Probing the path-length dependence of parton energy loss in quark-gluon plasma

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FA, Phys. Rev. Lett. 119 (2017) 062302 [1703.10852]

FA, G. Falmagne, to appear

Context

Over the last decade, tremendous development on jet quenching

Experiment

- First reconstruction of jets in heavy ion collisions
- Jet substructure
- Fragmentation functions
- Jet-tagged and photon-tagged correlations, etc.

Phenomenology

- Monte-Carlo event generators in heavy-ion collisions
- Gluon emission off multi-particle antennas
- Jet fragmentation in a realistic medium, etc.

This talk

Here, looking for simpler things

Simple analytic model based on a single process – radiative energy loss – to describe the quenching of single hadrons at large $p_\perp$

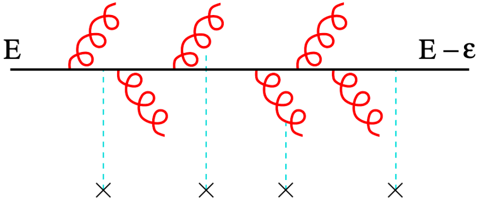
1. **Why hadron quenching ?**
   - hadrons = particles
     - in a sense much simpler than jets: good proxy for parton energy loss
   - very precise data at the LHC

2. **Why large transverse momentum ?**
   - cold nuclear matter effects weaken/vanish when $p_\perp \gg Q_s$
   - radiative energy loss likely the dominant physical process
   - pp cross section has simple power-law behavior $\sigma^{pp} \propto p_\perp^{-n}$

The model

Take the simplest energy loss model for production of parton k

$$\frac{dN^k_{AA}}{dy\,dp_\perp} = N_{coll} \int_0^\infty d\epsilon \; \frac{dN^k_{pp}(p_\perp + \epsilon)}{dy\,dp_\perp} \; P_k(\epsilon)$$



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Quenching weight

- In BDMPS, the quenching weight depends on a single energy loss scale $\langle\epsilon\rangle$ at high parton energy

$$P(\epsilon) = \frac{1}{\langle\epsilon\rangle}\, \bar{P}\left(\frac{\epsilon}{\langle\epsilon\rangle}\right)$$

- Computed numerically from the BDMPS (and GLV) gluon spectrum
- Due to hadronization, scale accessible from data is $\bar{\epsilon} \equiv \langle z\rangle\langle\epsilon\rangle$

The model

Take the simplest energy loss model for production of hadron h

$$\frac{dN^h_{AA}}{dy\,dp_\perp} = N_{coll} \int_0^\infty d\epsilon \; \frac{dN^h_{pp}(p_\perp + \langle z \rangle \epsilon)}{dy\,dp_\perp} \; P_k(\epsilon)$$

pp production cross section

- Power-law behavior expected at high $p_\perp \gg \Lambda_{\rm QCD}$

$$\frac{dN^k_{pp}}{dy\,dp_\perp} \propto p_\perp^{-n}$$

- Power law index $n(h, \sqrt{s}) \simeq 5 - 6$ fitted from pp data
- Absolute magnitude of cross section irrelevant to compute $R_{\rm AA}$

Nuclear modification factor

$$R^h_{\mathrm{AA}}(p_\perp, \bar{\epsilon}, n) = \int_0^\infty \mathrm{d}x\ \bar{P}(x)\ \left(1 + \frac{x}{u}\right)^{-n}\ \simeq\ \int_0^\infty \mathrm{d}x\ \bar{P}(x)\ \exp\left(-\frac{nx}{u}\right)$$

with $u \equiv p_\perp/\bar{\epsilon}$

- R_{AA} uniquely predicted once the only parameter $\bar{\epsilon}$ is known
  - determined from a fit to R_{AA} data
- Approximate scaling: $R_{\mathrm{AA}}(p_\perp, \bar{\epsilon}, n) = f(u, n) \simeq f'(u/n)$
- **Universal shape** of $R_{\mathrm{AA}}(p_\perp)$ for all centralities, collision energies, hadron species

Nuclear modification factor

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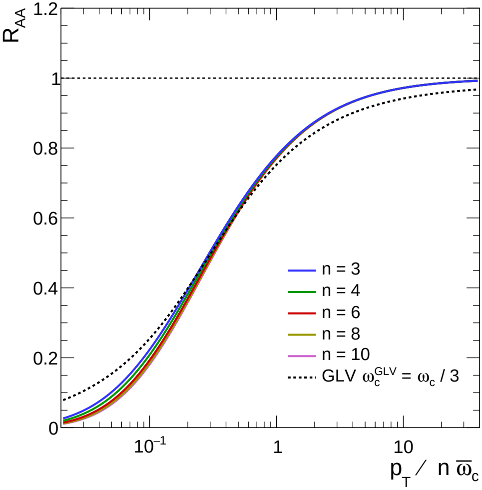
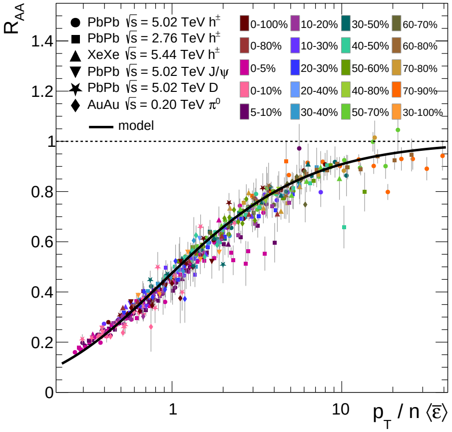


- R_{AA} unique ... known
  - determi ...
- Approximat ... n)
- **Universal s** ... ion energies, hadron spec ...

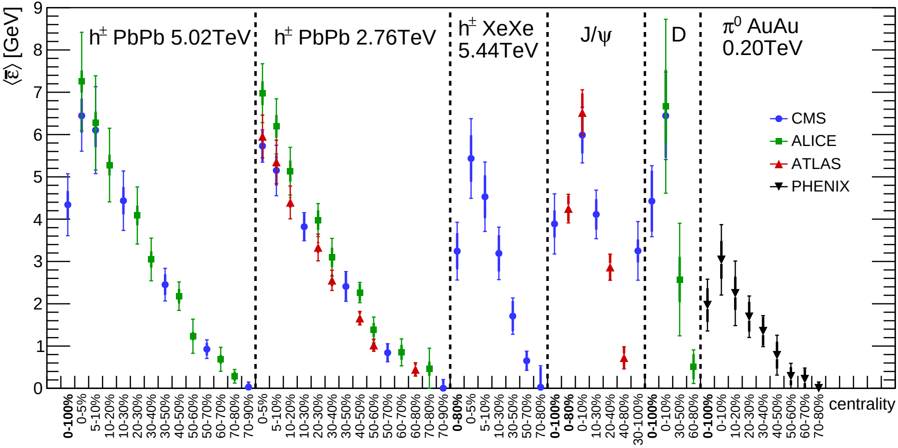
Scaling



- Predicted scaling **nicely observed**
  - Energies from $\sqrt{s} = 0.2$ TeV (RHIC) to $\sqrt{s} = 5.44$ TeV (LHC)
  - Different collision systems (AuAu, XeXe, PbPb) and centrality classes
  - Various hadron species: $h^{\pm}$, J/ψ, D

Average parton energy loss

Fits allow for the determination of $\bar{\epsilon} = \langle z \rangle \langle \epsilon \rangle$



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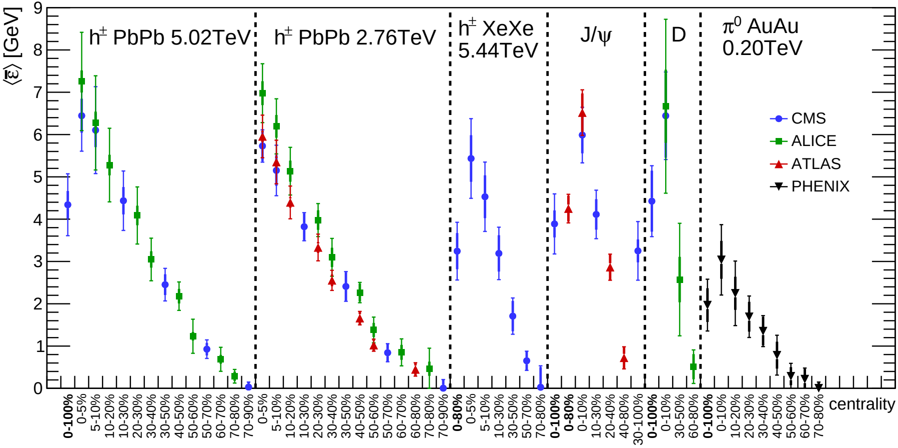


Next step: how to relate $\bar{\epsilon}$ to other physical quantities ?

Energy loss vs. multiplicity and path-length

BDMPS $\langle \epsilon \rangle = \frac{1}{4}\, \alpha_s\, C_k\, \langle \hat{q} \rangle\, L^2$

QGP expansion $\langle \hat{q} \rangle = \frac{2}{2-\alpha}\, \hat{q}_0\, \left(\frac{\tau_0}{L}\right)^{\alpha}$

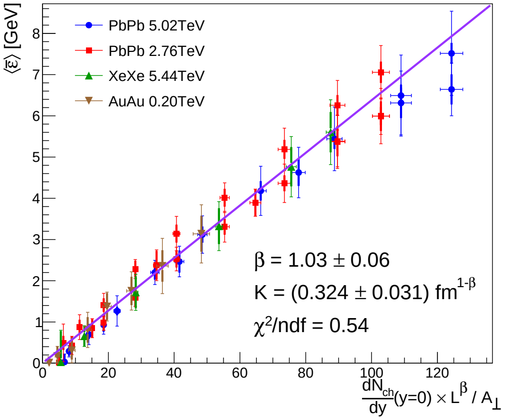
Bjorken density $\hat{q}_0 \propto n_0 = \frac{3}{2}\, \frac{1}{A_\perp \tau_0}\, \left.\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}y}\right|_{y=0}$

Expected scaling

$$\bar{\epsilon} = K \times \left(\frac{1}{A_\perp}\, \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}y}\, L^{\beta} \right)$$

- Free parameters $\beta = 2 - \alpha$ and $K = 27\pi/(8\beta) \times \alpha_s^3\, \tau_0^{1-\beta}\, \langle z \rangle_k\, C_k$
- L, $A_\perp$ taken from various Glauber models, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$ from experiment

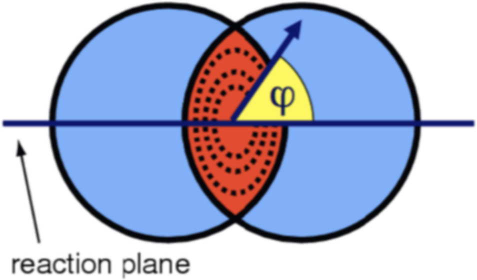
Scaling with multiplicity and path-length



- Very nice scaling observed for all energy loss scales
- $\beta = 1.03\pm^{0.09}_{0.06}$, compatible with pQCD in longitudinally exp. QGP
- Value of K also in the ballpark of pQCD estimates

Azimuthal anisotropy and path-length

Azimuthal anisotropy sensitive to L dependence of parton energy loss



Azimuthal anisotropy and path-length

Azimuthal anisotropy sensitive to L dependence of parton energy loss

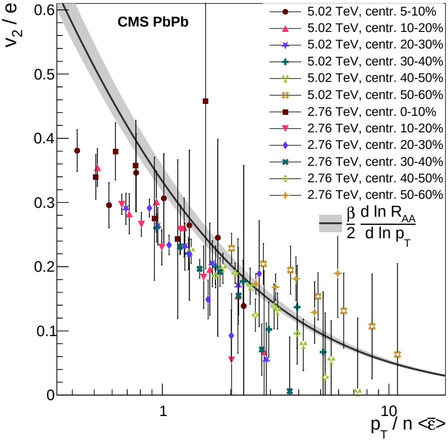
$$\frac{R_{\mathrm{AA}}(p_\perp, \langle\epsilon\rangle, \phi)}{R_{\mathrm{AA}}(p_\perp, \langle\epsilon\rangle)} \simeq 1 + 2\, v_2 \cos(2\phi)$$

$$\frac{v_2(p_\perp)}{\mathrm{e}} \simeq \frac{\beta}{2}\, \frac{p_\perp}{R_{\mathrm{AA}}(p_\perp)}\, \frac{\partial R_{\mathrm{AA}}(p_\perp)}{\partial p_\perp} \quad \text{with} \quad \mathrm{e} \equiv \frac{L(\pi/2) - L(0)}{L(\pi/2) + L(0)}$$

$$\Rightarrow \quad \frac{v_2(u,n)}{\mathrm{e}} = \frac{\beta}{2}\, \frac{n}{u} \int \mathrm{d}x\, \bar{P}(x)\, \frac{x}{(1+x/u)^{n+1}} \Big/ \int \mathrm{d}x\, \bar{P}(x)\, \frac{1}{(1+x/u)^{n}}\,,$$

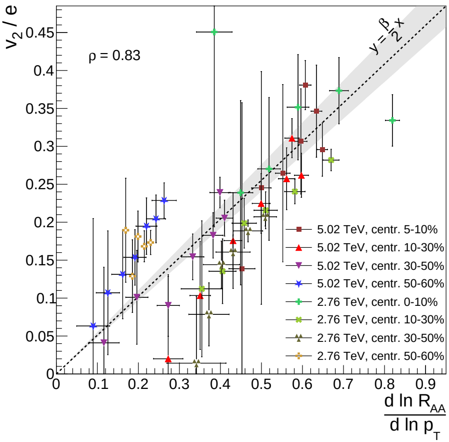
- Simple relation between v_2/e and R_{AA} could be tested using measurements only, allowing for a direct access to β
- v_2/e should exhibit the same $p_\perp/\langle\epsilon\rangle$ scaling as R_{AA}

v_2/e scaling



- Scaling observed in CMS data, within uncertainties
  - might be improved with more realistic eccentricity parameter
- Rather good trend of the model except at lower $p_{\perp} \lesssim 15\,\text{GeV}$

v_2/e vs. R_{AA}



- Significant correlation observed ($\rho = 0.83$)
- Linear behavior for all centrality classes at both energies
- Larger v_2/e in the most peripheral 50-60% class

Summary

- Analytic energy loss model revisited in light of the recent LHC data
- Measured R_{AA} exhibit a universal shape (scaling)
  - At different centralities and at different energies
  - D and J/ψ follow the same behavior
- Energy loss values $\langle\epsilon\rangle$ scales linearly with L^{β} and $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$
  - $\beta = 1.03\pm^{0.09}_{0.06}$
- Azimuthal anisotropy v_2/e data scale with $p_{\perp}/\langle\epsilon\rangle$
  - Same universal behavior as R_{AA}
  - Trend predicted by the model with above values of β
- Relation between v_2/e and R_{AA} offers purely data-driven access to β