Transport coefficients and e-loss in an expanding QGP

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in collaboration with

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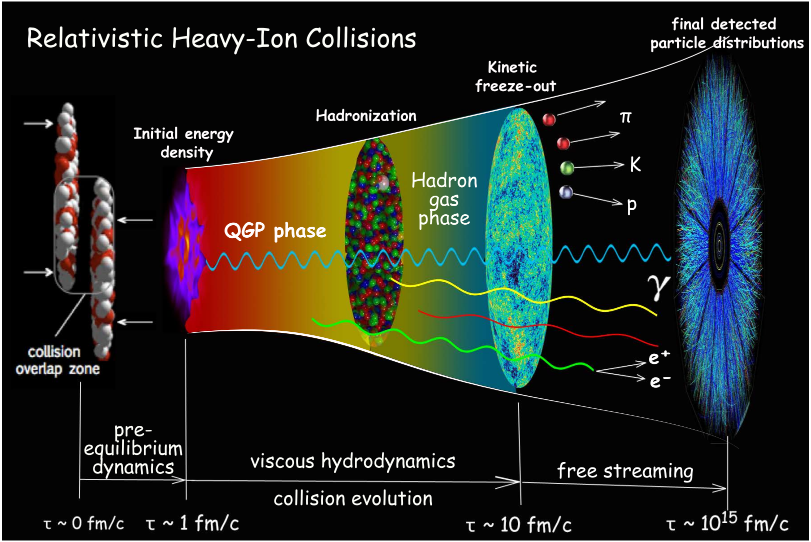
XXX Reunión Anual de la División de Partículas y Campos
24-05-2016, Edificio Carolino, BUAP

A Standard Model in the making



QGP: feats and aims

- $\surd$ Beyond any doubt, QGP created in ultra-relativistic in HICs at RHIC and LHC
- We want direct access to QGP (mostly local equilibrium) properties: T, EoS, transport coefficients, etc.
- We only have spectra of final state particles
- To connect both: solve microscopic, non-equilibrium, many-body QCD problem
- Or build theoretical (many scale) model
- And/Or realise that problem tractable as coarse-grained collective motion (after local equilibrium is established) $\rightarrow$ hydrodynamics

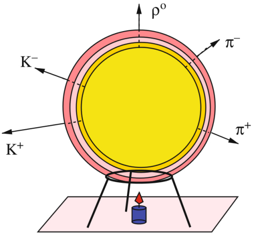
Nuclear physics programs at RHIC and LHC

- primary goal: to study high temperature QCD
- collide large nuclei at extremely high energies
- hot matter created where nucleons are no longer the relevant d.o.f.
- QGP: quarks and gluons are deconfined over an extended volume
- first observables: γ's radiated from this matter $\rightarrow$ hottest matter ever created in the lab!

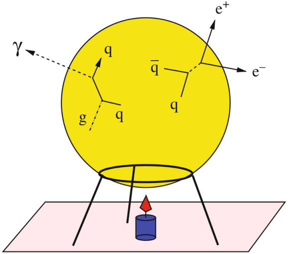
How do we learn about QGP's properties?

H. Satz et. al. The Physics of the Quark-Gluon Plasma, Lecture Notes in Physics 785 (2010)

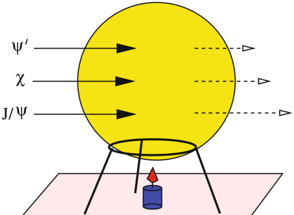
Hadron radiation



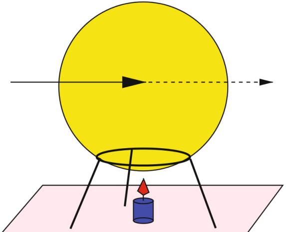
Electromagnetic radiation



Dissociation of quarkonia



Energy loss of parton/jet √



Focus on

- $\surd$ bulk matter well described by hydro models with small η/s
- $\surd$ matter is nearly opaque to the passage of high p_T quarks and gluons
- $\surd$ basic probes high p_T quarks and gluon produced by hard (large momentum transfer) QCD processes
  - probe on short length scales and lose energy via gluon bremsstrahlung and multiple scattering
- → Collisions: proton-proton (pp) [benchmark], gold-gold (Au+Au) and lead-lead (Pb+Pb)

Focus on

√ Jets:

- jet quenching, e-loss and transport coefficients

√ Correlations:

- small azimuthal angle (near-side) large pseudorapidity
- broadening in large azimuthal angle (away-side) correlation

√ Asymmetry and imbalance:

- p_T asymmetry, in/out-of-cone radiation as probe of e-loss mechanism

ADJMT Toolkit:

- pQCD, vacuum/in-medium FFs, hydro, hadron dist at freeze-out
- hard probe event generator, medium geometry, e-loss mechanism

Outline

ADJMT Toolkit

pQCD

MadGraph 5 for $2 \rightarrow 2$ and $2 \rightarrow 3$ parton events in p + p collisions at RHIC and LHC energies

subsequently make them loose energy → e-loss mechanism

hydro

linear viscous hydrodynamics (small η, null ζ and $c_s^2/v^2 < 1$)*

in-medium hard probe as point-like source*

hadron dist

Cooper-Frye hadronization

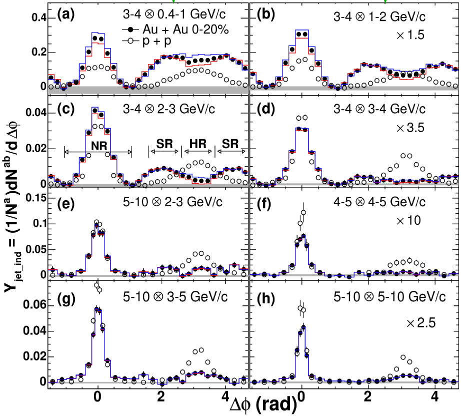
energy and momentum deposited in-medium small compared to unperturbed medium

Azimuthal angular correlations at RHIC

The *ridge* and *broad away side*: excess yield of correlated particles at $\Delta\phi = 0$ and $\Delta\phi \approx \frac{2\pi}{3}, \frac{4\pi}{3}$ rad

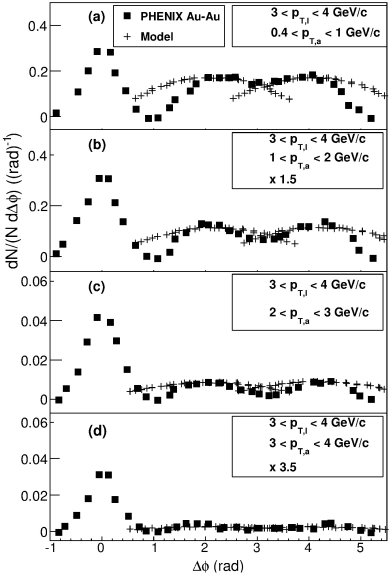
azimuthal correlations for large momentum difference, develop a “double hump” in the away side

PHENIX PRC78:014901,2008

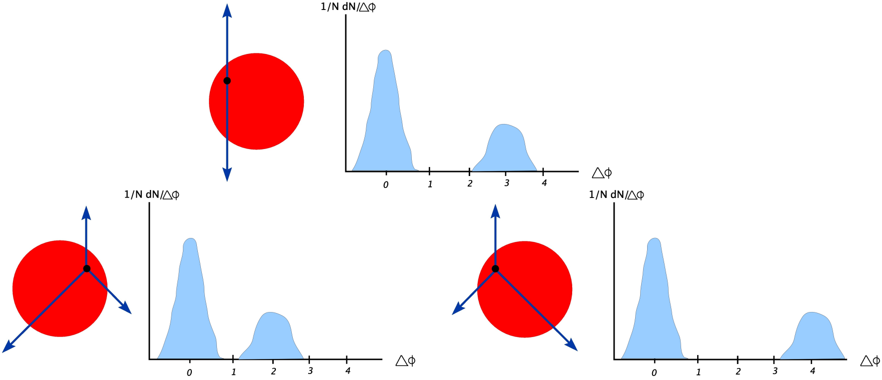


Azimuthal correlations: ADJMT vs PHENIX data

Per-trigger
azimuthal
angular
correlations
PHENIX 0-20%
Au+Au
@ 200 GeV
vs
ADJMT Toolkit
PRC 88 (2013)
arXiv: 1212.1127



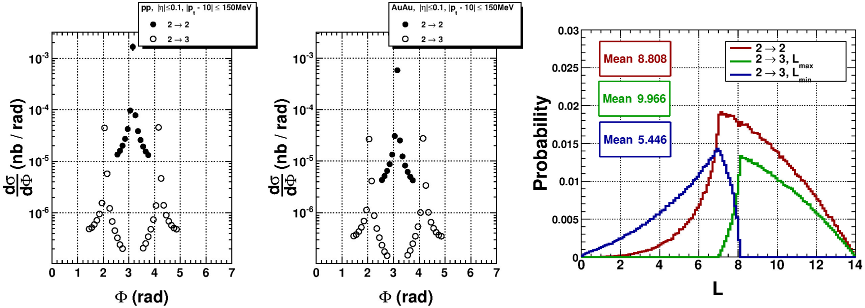
Key idea # 1: path length $2 \to 2$ vs $2 \to 3$



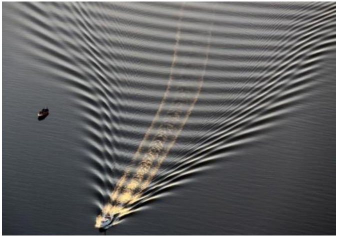
Key idea # 1: path length $2 \to 2$ vs $2 \to 3$

Ayala, Jalilian-Marian, Magnin, Ortiz, Paic, T-Y, PRL 104 (2010)

Path length $+$ scenario enhances 3 vs 2 particles: medium induced energy loss on LO $2 \to \{2,\ 3\}$ xsecs $\rightsquigarrow$ different geometry for trajectories of 3 as opposed to 2 particles in the final state of $A + A$ collisions, one particle absorbed by the medium, the other one punches through: *double hump*



Key idea # 2: head shock vs Mach cones



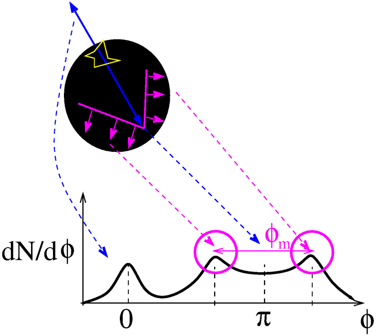


diagram: Torrieri et al. Acta Phys.Polon. B39 (2008)

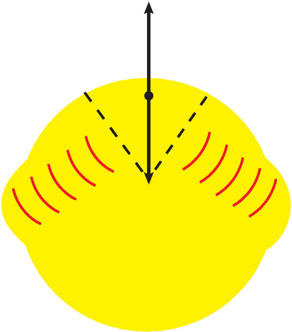
Less of a wave and more of a wake?

2012 fast moving parton under conditions in HICs (low viscosity, large parton velocity) doesn't generate double-hump via Mach cone

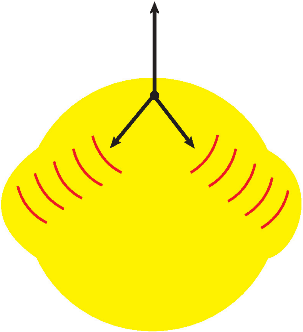
energy momentum deposition in the head shock region is strongly forward-peaked

Bouras et al PLB**710** (2012)], Neufeld and Vitev, PRC**86** (2012)]

Key idea # 2: head shock vs Mach cones

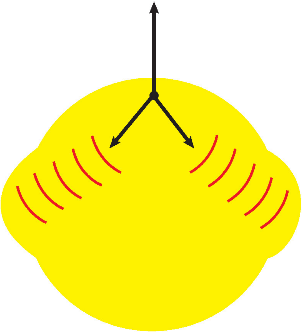


1 parton deposits energy as shock wave (Mach cone)



2 partons deposit energy as a wake (Head shock)

Combine key ideas # 1 and # 2



Two away-side partons in $2 \to 3$ processes deposit energy momentum into medium, so model the current they produce with localized disturbance:

$$J^{\nu}(\mathbf{x},t) = \left(\frac{dE}{dx}\right) v^{\nu} \delta(\mathbf{x} - \mathbf{v}t)$$

$\frac{dE}{dx}$ energy loss per unit length and $v^{\nu} \equiv \gamma(1, \mathbf{v})$ with $\mathbf{v}$ parton velocity

Neufeld and Renk, PRC **82** (2010)

ADJMT Toolkit: linearized (small viscosity) hydro

Medium tot energy momentum $T^{\mu\nu}$ as underlaying medium in equilibrium with small perturbation

$$T^{\mu\nu} = T_0^{\mu\nu} + \delta T^{\mu\nu},$$

Leads to hydro equations with J^ν source of disturbance (fast moving parton)

$$\partial_\mu \delta T^{\mu\nu} = J^\nu \quad \Rightarrow \begin{cases} \delta T^{00} = \delta\epsilon \\ \delta T^{0i} = \mathbf{g} \\ \delta T^{ij} = \delta_{ij} c_s^2 \delta\epsilon - \frac{3}{4}\Gamma_s(\partial^i \mathbf{g}^j + \partial^j \mathbf{g}^i - \frac{2}{3}\delta_{ij}\nabla\cdot\mathbf{g}) \end{cases}$$

$\Gamma_s \equiv \frac{4\eta}{3\epsilon_0(1+c_s^2)}$ sound attenuation length, $c_s = \sqrt{1/3}$ speed of sound

ADJMT Toolkit: linearized (small viscosity) hydro

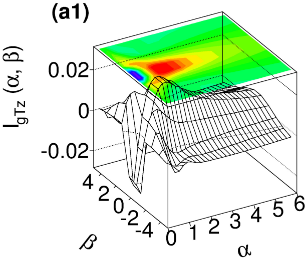
So if current associated with the source is

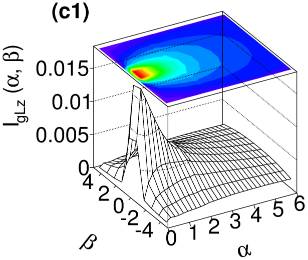
$$J^\nu(\mathbf{r},t) = \left(\frac{dE}{dx}\right) v^\nu \delta^3(\mathbf{x}-\mathbf{v}t)$$

where (dE/dx) is the energy loss per unit length then

$$\begin{aligned}\delta\epsilon &= \left(\frac{1}{4\pi}\right)\left(\frac{dE}{dx}\right)\left(\frac{2v}{3\Gamma_s}\right)^2\left(\frac{9}{8v}\right) I_{\delta\epsilon}(\alpha,\beta) \\ \mathbf{g}_i &= \left(\frac{1}{4\pi}\right)\left(\frac{dE}{dx}\right)\left(\frac{2v}{3\Gamma_s}\right)^2 I_{\mathbf{g}_i}(\alpha,\beta),\end{aligned}$$

for $c_s^2/v^2 < 1$





ADJMT Toolkit: $\delta\epsilon$ and $\mathbf{g}_i$ into hadrons

Particle yield at central rapidity (Cooper-Frye):

$$\frac{dN}{d\phi}(y=0) = \int_{p_T^{\min}}^{p_T^{\max}} \frac{dp_T\ p_T}{(2\pi)^3} \int d\Sigma_\mu p^\mu [f(p\cdot u) - f(p_0)]$$

constant freeze-out hyper surface $d\Sigma_\mu p^\mu = d^3r\ p_T$

equilibrium distribution (Boltzmann): $f(p_0) = \mathrm{e}^{-p_T/T_0}$

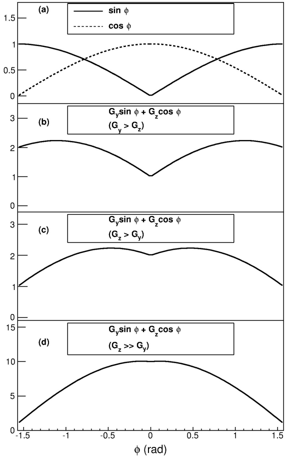
background medium's energy density and temperature: ϵ_0, T_0

ADJMT Toolkit: $\delta\epsilon$ and $\mathbf{g}_i$ into hadrons

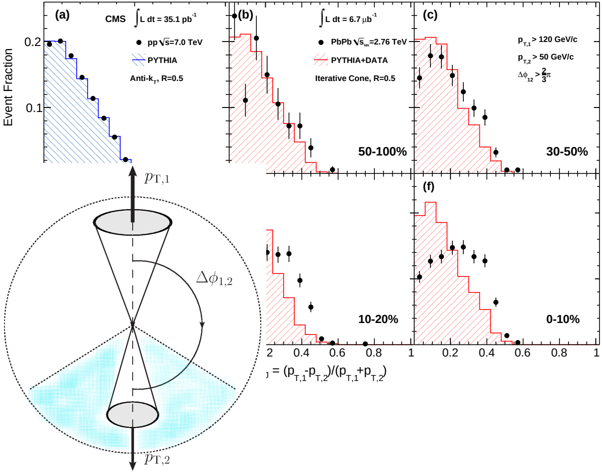
$$f(p\cdot u) - f(p_0) \quad \simeq \quad \left(\frac{p_T}{T_0}\right)\left(\frac{\delta\epsilon}{4\epsilon_0} + \frac{\mathbf{g}_y \sin\phi + \mathbf{g}_z\cos\phi}{\epsilon_0(1+c_s^2)}\right) \mathrm{e}^{-p_T/T_0}$$

Shape of distribution depends on $G_i \equiv \int d^2r\, \mathbf{g}_i$

- $G_y > G_z$: $\sin\phi$ two peaks away from $\phi = 0$
- $G_z > G_y$: $\cos\phi$ two peaks close to $\phi = 0$
- $G_z \gg G_y$: peaks become one



Asymmetry in PbPb at 2.76 TeV



Phys.Rev.C84 (2011)

- 1, leading; 2, subleading; so $A_J > 0$
- $p_{\mathrm{T},1} >$ 120 GeV/c and $p_{\mathrm{T},2} >$ 50 GeV/c
- A_J near $p_{\mathrm{T},1}$ threshold: $A_J < 0.41$
- 300 GeV/c leading jets $A_J = 0.7$

→ pp data at $\sqrt{s} = 7$ TeV and PbPb data at $\sqrt{s} = 2.76$ TeV

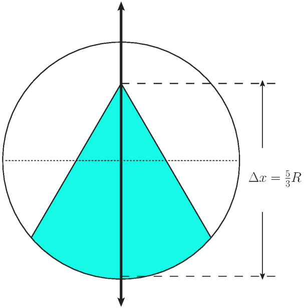
For most central

→ deficit of balanced pairs and excess of unbalanced pairs

Set up

Parton with E @hard scattering, travels in-medium ΔL, looses ΔE, emerges with $E - \Delta E$ and fragments in vacuum

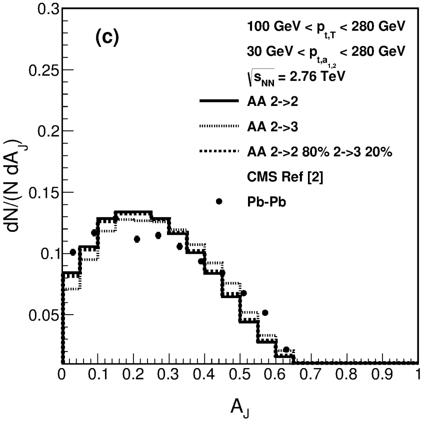
- E-loss: $\Delta E = \Delta L \left(\frac{dE}{dx}\right) \rho(\mathcal{E})\, d\mathcal{E}$ with $\frac{dE}{dx} = 5$ GeV/fm
- Gaussian e-loss profile: $\rho(\mathcal{E})$ with $\bar{\mathcal{E}} = 50$ GeV and $\Delta\mathcal{E} = 10$ GeV
- away side particle deposits



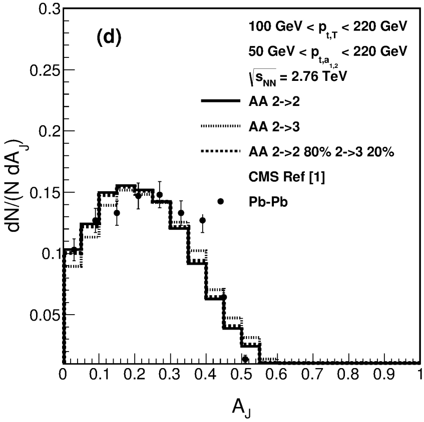
$$\delta p|_{\phi^{\text{max}}} = \frac{2\Delta\tau(\Delta y)^2}{(2\pi)^3} \int_0^\infty dp_T \frac{p_T^4}{T_0} \mathrm{e}^{-p_T/T_0} \int_0^{\phi^{\text{max}}} d\phi \left(\frac{\delta\epsilon}{4\epsilon_0} + \frac{\mathbf{g}_y \sin\phi + \mathbf{g}_z \cos\phi}{\epsilon_0(1+c_s^2)} \right)$$

Latest results: asymmetry in PbPb at 2.76 TeV

Ayala, Dominguez, Jalilian-Marian and T-Y, PRC **92** (2015)
`arXiv:1503.06889 [hep-ph]`



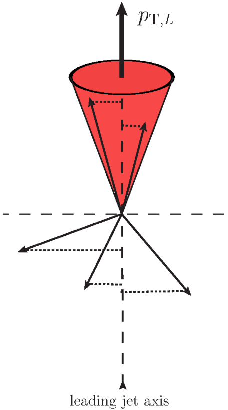
[2] CMS CMS-HIN-14-010 (2014)

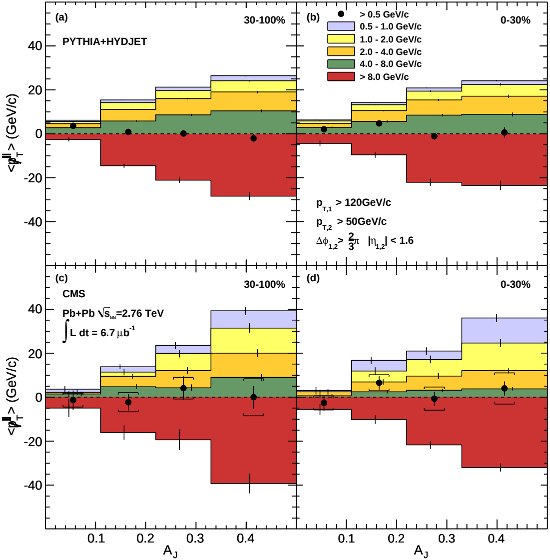


[1] CMS PRC **84** (2011)

p_{T} imbalance in PbPb at 2.76 TeV

$$\not{p}_{\mathrm{T}}^{\parallel} = \sum_i -p_{\mathrm{T}}^i \cos(\phi_i - \phi_L)$$

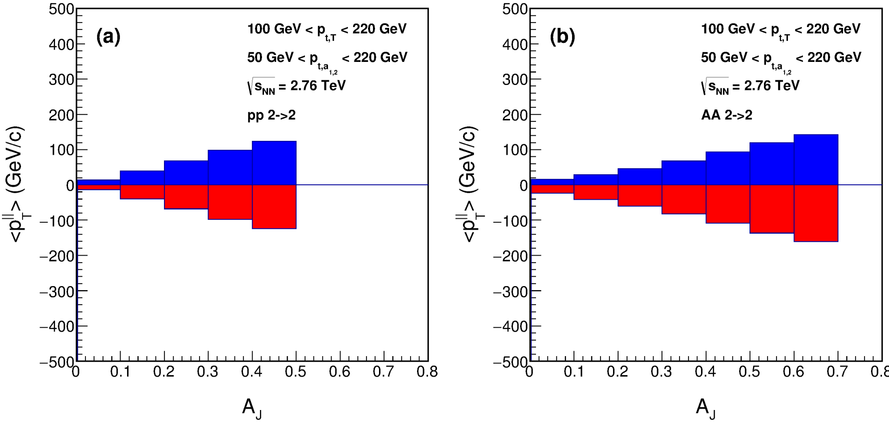




Latest results: momentum imbalance and e-loss

Ayala, Dominguez, Jalilian-Marian and T-Y, PRC **92** (2015)
`arXiv:1503.06889 [hep-ph]`

$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$ in/out-cone $p_{T,2} \to p_{T,2} \pm \delta p$,



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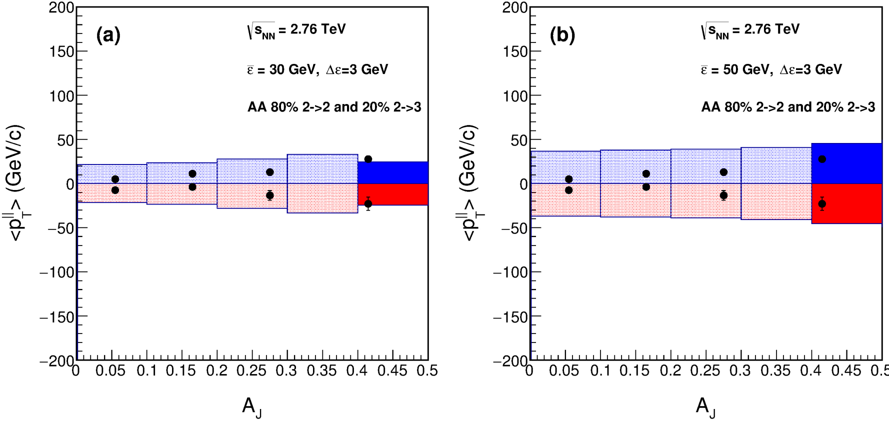


What does linear vHydro say about $\hat{q}$?

Ayala, Dominguez, Jalilian-Marian and T-Y (2016)
Relating $\hat{q}$, η/s and ΔE in an expanding QGP
`arXiv:1603.09296 [hep-ph]`

part. mom. dist. around the direction of motion of a fast moving parton in hydro approx.

$$\begin{aligned}\mathcal{P}(p_T, r, \phi) &\equiv \frac{1}{N}\frac{dN}{p_T dp_T d\phi d^2 r} \\ &= \frac{1}{N}\frac{\Delta\tau(\Delta y)^2}{(2\pi)^3}\frac{p_T^2}{T_0}\mathrm{e}^{-p_T/T_0}\left(\frac{\delta\epsilon}{4\epsilon_0} + \frac{\mathbf{g}_y \sin\phi + \mathbf{g}_z \cos\phi}{\epsilon_0(1+c_s^2)}\right)\end{aligned}$$

avg mom squared carried by the disturbance (transverse to v)

$$\langle q^2 \rangle \equiv 2\int d^2 r \int dp_T p_T \int_0^{\pi/2} d\phi\, \mathcal{P}(p_T, r, \phi) p_T^2 \sin^2\phi,$$

What does linear vHydro has to say about $\hat{q}$?

Integrating over p_T and ϕ, the average momentum squared *given to the medium by the fast parton* is

$$\langle q^2\rangle \;=\; 20\,T_0^2\,\frac{\int d^2r\left[\frac{\pi}{8}\delta\epsilon+\frac{(4/3)\mathbf{g}_y+(2/3)\mathbf{g}_z}{(1+c_s^2)}\right]}{\int d^2r\left[\frac{\pi}{4}\delta\epsilon+\frac{2\mathbf{g}_y+2\mathbf{g}_z}{(1+c_s^2)}\right]}$$

Q: Can this $\langle q^2\rangle$ be identified with the average momentum squared *given to the fast parton* by the medium and therefore with $\hat{q}$ upon dividing by the medium's length?

A: If the parton's ΔE is small, main overall effect is deflection. This in turn comes with energy and momentum deposited within the medium via radiation or collisional processes so

$$\hat{q}=\frac{\langle q^2\rangle}{L}$$

Qin, Majumder, Song, Heinz PRL 103 (2009)

But $\hat{q}$ from an expanding medium?

Attempt a phenomenological description based on modelling the way the medium gets diluted during the first stages of the collision due to longitudinal expansion: avg. # scatterings $\langle n \rangle$ is

$$\langle n \rangle = \int_{\tau_0}^{\infty} d\tau \frac{1}{\lambda_0\, \rho_0}\, \rho_g(\tau, \mathbf{b}, \mathbf{r}, \hat{\mathbf{n}}\tau),$$

e-loss with evolving medium

$$\Delta E = \left\langle \frac{dE}{dx} \right\rangle_{1d} \int_{\tau_0}^{\infty} d\tau \frac{\tau - \tau_0}{\tau_0\, \rho_0}\, \rho_g(\tau, \mathbf{b}, \mathbf{r} + \hat{\mathbf{n}}\tau)$$

gluon density related to nuclear geometry

$$\begin{aligned}\rho_g(\tau, \mathbf{b}, \mathbf{r}, \hat{\mathbf{n}}) &= \frac{\tau_0\, \rho_0}{\tau} \frac{\pi R_A^2}{2A} \\ &\times \left[T_A(|\mathbf{r} + \hat{\mathbf{n}}\tau|) + T_A(|\mathbf{b} - \mathbf{r} - \hat{\mathbf{n}}\tau|)\right]\end{aligned}$$

Zhang, J. F. Owens, E. Wang, and X.-N Wang, PRL **98** (2007)

$\hat{q}$ and η/s in an expanding medium

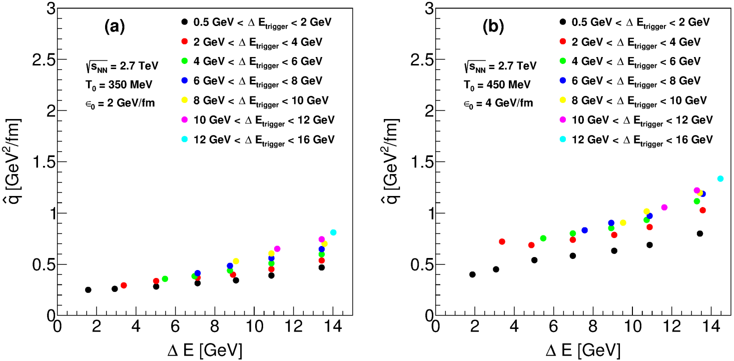
Approximate the average energy loss per unit length with the energy loss given by the above described model divided by the in-medium length L

$$\left(\frac{dE}{dx}\right) \sim \frac{\Delta E}{L(\mathbf{r},\hat{\mathbf{n}})} \qquad \longrightarrow J^{\nu}(\mathbf{r},t) = \left(\frac{dE}{dx}\right) v^{\nu}\delta^{3}(\mathbf{x}-\mathbf{v}t)$$

to study the interplay of transport coefficients in connection with e-loss and geometry

$$\hat{q}_{\Delta E} \quad = \quad \frac{20\, T_0^2 \int d^2r \left(\frac{\pi}{8}\delta\epsilon + \frac{(4/3)\mathbf{g}_y + (2/3)\mathbf{g}_z}{(1+c_s^2)}\right|_{\Delta E}}{\sum_{\Delta E} L(\mathbf{r},\hat{\mathbf{n}}) \int d^2r \left(\frac{\pi}{4}\delta\epsilon + \frac{2\mathbf{g}_y + 2\mathbf{g}_z}{(1+c_s^2)}\right|_{\Delta E}} \Longleftrightarrow \frac{\eta}{s} \sim T\,\frac{L(\mathbf{r},\hat{\mathbf{n}})}{\langle n\rangle}$$

$\hat{q}$ and ΔE in an expanding medium



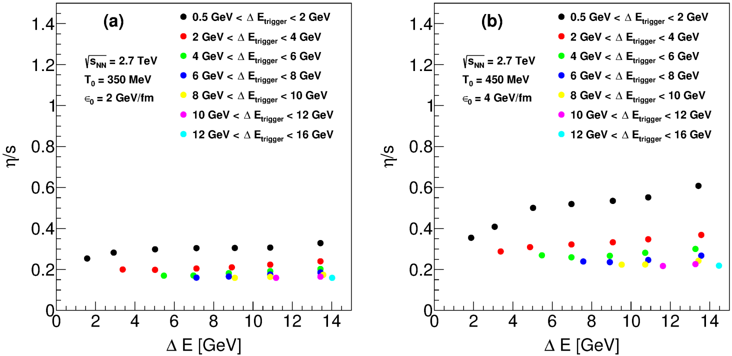
$$\hat{q}(\Delta E) \sim \begin{cases} 0.2 - 1 \text{ GeV}^2/\text{fm} & (T_0 = 350 \text{ MeV}) \\ 0.4 - 1.5 \text{ GeV}^2/\text{fm} & (T_0 = 450 \text{ MeV}) \end{cases}$$

$$\frac{\hat{q}(\Delta E)}{T^3} \sim \begin{cases} 0.9 - 4.6 & (T_0 = 350 \text{ MeV}) \\ 0.8 - 3.3 & (T_0 = 450 \text{ MeV}) \end{cases}$$

$$\frac{\hat{q}}{T^3} \sim 3.7 \pm 1.4 \text{ at LHC}$$

JET Collaboration PRC 90 (2014)

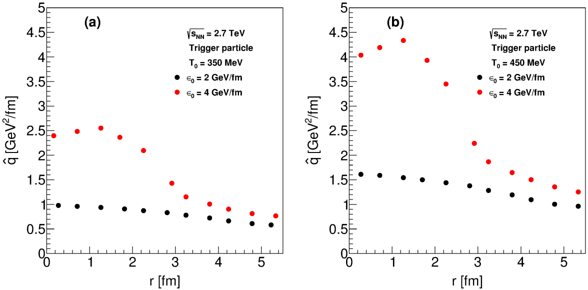
η/s and ΔE in an expanding medium

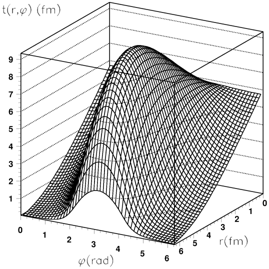


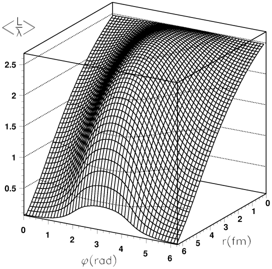
$$\frac{\eta}{s}(\Delta E) \sim \begin{cases} 0.18 - 0.3\ \text{GeV}^2/\text{fm} & (T_0 = 350\ \text{MeV}) \\ 0.25 - 0.6\ \text{GeV}^2/\text{fm} & (T_0 = 450\ \text{MeV}) \end{cases}$$

$$\frac{T^3}{\hat{q}(\Delta E)} \sim \begin{cases} 0.21 - 1.07 & (T_0 = 350\ \text{MeV}) \\ 0.31 - 1.25 & (T_0 = 450\ \text{MeV}) \end{cases}$$

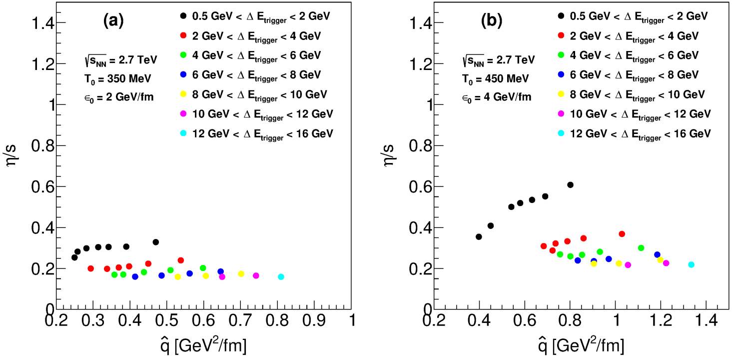
$\hat{q}$ and r in an expanding medium







η/s and $\hat{q}$ in an expanding medium



$$\frac{T^3}{\hat{q}} \begin{cases} \approx \frac{\eta}{s} \quad , \text{ weakly-coupled} \\ \ll \frac{\eta}{s} \quad , \text{ strongly-coupled} \end{cases}$$

Majumder, Muller, Wang, PRL 99 (2007); Casalderrey-Solana, Wang, PRC (2008); Qin, Wang, IntJMP E 24 (2015).

Final remarks

ADJMT Toolkit:

- pQCD event generator, medium geometry and e-loss mechanism
- hydrodynamics and hadronization

Hadron correlations:

- interplay of pQCD, e-loss mechanism and geometry

√ study broadening in large azimuthal angle

p_T asymmetry and imbalance:

√ study asymmetry dist and in/out-of-cone radiation

Transport coefficients and e-loss:

√ interplay of $\hat{q}$ and η/s with ΔE and geometry

Work in progress

→ initial conditions

→ R_{AA} and v_2

→ balance of p_{T} for $p_{\mathrm{T}} < 8$ GeV/c in connection with e-loss mechanism