Probing path-length dependence of parton energy loss via scaling properties in heavy ion collisions

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

FA, G. Falmagne, Phys. Rev. D 109 (2024) (L) 051503 [2212.01324]

Context

Over the last decade, tremendous development on jet quenching

- Experiment
  - First reconstruction of jets in AA collisions, jet substructure...
- Theory/Phenomenology
  - Monte-Carlo event generators in AA collisions, gluon emission off multi-particle states, embedding in realistic media, etc.

Context

Over the last decade, tremendous development on jet quenching

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Here, **looking for simpler things**

- Analytic model based on a single process – radiative energy loss – to describe the quenching of single hadrons at large $p_\perp$
- Why hadron quenching ?
  - hadrons = particles, good proxy for hard **parton** ($\neq$ jet) energy loss
- Why large transverse momentum ?
  - radiative energy loss likely the dominant physical process

The model

Take the simplest energy loss model for production of hadron h

$$\frac{\mathrm{d}N^h_{\mathrm{AA}}}{\mathrm{d}y\,\mathrm{d}p_\perp} = N_{\mathrm{coll}} \int_0^\infty \mathrm{d}\epsilon\ \frac{\mathrm{d}N^h_{\mathrm{pp}}(p_\perp + \langle z\rangle\,\epsilon)}{\mathrm{d}y\,\mathrm{d}p_\perp}\ P(\epsilon)$$

Ingredients

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

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

- Due to hadronization, scale accessible from data is $\bar{\epsilon} \equiv \langle z\rangle\langle\epsilon\rangle$
- pp cross section has approximate power-law behavior at $p_\perp \gg \Lambda_{\mathrm{QCD}}$

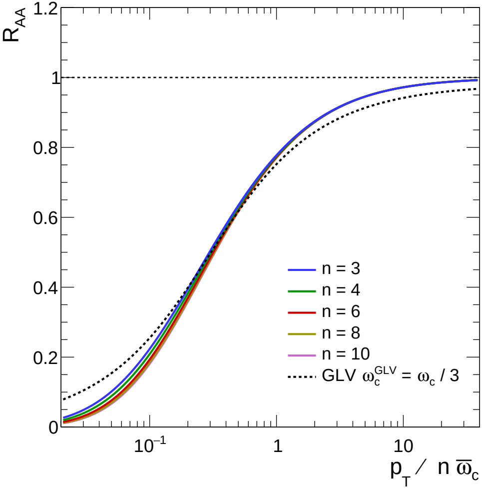
$$\frac{\mathrm{d}N_{\mathrm{pp}}}{\mathrm{d}y\,\mathrm{d}p_\perp} \propto p_\perp^{-n} \qquad (n \simeq 5\text{–}6)$$

Nuclear modification factor

$$R^h_{\mathrm{AA}}(p_\perp, \bar{\epsilon}, n) \simeq \int_0^\infty \mathrm{d}x \; \bar{P}(x) \exp\left(-\frac{x}{u}\right) \qquad u \equiv p_\perp \,/\, n\bar{\epsilon}$$

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

Nuclear modification factor



$R^h_{\rm AA}(p_\perp$ ... $p_\perp / n\bar{\epsilon}$

- $R_{\rm AA}$ unique ... known
  - determi...
- Approximat...
- **Universal s**... ion energies, hadron spec...

Strategy

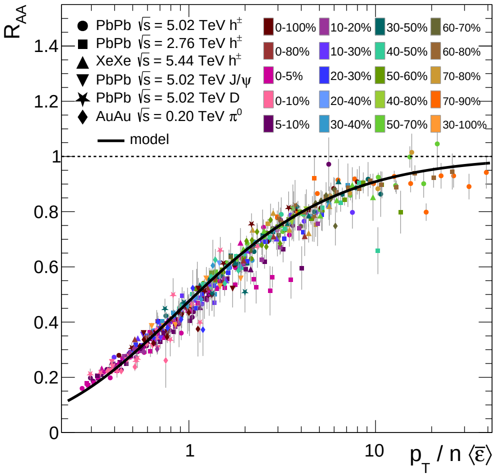
- Use the universal shape to **fit the $p_\perp$ dependence of $R_{\rm AA}$**
- **Extract the energy loss** $\bar{\epsilon}$ for each centrality, energy, hadron species
- Relate $\bar{\epsilon}$ to **physical quantities** like multiplicity
- Address other observables like **azimuthal anisotropies**

Data used

Species	Collision	$\sqrt{s}$ [TeV]	Experiment
π^0	AuAu	0.2	PHENIX
$h^\pm$	PbPb	2.76	ALICE, ATLAS, CMS
$h^\pm$	PbPb	5.02	ALICE, CMS
$h^\pm$	XeXe	5.44	CMS
D	PbPb	5.02	ALICE, CMS
J/ψ	PbPb	5.02	ATLAS, CMS

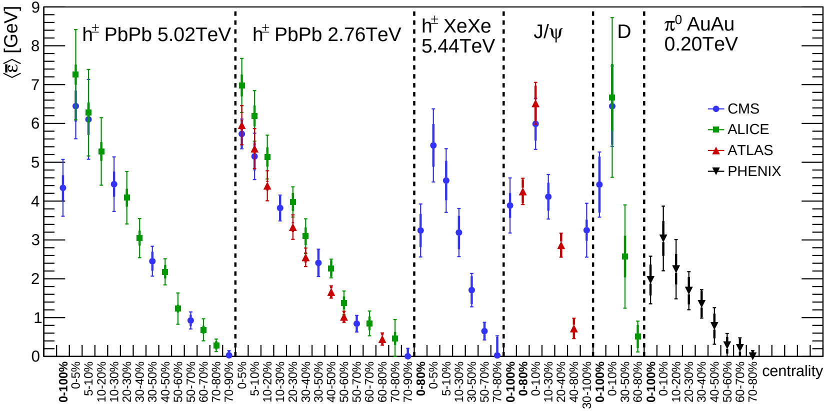
- Energies from $\sqrt{s} = 0.2$ TeV (RHIC) to $\sqrt{s} = 5.44$ TeV (LHC)
- Different collision systems and centrality classes
- Various hadron species: π^0, $h^\pm$, J/ψ, D

Scaling



☞ Predicted scaling **nicely observed**

Average parton energy loss from data



- Nice systematic behavior from central to peripheral collisions
- Smaller energy loss scales at RHIC
- **Next step:** How to relate $\bar{\epsilon}$ to physical quantities ?

Energy loss vs. multiplicity and path-length

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

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

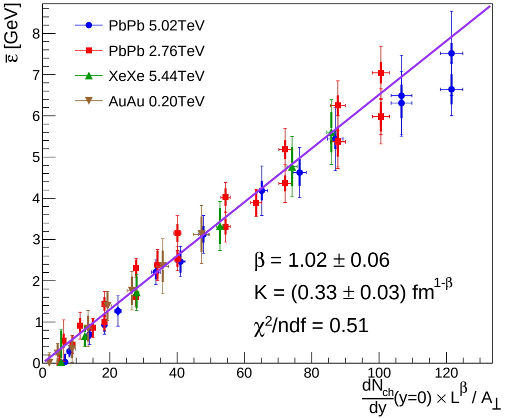
Bjorken density $\hat{q}_0 \propto n_0 = \frac{3}{2}\,\frac{1}{A_\perp \tau_0}\,\left.\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}y}\right|_{y=0}$

Expected (another) scaling with multiplicity and path-length

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

- Simple linear relationship between $\bar{\epsilon}$ and scaling variable
- $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$ from experiment, L, $A_\perp$ taken from custom Glauber models
- Free parameters β $(= 2-\alpha)$ and K $(= 27\pi/(8\beta)\times\alpha_s^3\,\tau_0^{1-\beta}\,\langle z\rangle_k\,C_k)$

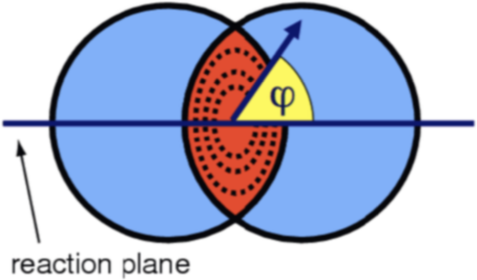
Scaling with multiplicity and path-length



- Very nice scaling observed for all energy loss scales
- $\beta = 1.02\pm^{0.09}_{0.06}$, 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

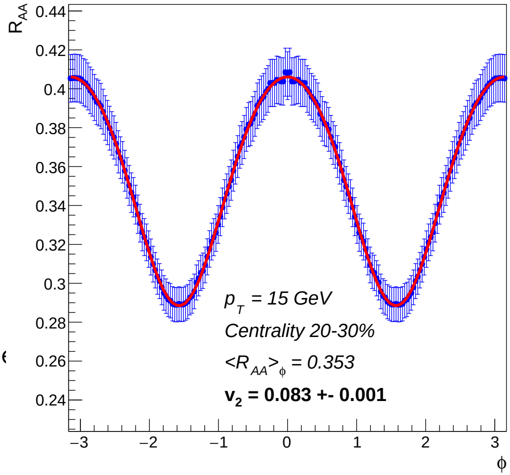


Neglecting higher harmonics at large $p_\perp$

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

Azimuthal anisotropy and path-length

Azimuthal anisotropy sensitive to *L* dependence of parton energy loss



Neglecting highe

Azimuthal anisotropy and path-length

Using the previous model $R_{\rm AA}(u, n, \phi) = f\left(u \times (L/L(\phi))^{\beta}, n\right)$

$$2v_2 \simeq \frac{R_{\rm AA}(0) - R_{\rm AA}(\pi/2)}{R_{\rm AA}(0) + R_{\rm AA}(\pi/2)} = \frac{f(u/(1-{\rm e})^{\beta}) - f(u/(1+{\rm e})^{\beta})}{f(u/(1-{\rm e})^{\beta}) + f(u/(1+{\rm e})^{\beta})}\,.$$

$$\text{where } L(\phi) \simeq L \times (1 - {\rm e}\cos(2\phi)) \;\; \left({\rm e} \equiv \frac{L(\pi/2) - L(0)}{L(\pi/2) + L(0)}\right)$$

Azimuthal anisotropy and path-length

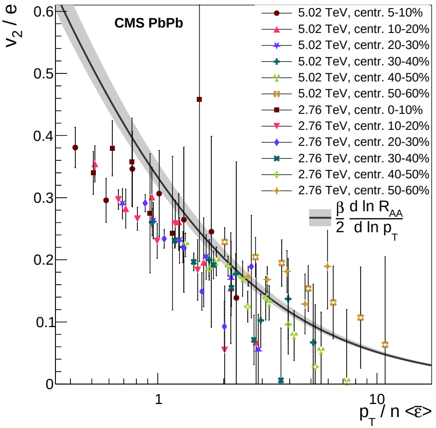
Taylor expansion at small e leads to

$$\frac{v_2(p_\perp)}{\text{e}} \quad \simeq \quad \frac{\beta}{2}\,\frac{p_\perp}{R_{\text{AA}}(p_\perp)}\,\frac{\partial R_{\text{AA}}(p_\perp)}{\partial p_\perp}\,.$$

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

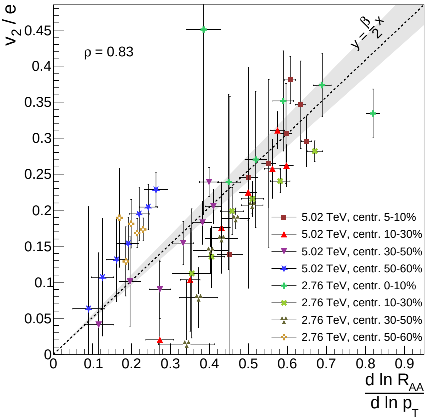
- ☞ v_2/e should exhibit the same $p_\perp/\langle\epsilon\rangle$ scaling as R_{AA}
- ☞ Simple relation between v_2/e and R_{AA}
  - could be tested using data only, **allowing for a direct access to β**

v_2/e scaling



- Scaling observed in CMS data, within uncertainties
  - might be improved with more realistic eccentricity parameter
- Good trend of the model except at lower $p_\perp \lesssim 15\,\text{GeV}$
  - QGP transverse expansion would reduce theory by 10–30%

v_2/e vs. R_{AA}: data vs. data



- Significant correlation observed
- Linear behavior for all centrality classes at both energies
  - but larger v_2/e in the most peripheral 50-60% class

☞ Independent but consistent estimate of $\beta \simeq 1$

Summary

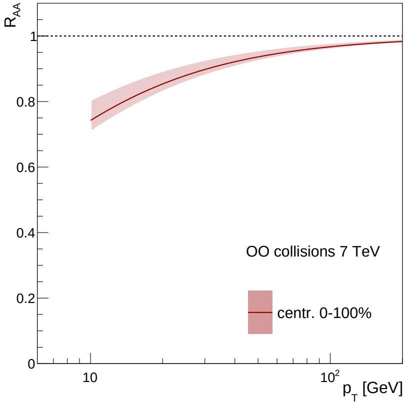
- Analytic energy loss model revisited in light of LHC data
  - R_{AA} exhibit a universal scaling behavior
- Energy loss values $\langle\epsilon\rangle$ scale linearly with $L^{\beta} \times \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$
  - $\beta = 1.02\pm^{0.09}_{0.06}$ consistent with pQCD and Bj longitudinal expansion
- Azimuthal anisotropy v_2/e data scale with $p_{\perp}/\langle\epsilon\rangle$
  - Same scaling as R_{AA}, consistent with data
- Relation between v_2/e and R_{AA} offers purely data-driven access to β
  - CMS data are consistent with this prediction and leads to $\beta \simeq 1$
- A lot to be learned from an observable 'as simple as' hadron R_{AA}
  - Truly probe hard parton energy loss
  - Looking forward to discovering Run 3 data !

Predicting other systems

Scaling with multiplicity and L allows for predicting R_{AA} in other systems, eg OO collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ planned at LHC Run 3

- Path-length obtained from Glauber model
- Multiplicity estimated using Monte Carlo (`EPOS3.402`)

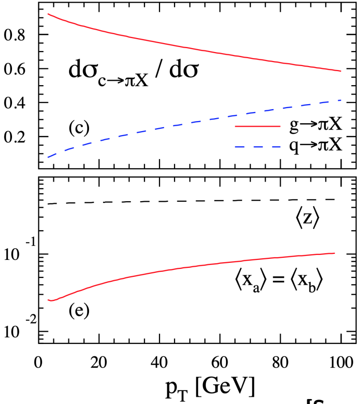
$$\bar{\epsilon}_{\mathrm{OO}} = 0.61^{+0.17}_{-0.10}\,\mathrm{GeV}$$



2-flavour model extension

So far only one parton flavour is assumed while at LHC both quarks (fraction $x_q = 0.1$-0.3) and gluons $(1 - x_q)$ fragment into hadrons

- different color factors $(C_F \neq C_A)$ and possibly different partonic slopes $(n_q \lesssim n_g)$ and momentum fractions $(z_q \gtrsim z_g)$



[Sassot Stratmann Zurita 2010]

2-flavour model extension

In the more general case

$$R_{\rm AA}^{\rm 2f} = \int {\rm d}\epsilon \left[P_q(\epsilon)\, x_q(p_\perp) \left(1 + \frac{\langle z_q \rangle\, \epsilon}{p_\perp}\right)^{-n_q} + P_g(\epsilon)\, (1 - x_q(p_\perp)) \left(1 + \frac{\langle z_g \rangle\, \epsilon}{p_\perp}\right)^{-n_g} \right]$$

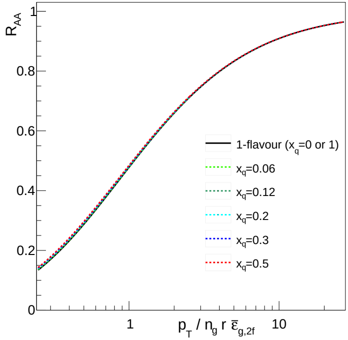
Within approximations, $R_{\rm AA}^{\rm 2f}$ formally analogous to the 1-flavour model

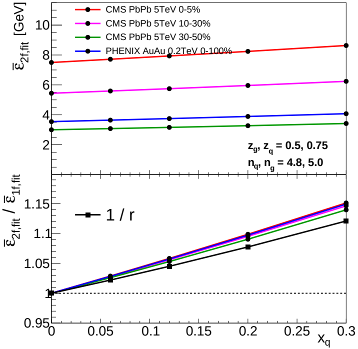
$$R_{\rm AA}^{\rm 2f}(p_\perp, \bar{\epsilon}_{\rm 2f}, x_q) \simeq \int {\rm d}x\, \bar{P}(x) \left(1 + \frac{x\, r(x_q)\, \bar{\epsilon}_{\rm 2f}}{p_\perp}\right)^{-n_g} = R_{\rm AA}^{\rm 1f}(p_\perp, r(x_q)\, \bar{\epsilon}_{\rm 2f})$$

up to a (small) rescaling of the expected average energy loss scale

$$r(x_q) \equiv 1 - x_q + x_q\, \frac{n_q}{n_g}\, \frac{C_F}{C_A}\, \frac{\langle z_q \rangle}{\langle z_g \rangle} \simeq 0.9$$

2-flavour model extension





- Fitting data with 2-flavour model indeed affects $\bar{\epsilon}$ by $\sim 10\%$
- Rescaling only affects prefactor K (not the scaling) which is in any case very uncertain ($K \propto \alpha_s^3$)
- Variation of n and z have marginal impact