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

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Advancing the understanding of non-pert. QCD using energy flow

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

FA, G. Falmagne, 2212.01324

Context

Over the last decade, tremendous development on jet quenching

Experiment

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

Phenomenology

- Monte-Carlo event generators in heavy-ion collisions
- Gluon emission off multi-particle states
- 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 energies, various hadron species, wide $p_\perp$ coverage

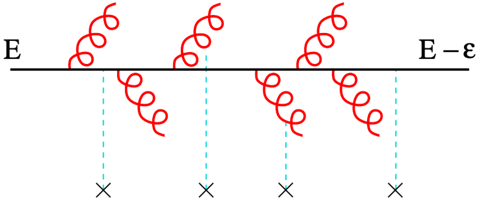
2. Why large transverse momentum ?

- 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 $\sigma^{\rm pp} \propto p_\perp^{-n}$

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

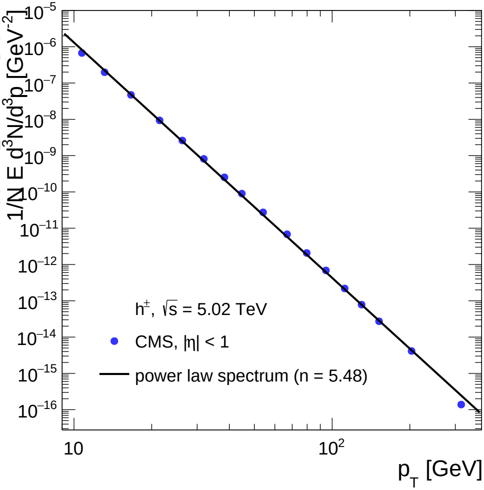
- Power-law behavior expected at high $p_\perp \gg \Lambda_{\rm QCD}$

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

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

The model

Take the simplest energy loss model for production of hadron h



$\frac{d}{dy}$ (ϵ)

pp production

- Power-law l
- Power law i
- Absolute m … pute $R_{\rm AA}$

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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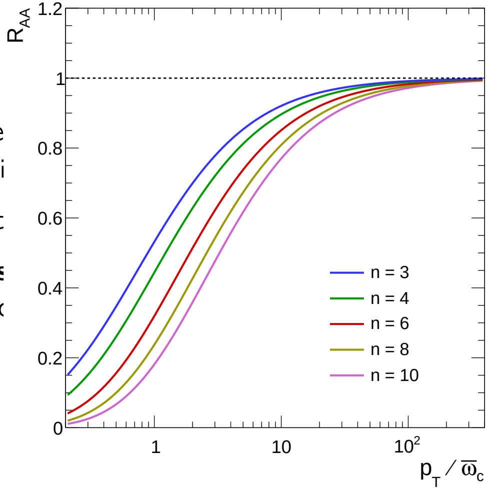

- $R_{\rm AA}$ unique … known
  - determi…
- Approximat … $n)$
- **Universal s…** … ion energies, hadron spec…

Nuclear modification factor

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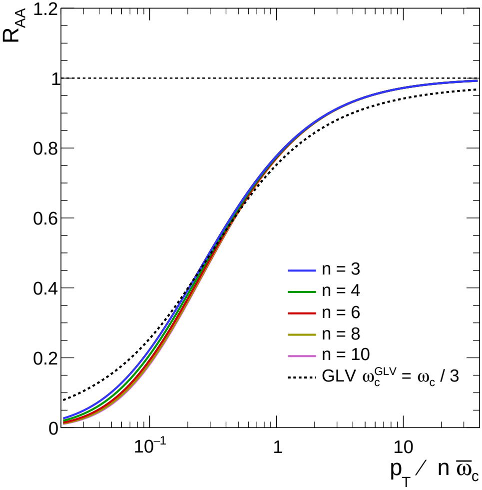

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Strategy

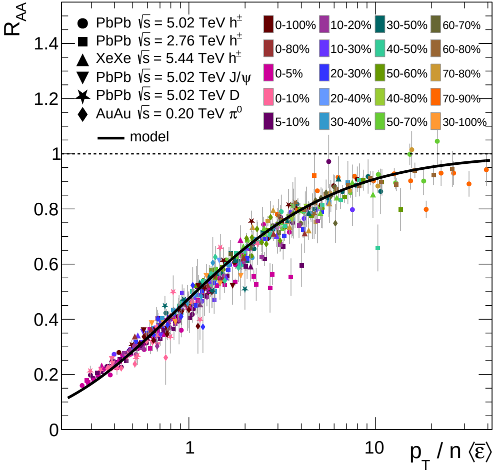
- Use the universal shape $R_{\rm AA}(p_\perp/n\bar{\epsilon})$ to fit the $p_\perp$ dependence of $R_{\rm AA}$ measured experimentally
- $\bar{\epsilon}$ single free parameter determined for each centrality class, collision energy, hadron species
- Check for scaling
- Relate $\bar{\epsilon}$ to physical quantities
- Address v_2 at large $p_\perp$

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 (AuAu, XeXe, PbPb) and centrality classes
- Various hadron species: π^0, $h^\pm$, J/ψ, D

Scaling

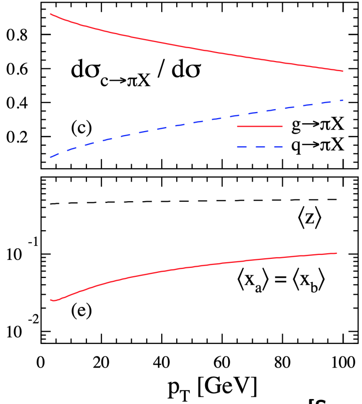


☞ Predicted scaling **nicely observed**

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

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

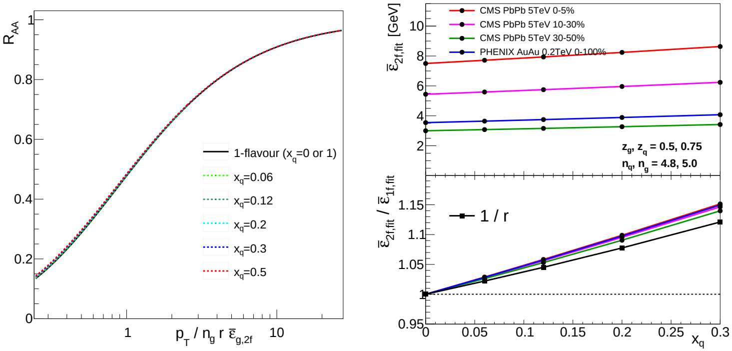
Within approximations, $R_{\rm AA}^{\rm 2f}$ formally analogous to the 1-flavour model

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

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

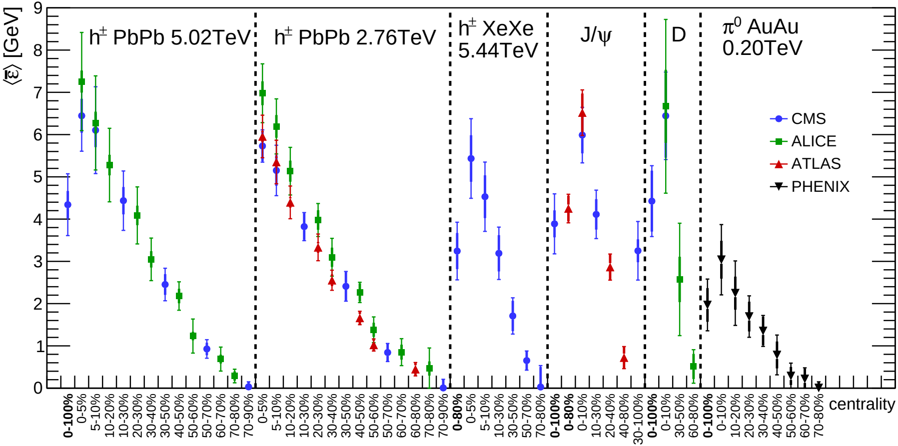
$$r(x_q) \equiv 1 - x_q + x_q\, \frac{n_q}{n_g}\, \frac{C_F}{C_A}\, \frac{\langle z_q \rangle}{\langle z_g \rangle} \simeq 0.9$$

2-flavour model extension



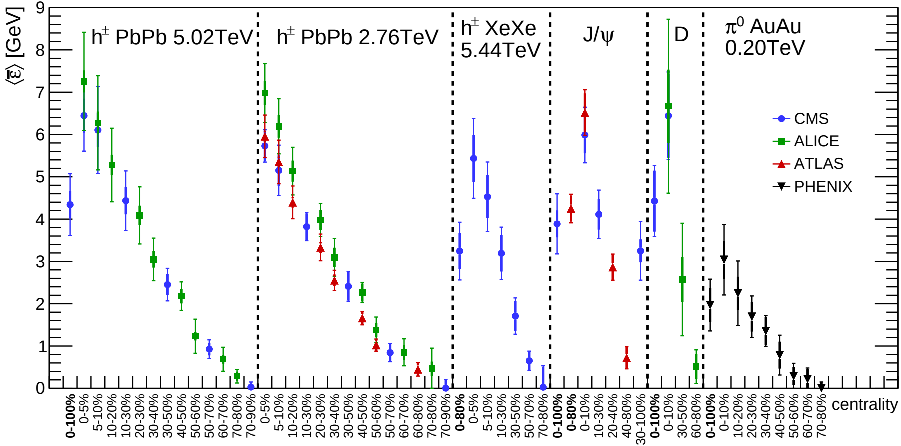
- Fitting data with 2-flavour model indeed affects $\bar{\epsilon}$ by $\sim 10\%$
- Rescaling only affects prefactor K (not the scaling) which is in any case very uncertain ($K \propto \alpha_s^3$)
- Variation of n and z have marginal impact

Average parton energy loss from data



- Nice systematic behavior from central to peripheral collisions
- Smaller energy loss scales at RHIC

Average parton energy loss from data



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

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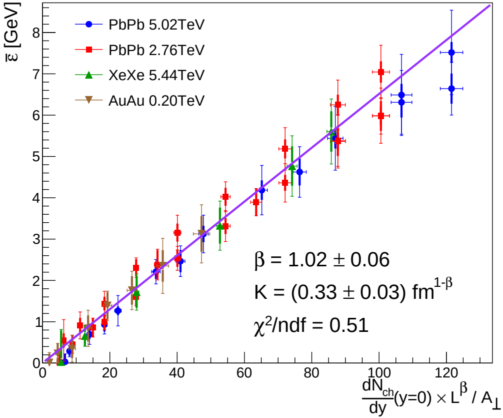
Expected (another) scaling with multiplicity and path-length

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

- Simple linear relationship between $\bar{\epsilon}$ and scaling variable
- 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 custom Glauber models, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$ from experiment

Scaling with multiplicity and path-length



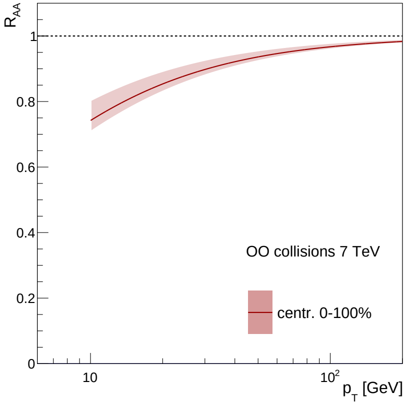
- Very nice scaling observed for all energy loss scales
- $\beta = 1.02^{+0.09}_{-0.06}$, compatible with pQCD in longitudinally exp. QGP
- Value of K also in the ballpark of pQCD estimates

Predicting other systems

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

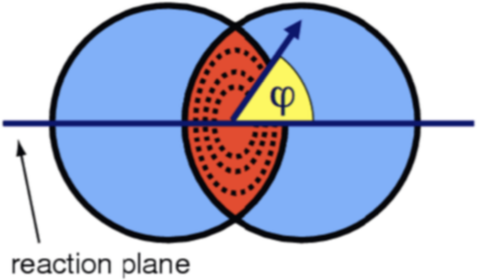
- Path-length obtained from Glauber model
- Multiplicity estimated using Monte Carlo (`EPOS3.402`)

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



Azimuthal anisotropy and path-length

Azimuthal anisotropy sensitive to L dependence of parton energy loss

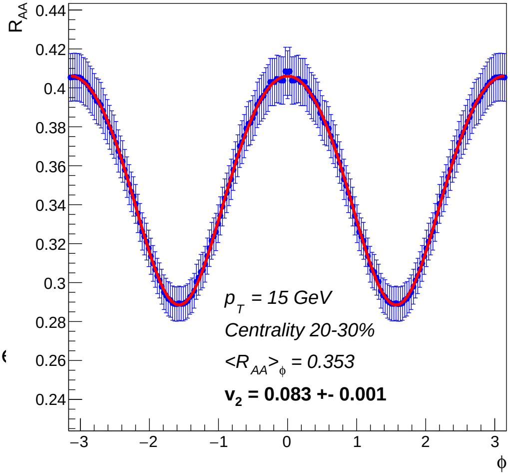


Neglecting higher harmonics at large $p_\perp$

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

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 $R_{\mathrm{AA}}(u, n, \phi) = f\left(u \times (L/L(\phi))^{\beta}, n\right)$

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

where $L(\phi) \simeq L \times (1 - \mathrm{e}\cos(2\phi))$ $\left(\text{eccentricity}\,\mathrm{e} \equiv \dfrac{L(\pi/2) - L(0)}{L(\pi/2) + L(0)}\right)$

Azimuthal anisotropy and path-length

Taylor expansion at small e leads to

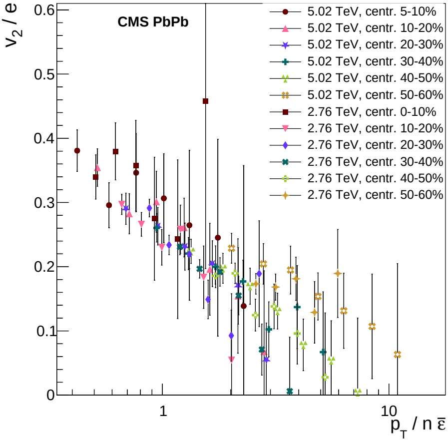
$$\frac{v_2(u,n)}{\mathrm{e}} \simeq \frac{\beta}{2}\,\frac{\partial \ln f(u,n)}{\partial \ln u}\,,$$

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

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

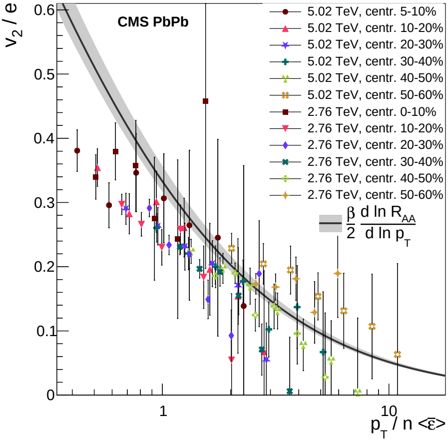
- ☞ v_2/e should exhibit the same $p_\perp/\langle\epsilon\rangle$ scaling as R_{AA}
- ☞ Simple relation between v_2/e and R_{AA} could be tested using measurements only, allowing for a direct access to β

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 $p_\perp \lesssim 15\,\text{GeV}$

v_2/e scaling



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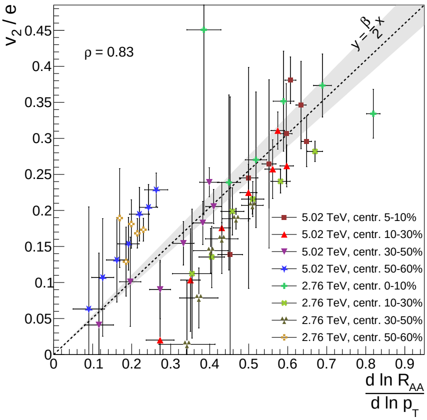
v_2/e vs. R_{AA}: data vs. data



- 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

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

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 $L^{\beta} \times \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$
  - $\beta = 1.02 \pm^{0.09}_{0.06}$ consistent with pQCD and Bj longitudinal expansion
- Azimuthal anisotropy v_2/e data scale with $p_{\perp}/\langle\epsilon\rangle$
  - Same universal behavior as R_{AA}
  - Trend predicted by the model 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}
  - Looking forward to discovering Run 3 data !