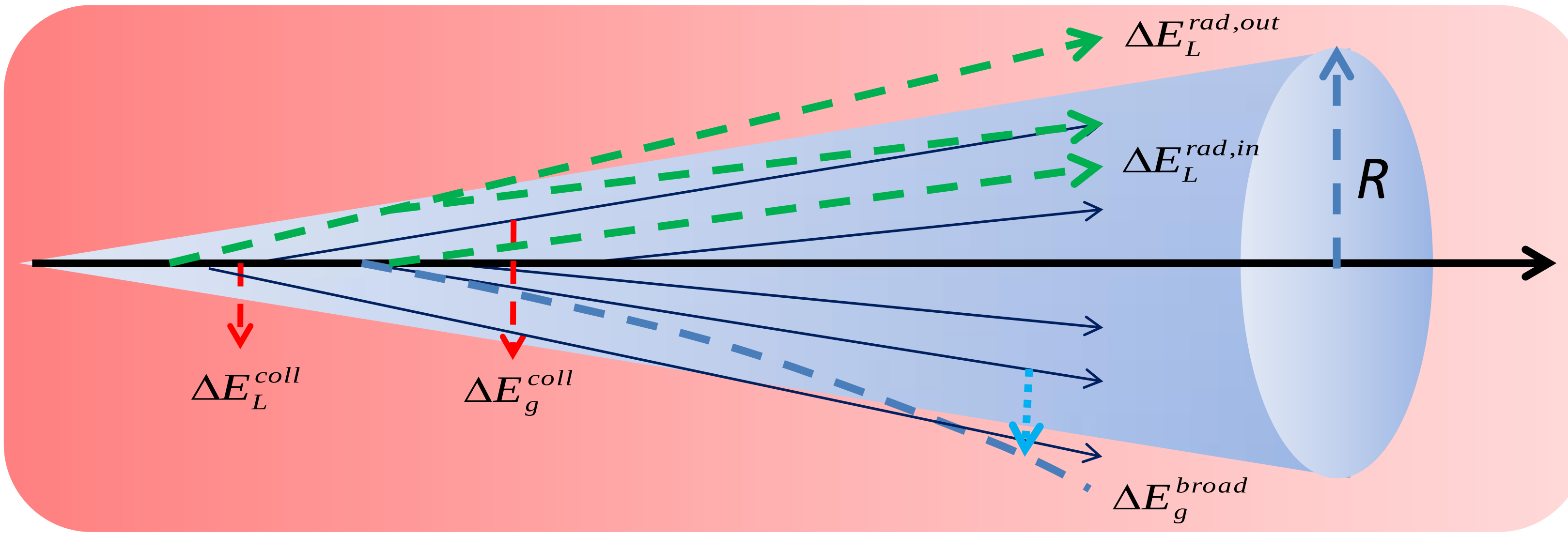




Medium modification of jet fragment (shape) profiles

- 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

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

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

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

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

Simulating full jet evolution in medium

- Solve the 3D (energy & transverse momentum) evolution for shower partons inside the full jet
- Include both collisional (quantified by longitudinal drag and transverse diffusion) and all radiative/splitting processes

$$\frac{d}{dt} f_j(\omega_j, k_{j\perp}^2, t) = \left(\hat{e}_j \frac{\partial}{\partial \omega_j} + \frac{1}{4} \hat{q}_j \nabla_{k_\perp}^2 \right) f_j(\omega_j, k_{j\perp}^2, t)$$

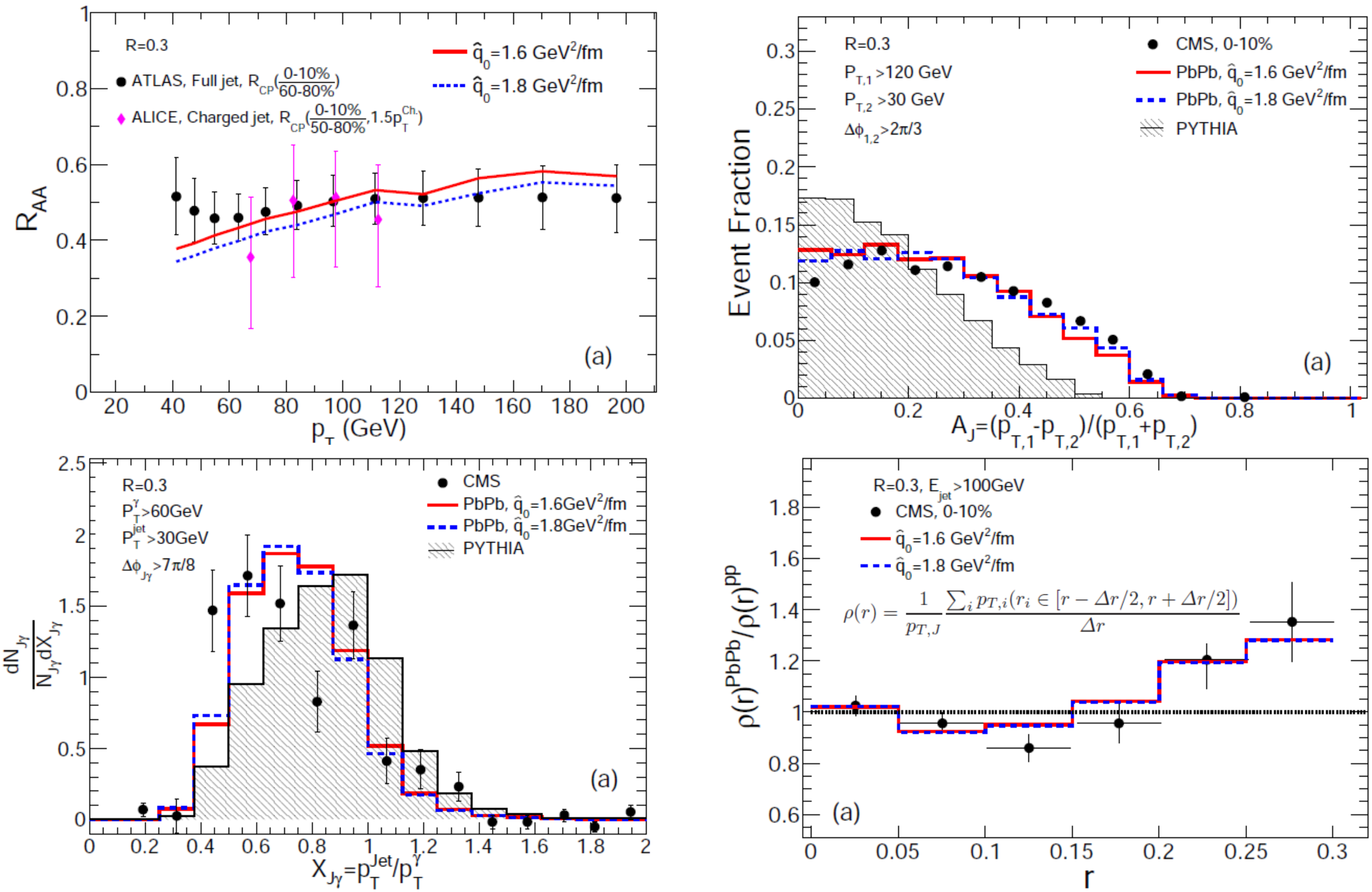
$$+ \sum_i \int d\omega_i dk_{i\perp}^2 \frac{d\tilde{\Gamma}_{i\to j}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2)}{d\omega_j d^2 k_{j\perp} dt} f_i(\omega_i, k_{i\perp}^2, t)$$

$$- \sum_i \int d\omega_i dk_{i\perp}^2 \frac{d\tilde{\Gamma}_{j\to i}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2)}{d\omega_i d^2 k_{i\perp} dt} f_j(\omega_j, k_{j\perp}^2, t)$$

$$E_{jet}(R) = \sum_i \int_R \omega_i f_i(\omega_i, k_{i\perp}^2) d\omega_i dk_{i\perp}^2$$

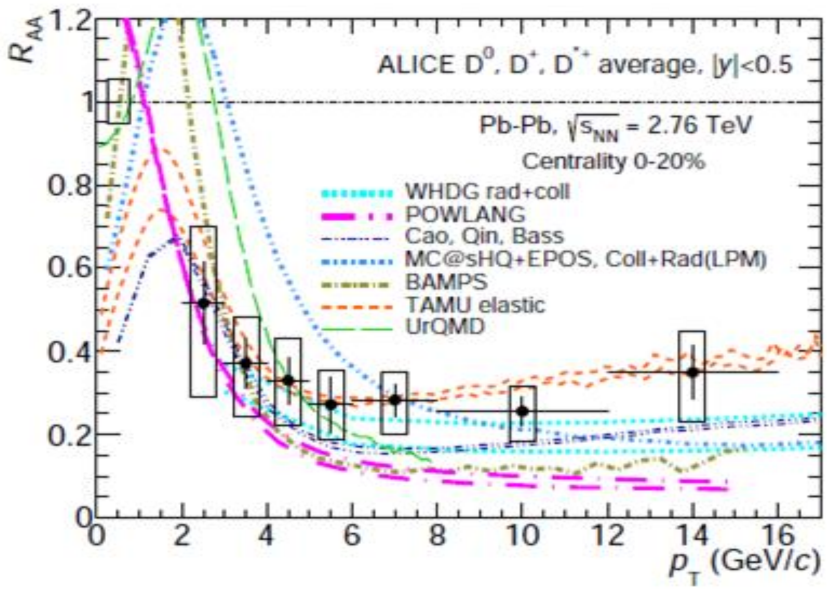
Ningbo Chang, GYQ, arXiv:1603.01920

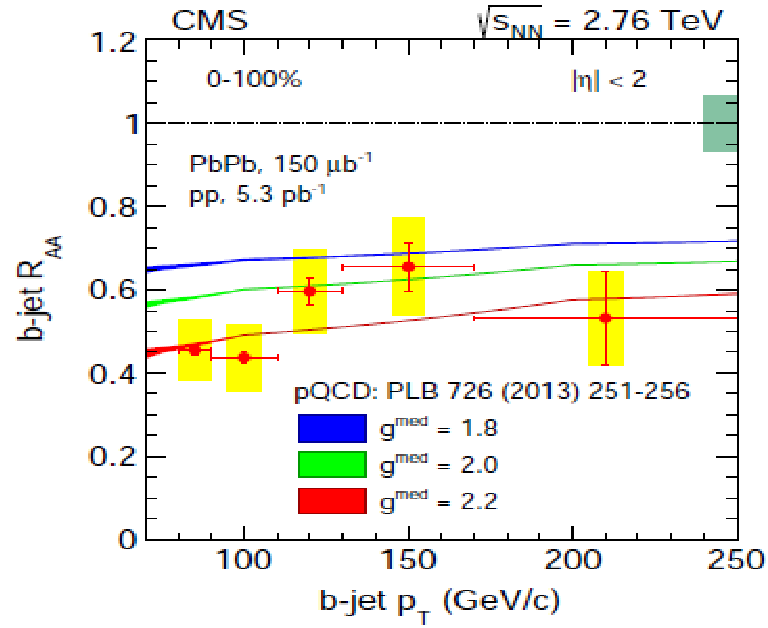
Various full jet observables



Ningbo Chang, GYQ, arXiv:1603.01920

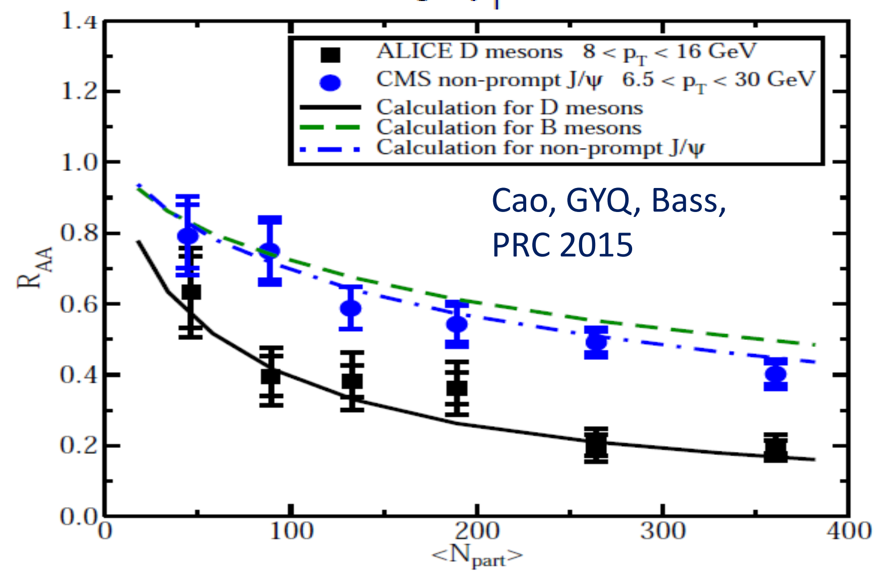
Open heavy flavors



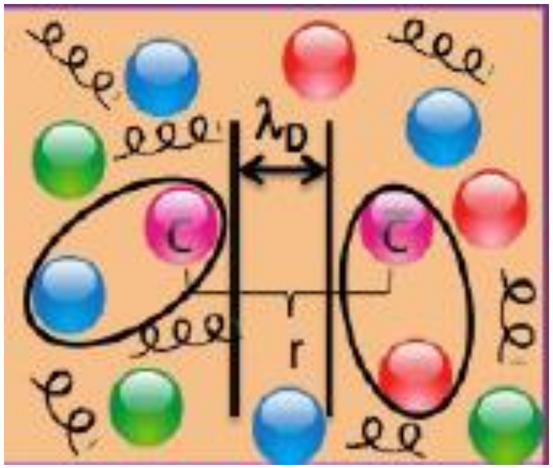


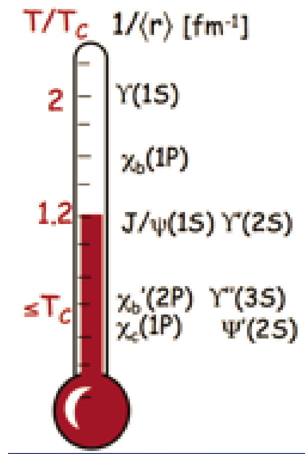
$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b?$$

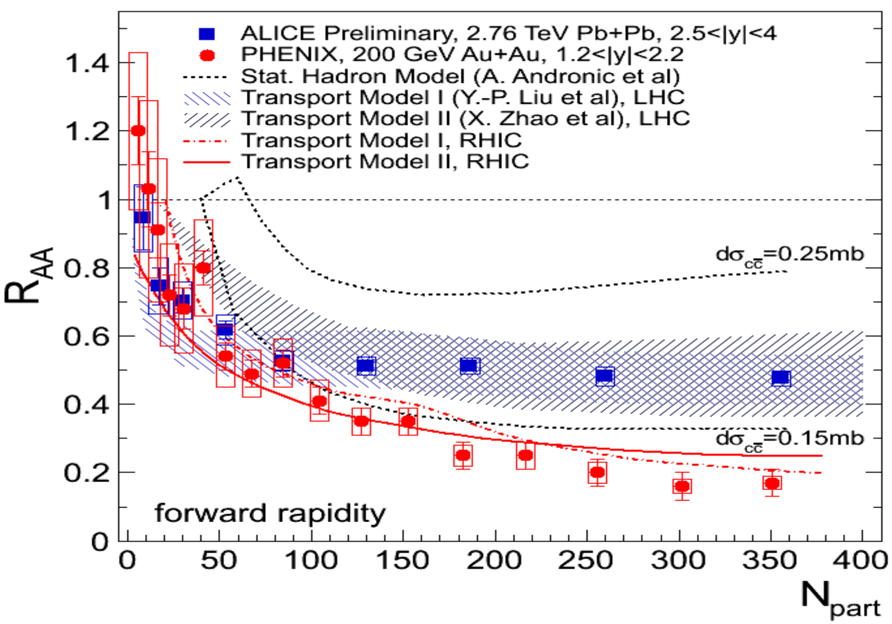
- D-mesons show similar suppression to light flavor mesons
- High-p_T b-quark jets show similar suppression to inclusive jets
- Comparison of D-meson production and non-prompt J/ψ from B decays indicates the mass ordering of parton energy loss



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 (from lattice) 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

Summary I

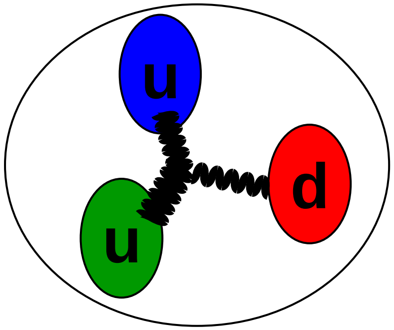
- QCD matter
  - Lattice QCD gives Tc~155MeV (the transition is a smooth crossover)
  - We have created the hottest matter in the Universe since it's a few μs old
- Soft probes
  - The QGP is a strongly-coupled liquid (η/s is larger at the LHC than at RHIC)
  - Quantum fluctuations of initial states persist and manifest in the final states (the knowledge of initial states is the largest uncertainties in determining η/s)
  - Evidences for collective behaviors in small collision systems
- Hard probes
  - The QGP is highly opaque to colored probes (hard partons are more weakly coupled to the hot medium at the LHC than at RHIC, mass ordering of jet quenching)
  - 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)
- ...

Summary II

- What is the detailed microscopic origin of the collective properties of QGP?
- What is the nature of the initial state?
  - Map out the high-density gluon fields of incoming nuclei and their fluctuations?
- How is QGP formed in heavy-ion collisions?
  - Thermalization mechanism?
- What is the smallest QGP droplet that we can create?
- How does QCD matter behaves over a wide range of length/momentum scales?
  - The precise values of different transport coefficients at various temperatures?
- ...

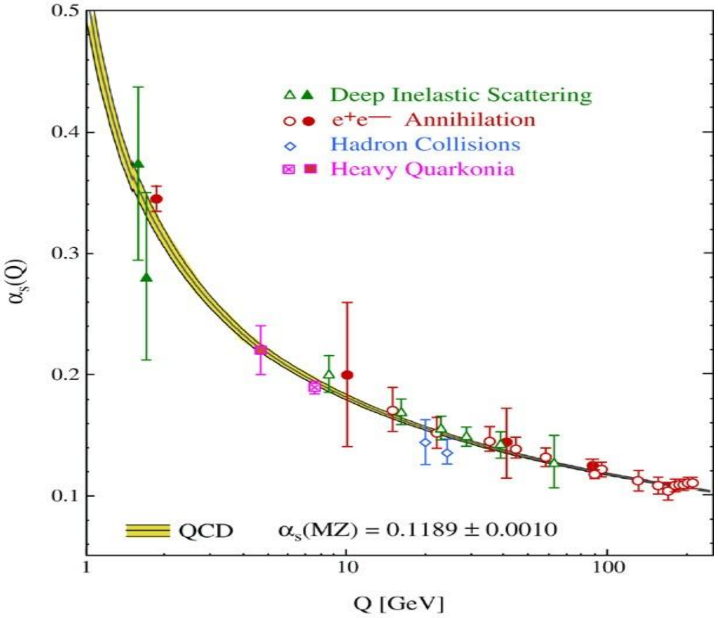
Thank you!

QCD and strong interaction



- QCD is the fundamental quantum field theory of the strong interaction, an essential ingredient of Standard Model

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



- Elementary fields: quarks and gluons which carry "color" degrees of freedom
- SU(3) non-Abelian gauge theory
- Confinement & asymptotic freedom
- …

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):**

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

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

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

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

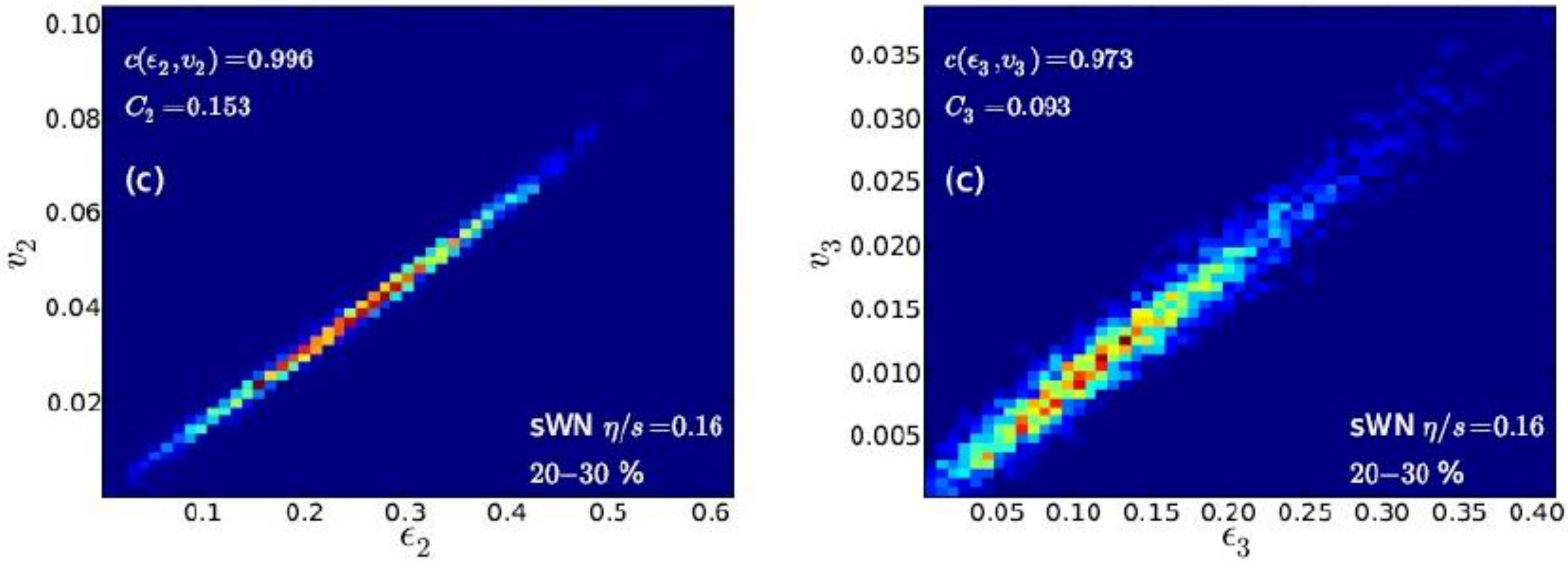
- **Hadron spectra from Cooper-Fry formula:**

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

- **Hadron rescattering and decay**

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

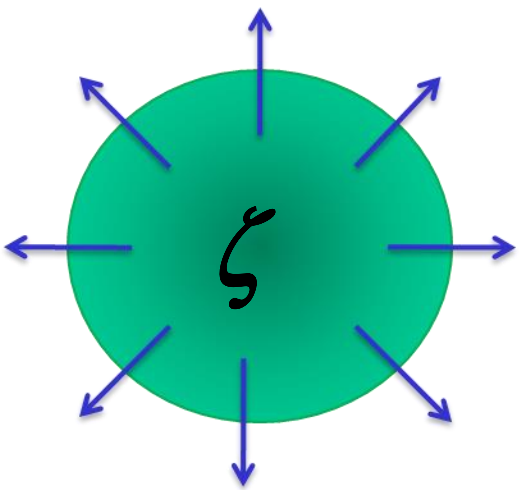
Hydrodynamic response to initial geometry

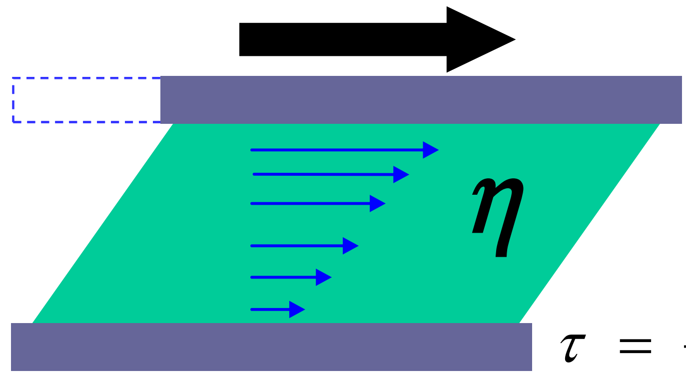


Niemi, Denicol, Holopainen, Huovinen, PRC 2013

Viscosity

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



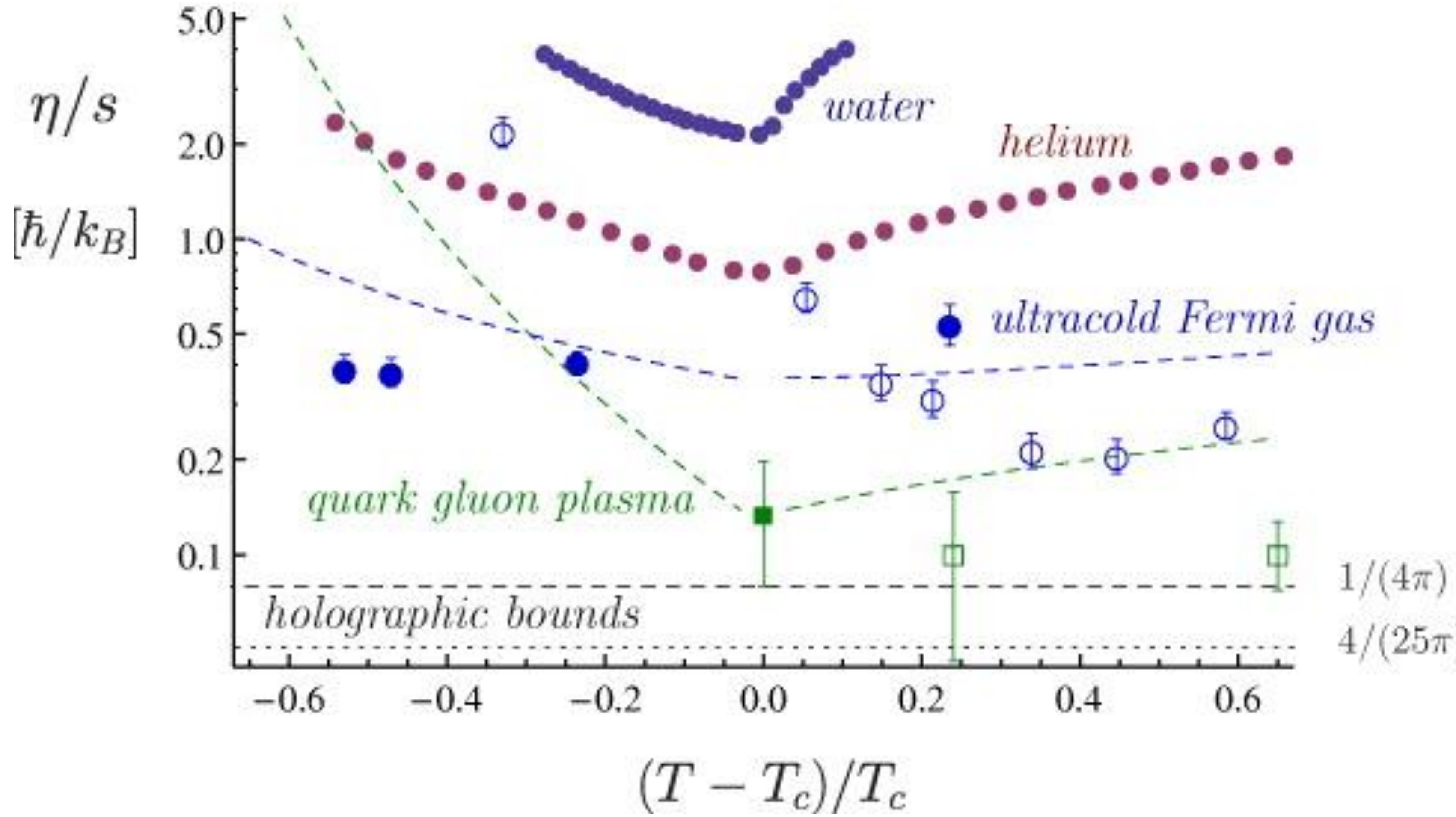


$$\tau = \frac{F}{A} = \eta \frac{\partial u}{\partial y}$$

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

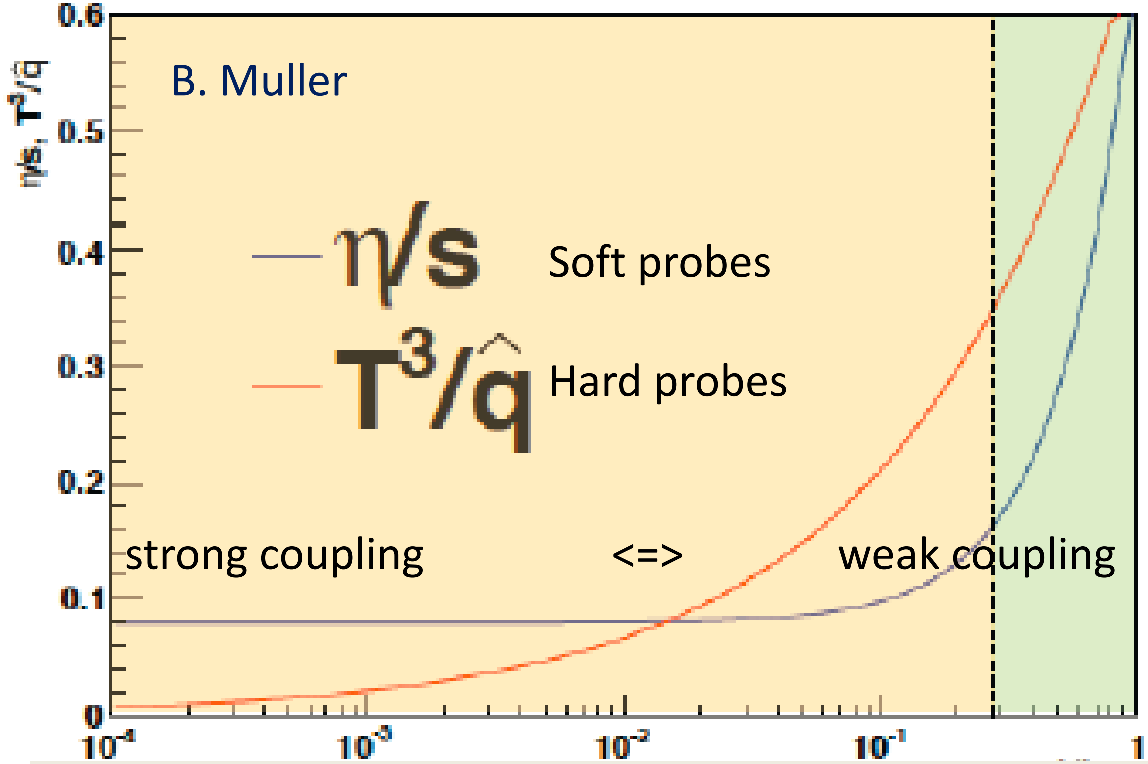
$$\eta \approx \tfrac{1}{3} n\bar{p}\lambda_f = \frac{\bar{p}}{3\sigma_{tr}}$$

Specific shear viscosity for strongly-correlated fluids



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

Transport coefficients



At weak coupling:

$$\frac{T^3}{\hat{q}} \approx \# \frac{\eta}{s}$$

At strong coupling:

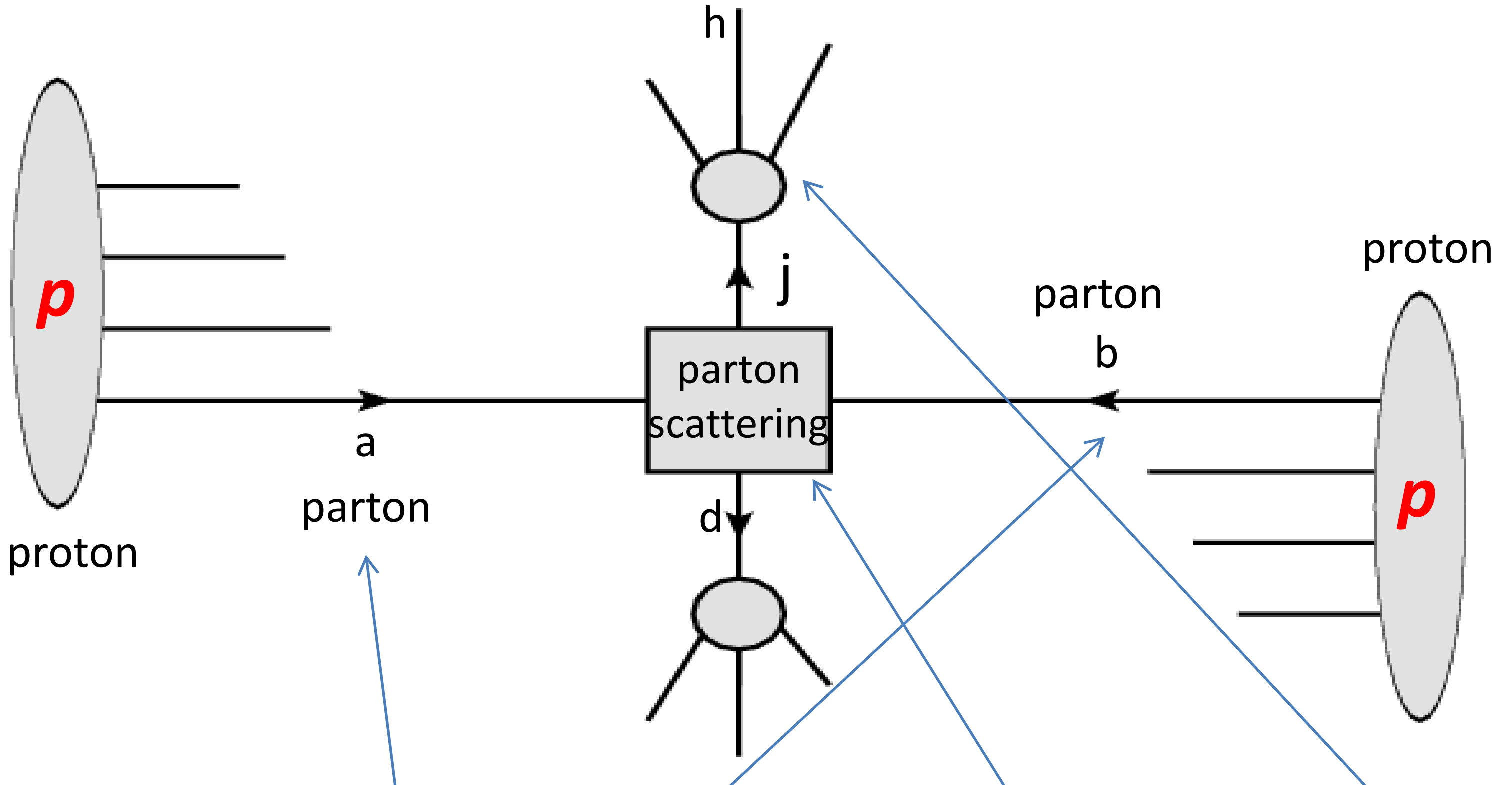
$$\frac{T^3}{\hat{q}} << \# \frac{\eta}{s}$$

Majumder, Muller, Wang, PRL 2007

Shear viscosity & jet transport coefficients encode much information of QGP

If we can determine them (their T dependence) precisely, we may figure out how (at what scale) QGP becomes strongly coupled (from a weakly-coupled high T regime)

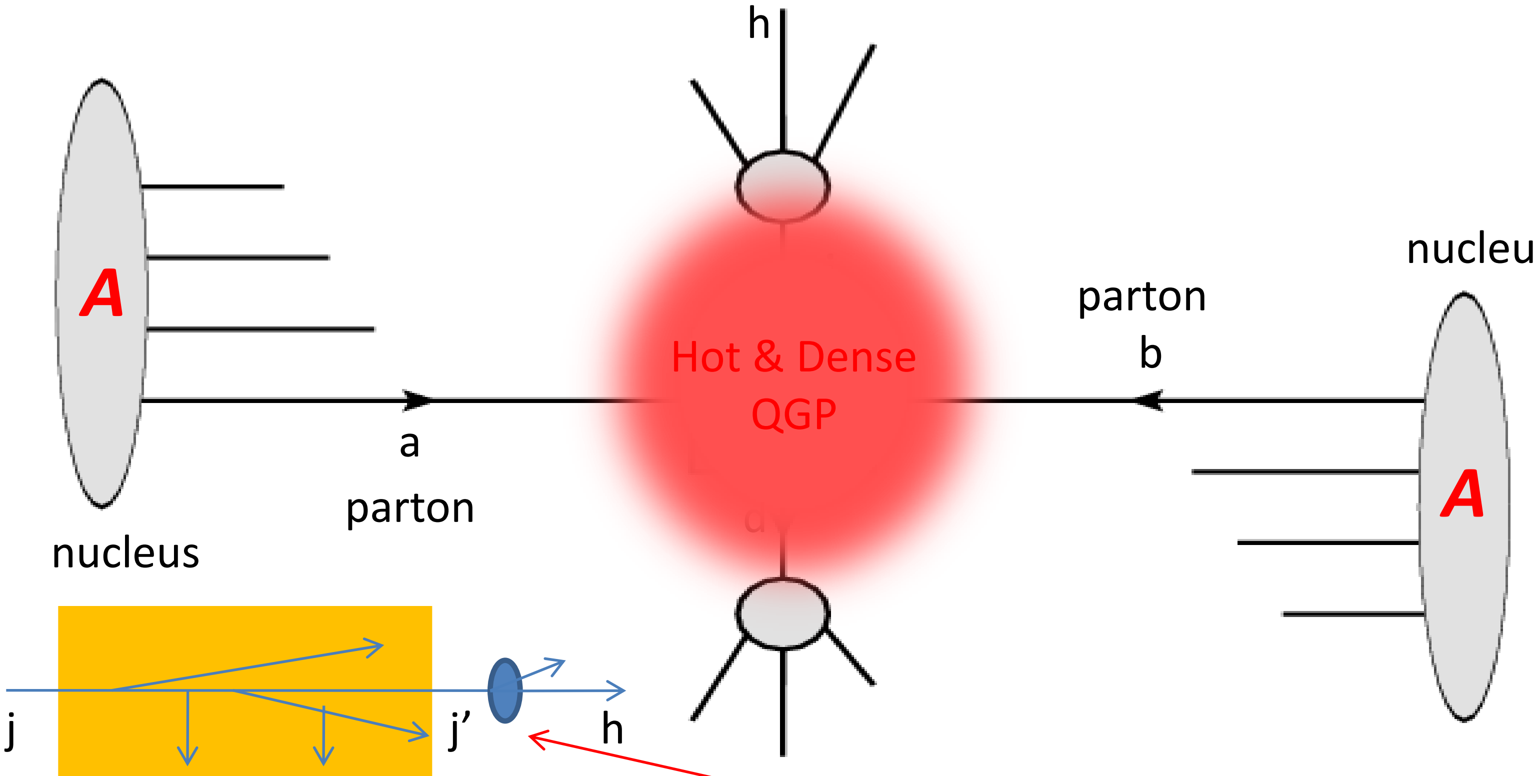
General framework for jet quenching study



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

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.

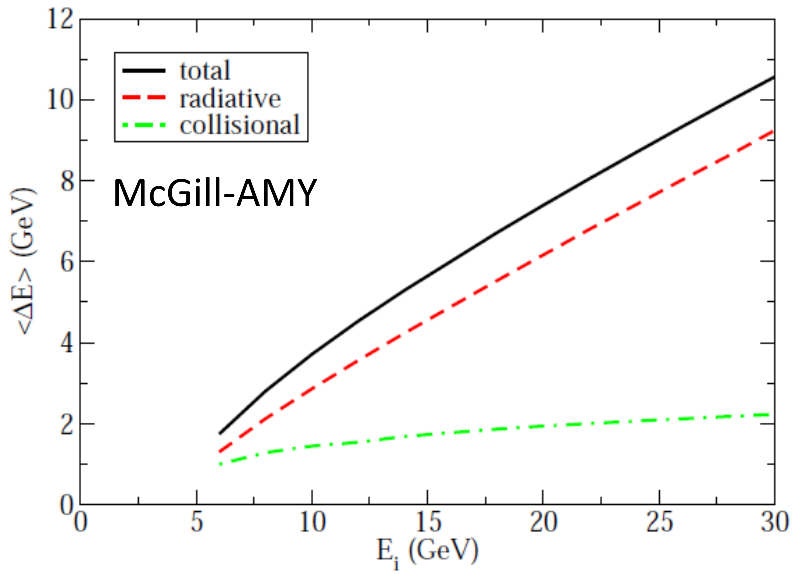
General framework for jet quenching study

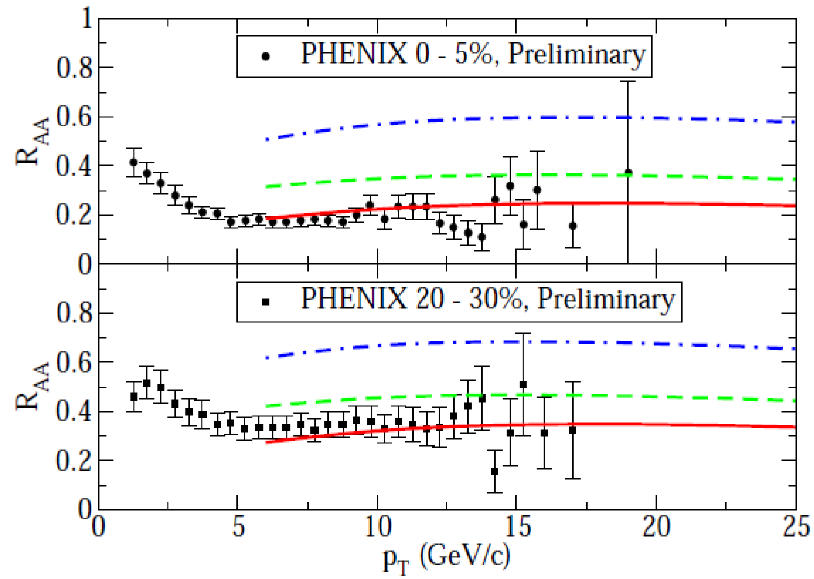


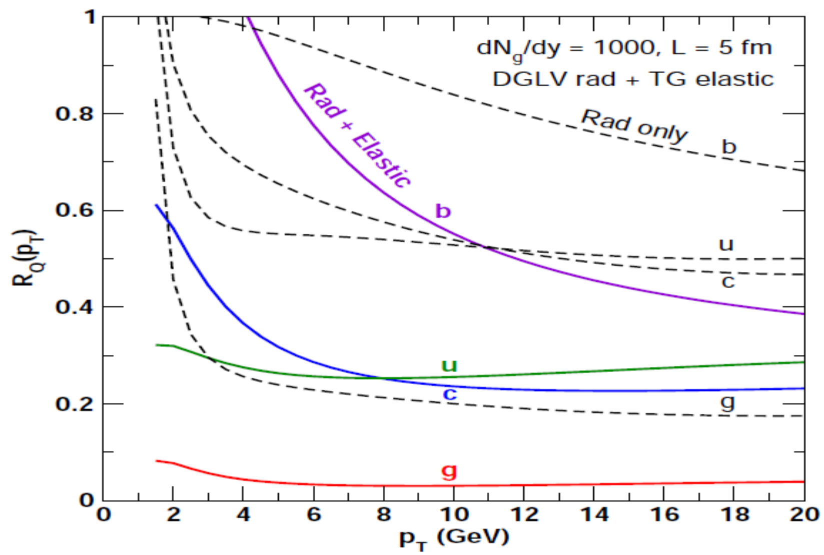
$$d\tilde{\sigma}_h = \sum_{abjX} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jX} \otimes \tilde{D}_{h/j}$$

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

Radiative and collisional contributions





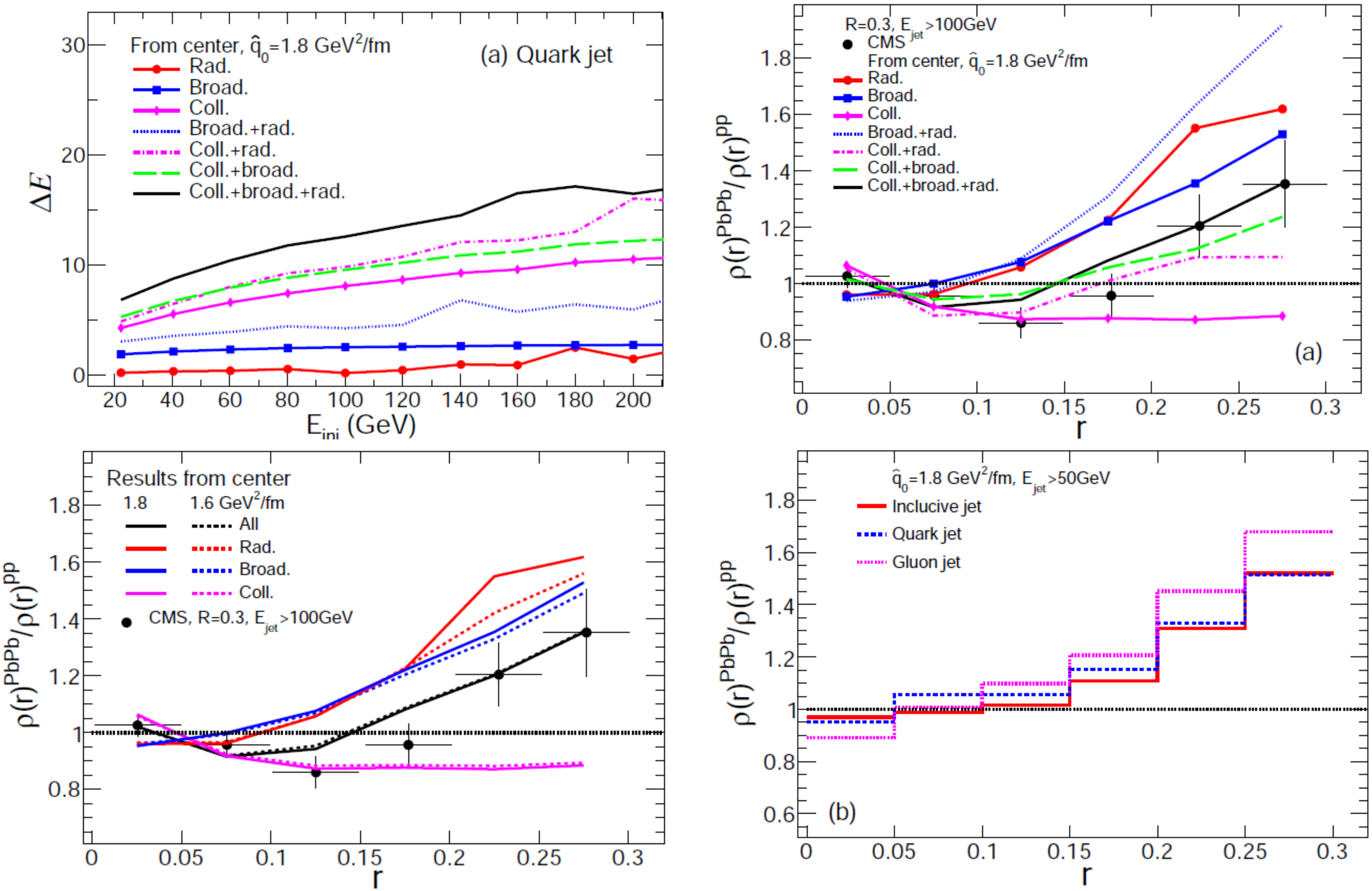


GYQ, Ruppert, Gale, Jeon, Moore, Mustafa, PRL 2008

Wicks, Horowitz, Djordjevic, Gyulassy, Nucl.Phys. A784 (2007) 426-442

Both collisional and radiative contributions are controlled by various jet transport coefficients

Roles of different mechanisms



Ningbo Chang, GYQ, arXiv:1603.01920

Heavy quark energy loss in QGP elastic & radiative processes

- **At low p_T, heavy quark energy loss is more dominated by collisional component**
- **Langevin approach has been widely utilized at RHIC for heavy quark evolution**
  (Moore, Teaney, PRC 2005; He, Fries, Rapp, PRC 2012; Young, Schenke, Jeon, Gale, PRC 2012 …)

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} \qquad \langle \xi^i(t)\xi^j(t')\rangle = \kappa\delta^{ij}\delta(t-t')$$

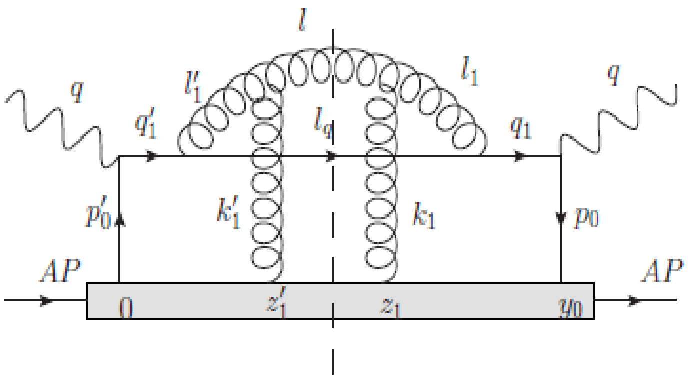
- **Einstein relation (detailed balance):**

$$\eta_D(p) = \frac{\kappa}{2TE} \qquad D = \frac{T}{M\eta_D(0)} = \frac{2T^2}{\kappa}$$

- **At high p_T, , heavy quark energy loss is more dominated by radiative component (similar to light flavors), necessary to include it at the LHC**
- **We utilize higher twist (HT) E-loss formalism**
  (Guo, Wang, PRL 2000; Majumder, PRC 2012)
- **HT model for heavy quark radiative energy loss**
  (Zhang, Wang, Wang, PRL 2004)

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

- **Include gluon radiation contribution as a recoil force exerted on the heavy quark**



$$\frac{d\vec{p}}{dt} = -\eta_D\vec{p} + \vec{\xi} - \vec{f}_g$$

Heavy quark hadronization

- **Most high momentum heavy quarks fragment into heavy mesons**
  - Use PYTHIA 6.4 "independent fragmentation model"
- **Most low momentum heavy quarks hadronize to heavy mesons via recombination (coalescence) mechanism**
  - use sudden recombination model based on Y. Oh, et al., PRC 79, 044905 (2009)

$$\frac{dN_M}{d^3p_M} = \int d^3p_1 d^3p_2 \frac{dN_1}{d^3p_1}\frac{dN_2}{d^3p_2} f_M^W(\vec{p}_1, \vec{p}_2)\delta(\vec{p}_M - \vec{p}_1 - \vec{p}_2)$$

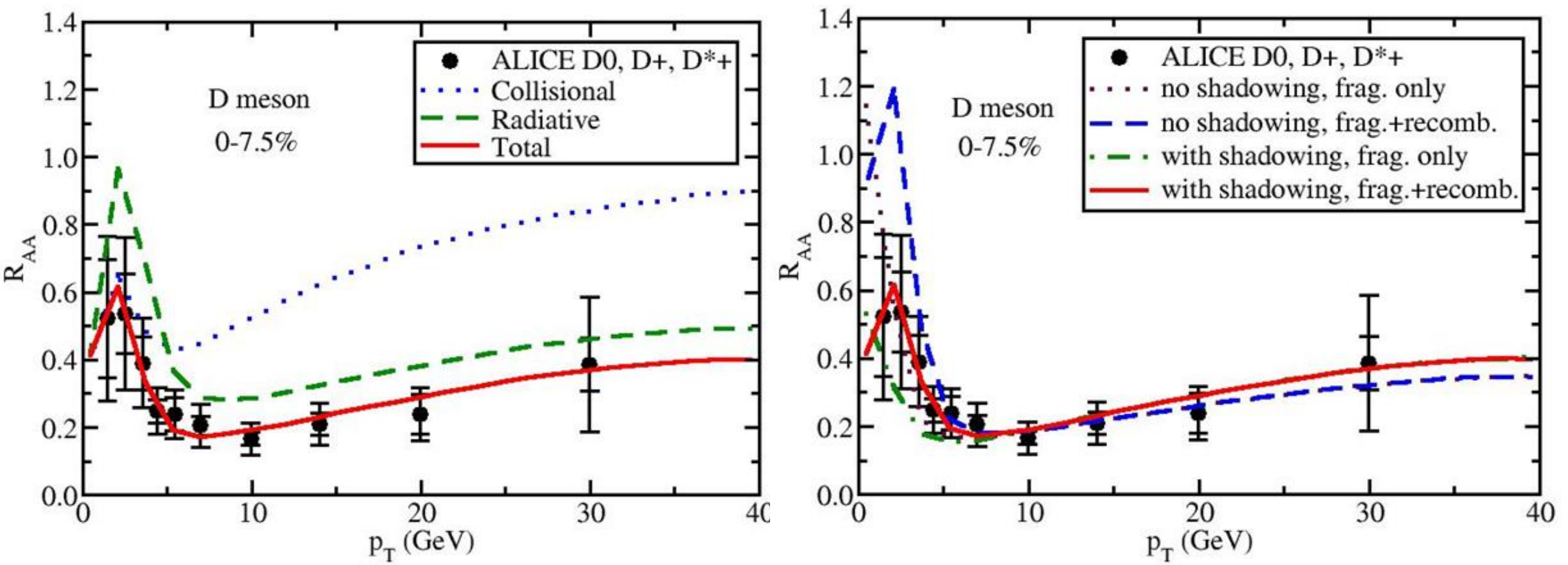
$$\frac{dN_B}{d^3p_B} = \int d^3p_1 d^3p_2 d^3p_3 \frac{dN_1}{d^3p_1}\frac{dN_2}{d^3p_2}\frac{dN_3}{d^3p_3} f_B^W(\vec{p}_1, \vec{p}_2, \vec{p}_3)\delta(\vec{p}_M - \vec{p}_1 - \vec{p}_2 - \vec{p}_3)$$

  - Inputs: heavy Q/Q^{bar} distribution after evolution, light q^{bar}/q distribution from QGP, and the Wigner function f^W
  - f^W is obtained from hadron wave functions (approximated by S.H.O.)

$$f_M^W(\vec{r}, \vec{q}) \equiv N g_M \int d^3r' e^{-i\vec{q}\cdot\vec{r}'} \phi_M(\vec{r} + \frac{\vec{r}'}{2})\phi_M^*(\vec{r} - \frac{\vec{r}'}{2})$$

  - Use f^W to calculate the recombination probability $P_{coal.}(p_{HQ})$ for all mesons & baryons: D/B, Λ_Q, Σ_Q, Ξ_Q, Ω_Q

Heavy meson R_{AA} after QGP (LHC)



- Collisional energy loss dominates at low p_T; radiative energy loss dominates at high p_T
- Nuclear shadowing effect leads to a decrease in D meson R_{AA} at low p_T, and a mild increase at high p_T
- Fragmentation is sufficient to describe D meson R_{AA} above 8 GeV, but at intermediate p_T, recombination becomes important

Cao, GYQ, Bass, PRC 2013; PRC 2015; PRC 2016