# Interpreting jet quenching measurements and charmonia suppression

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EPJC 76 (2016) no.2, 50
PLB 767 (2017) 10

Jet suppression at the LHC – striking features: the inclusive **jet $R_{AA}$ is almost flat** in the region 200 GeV – 1 TeV; the inclusive jet $R_{AA}$ exhibits **almost no dependence on η of jet**; fragmentation functions are suppressed at intermediate-$z$ but **enhanced at high-$z$**. Can we understand what drives these features? What basic information about the parton energy loss can we infer from inclusive jet measurements?

Goal: **interpret jet quenching measurements using minimal assumptions on the physics of jet quenching.** This is done within "Effective Quenching model". Steps in the modeling (simplified):

1) Find **functional form** that describes the unquenched jet-$p_T$ spectra and unquenched jet fragmentation.

2) Extract **parametric dependence** of the jet energy loss on initial parton $p_T$ using data on inclusive jet $R_{AA}$. Assume that energy loss of quark-initiated and gluon-initiated jets is related by color factor, $c_F$.

3) Assume that quenched jets fragment as in vacuum and find out how much of the features seen in the measured Pb+Pb **fragmentation functions** is due to the different quenching of quark-initiated and gluon-initiated jets under this assumption.

4) Implement the energy loss model into MC and **apply on other observables**.

5) Use the model to make **predictions**.

**Ad 1)** Jet spectra are not pure power-law, but an „extended" power law can describe outputs from both LO and NLO generators:

$$\frac{dn}{dp_T^{\rm jet}} = A\left(\frac{p_{T0}}{p_T^{\rm jet}}\right)^{n+\beta\log\left(p_T^{\rm jet}/p_{T0}\right)} \qquad (1)$$

Inclusive jet spectra are a combination of quark and gluon jet spectra, each weighted by a fraction of quark and gluon jets, respectively.

Fragmentation functions of jets initiated by a given flavor can be describe using functional form:

$$D(z) = a\cdot\frac{(1+dz)^b}{(1+ez)^c}\cdot\exp\left(-fz\right) \qquad (2)$$

Flavor inclusive fragmentation functions are a combination of quark and gluon fragmentation functions, each weighted by fraction of quark and gluon jets, respectively.

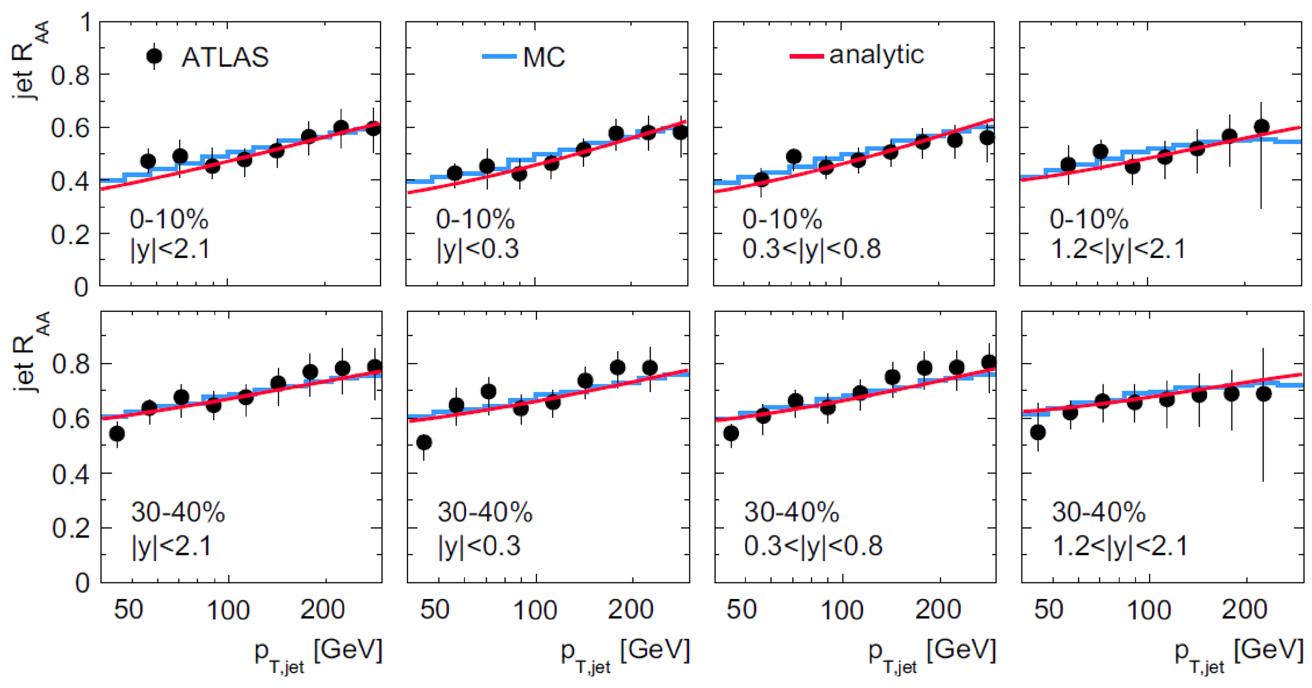


**Fig.1**: Inclusive jet $R_{AA}$ measured in several centrality bins by ATLAS compared to the analytic and MC calculation of the same quantity in the EQ model. Same level of agreement is obtained in other centrality bins. Agreement of the model and data in different rapidity bins implies that **the lack of rapidity dependence and flatness of jet $R_{AA}$ is consequence of different energy loss of quark- and gluon-initiated jets** on top of steeply falling $p_T$ spectra of initial partons. For more see „Ad 2)" frame.

**Ad 2)** Partons are assumed to lose energy depending on their initial transverse momentum, $p_{T,\rm ini}$, and an effective color factor, $c_F$, such that the total energy lost by a parton is

$$\Delta p_T = c_F\cdot s\cdot\left(\frac{p_{T,\rm ini}}{p_{T,0}}\right)^{\alpha} \qquad (3)$$

Where α, $s$ and $c_F$ are free parameters. The quenching of gluon jets is assumed to be stronger by $c_F$ compared to the quenching of quark jets (in a first approximation, $c_F$=9/4).This together with parameterization (1) allows to derive analytic formula for jet $R_{AA}$. Analytic formula for jet $R_{AA}$ is used to extract α, $s$ and $c_F$ using data on jet $R_{AA}$. Consistent and good description is achieved in all rapidity intervals (an example in Fig.1). It turns out that $\alpha$>0, which means that **data are incompatible with simple fractional energy loss**. Results of global minimization using 2.76 TeV data imply that the *average* jet quenching can be summarized in just 3 parameters:

| | |
|---|---|
| $s = x\cdot N_{\rm part} + y$ | $x = (12.3\pm1.4)\cdot10^{-3}$ GeV, $y = 1.5\pm0.2$ GeV |
| $\alpha$ | $0.52\pm0.02$ |
| $c_F$ | $1.78\pm0.12$ |

… notice that: in-medium value of $c_F$ is **consistent with the color factor measured in the vacuum** e.g. at Tevatron; that magnitude of **jet quenching is linear in $N_{\rm part}$**; data are consistent with **$\sqrt{p_T}$ dependence of jet quenching**.

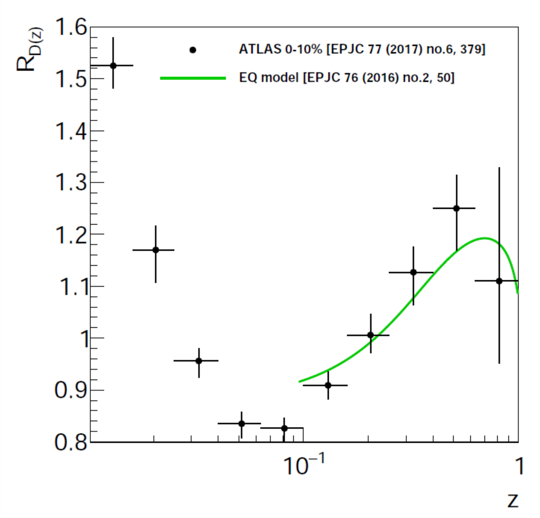


**Fig.3**: Ratio of $D(z)$ distributions measured by ATLAS compared to the EQ model. For more see "Ad 3)" frame. Notice the depletion at the highest-z: enhancement in the low-z region contributes to the high-z via the denominator of z. High statistics Run3 data on $D(z)$ will provide complex information about the medium recoil / in-cone radiation.

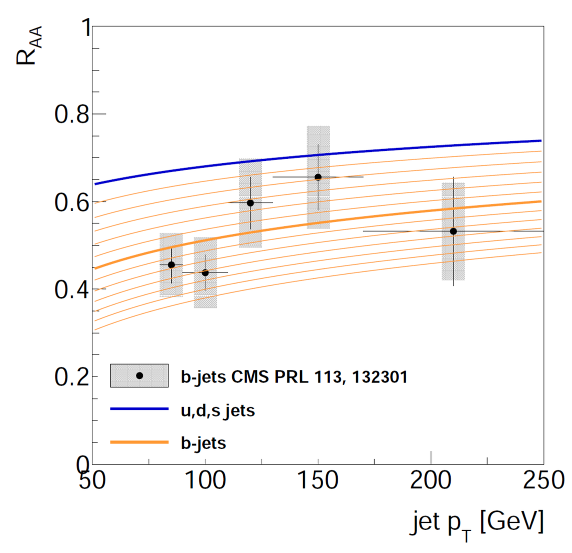


**Fig.4**: Blue line is the energy loss of b-jets for the case that they are suppressed by the same magnitude as the light-quark initiated jets. Orange lines are multiples of light-quark suppression. Thick orange line is a result of the minimization. **b-jets are quenched 1.5 ± 0.4 times more than the light-quark jets** (including effect from gluon splitting).

**Ad 3)** Inclusive jet fragmentation functions, $D(z)$, can be written as

$$D(z) = f_q^{\rm int}D_q(z) + (1-f_q^{\rm int})D_g(z) \qquad (4)$$

where $D_q(z)$ and $D_g(z)$ are the quark and gluon fragmentation functions, respectively, and $f_q^{\rm int}$ is the quark fraction integrated over a given $p_{T,\rm jet}$ range. Following a physics picture in which parton shower loses the energy largely coherently (see e.g. PLB 725 (2013) 357) one can assume that it is only $f_q^{\rm int}$ which is changed by the quenching. The $f_q^{\rm int}$ is calculated using parameters $\alpha$ and $s$ described in „Ad 2)". This allows to derive quenched-to-$pp$ ratios of $D(z)$ distributions which were measured. The result along with data by ATLAS are shown in Fig.3. EQ model can reproduce the data at intermediate and high-z which implies that **modifications observed in the data at intermediate $z$ and high $z$ result from quenching-driven changes in the quark fraction**. This also provides a **direct evidence for the importance of color coherent effects** since the results was obtained under the assumption that quenching does not change $D_q(z)$ and/or $D_g(z)$.

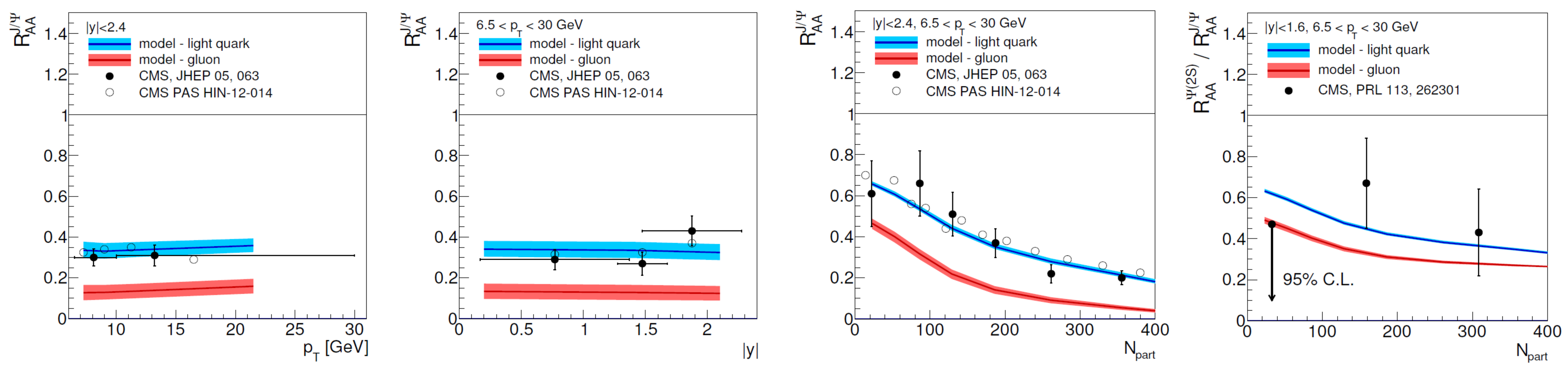


**Fig.5**: Suppression of both J/ψ and ψ(2S) is similar to the suppression of light-quark jets (for details see "Ad 4)" frame).

**Ad 4)**

- Understanding jet $R_{AA}$ and $D(z)$ at intermediate and high $z$ implies understanding the **charged particle $R_{AA}$**. Indeed, the measured charged particle $R_{AA}$ for $p_T$>20 GeV can be reproduced by the EQ model (not shown).
- EQ model allows to quantify the **suppression of b-jets**. Shown in Fig.4.
- Data say that color coherence effects are important (jet largely radiates as one object, see „Ad 3" frame). If that is so, let's explore the suppression of other composed objects, such as charmonia, by suppressing them using MC in the same way as jets (see „Ad 2" frame). The result is in Fig.5. Suppression of J/ψ and ψ(2S) for $p_T$>6 GeV in midrapidity is similar to the suppression of light-quark jets. This implies that coherent **energy loss is likely driving the suppression of high-$p_T$ charmonia**.

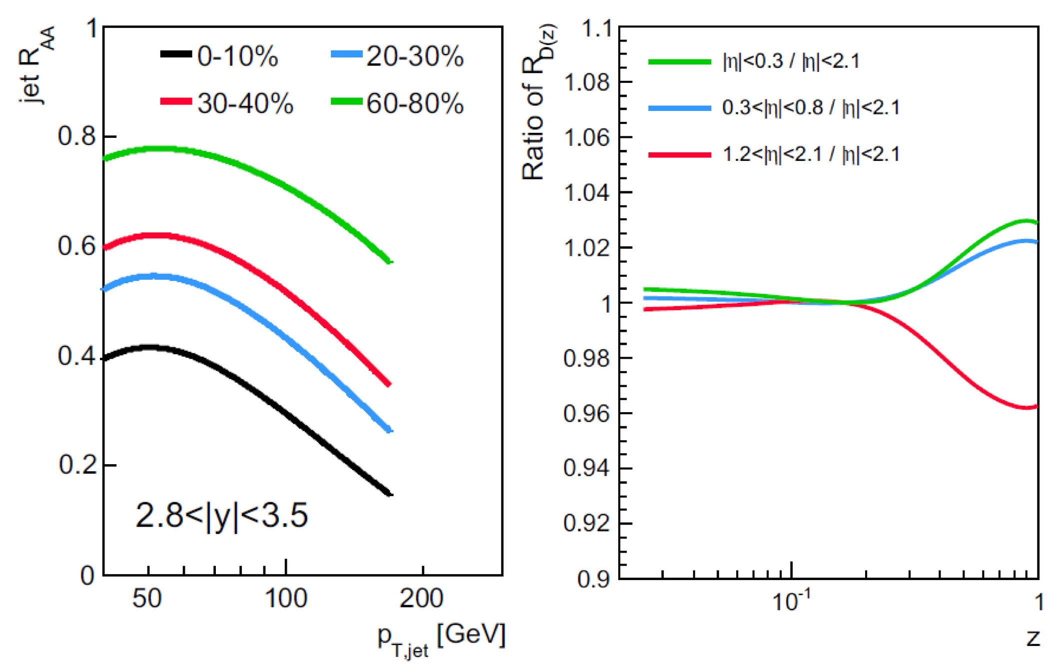


**Fig.6**: Left: EQ model predicted a decrease of the inclusive jet $R_{AA}$ with increasing $p_T$ in the forward region. This was recently observed in ATL-CONF-2017-009. Right: EQ model predicted a smaller signal in the central-to-peripheral ratio of $D(z)$ for forward rapidities. This was recently observed in EPJC 77 (2017) 379.

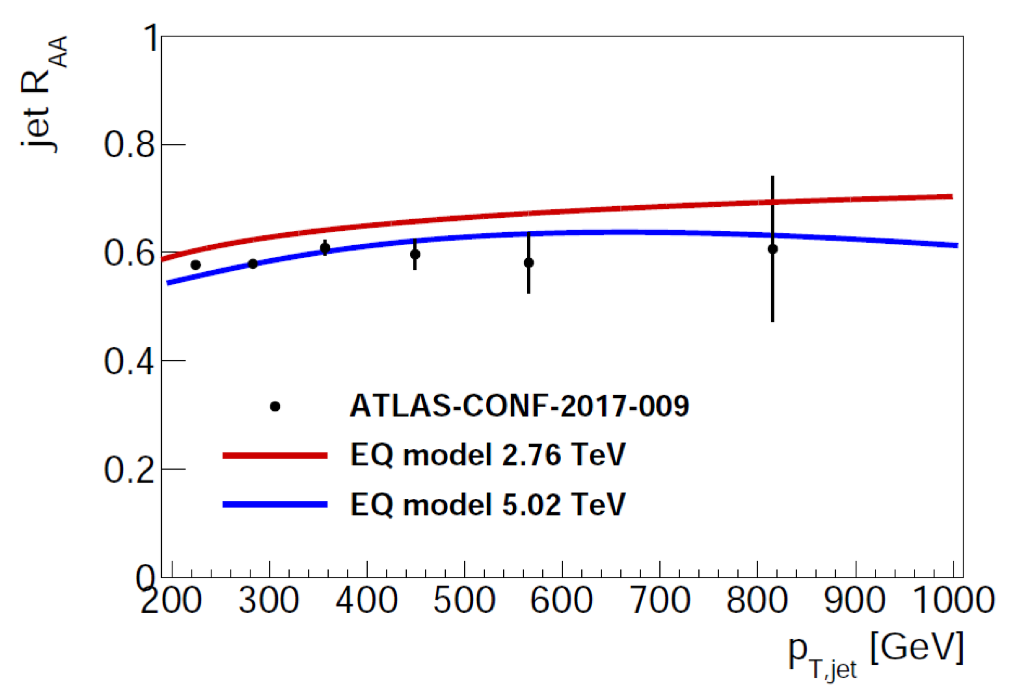


**Fig.7**: Jet $R_{AA}$ from EQ model compared to data from ATLAS. Values of parameters in 2.76 TeV version were obtained by minimizing with respect to 2.76 TeV jet $R_{AA}$ data (see Fig.1). Values of parameters in 5.02 TeV were obtain by minimizing with respect to data from ATLAS-CONF-2017-009. Jet quenching in 5.02 TeV is larger by about 10%.

**Ad 5)** The EQ model predicted the pseudorapidity dependence of $R_{D(z)}$ and the behavior of jet $R_{AA}$ in the forward rapidity, see Fig.6. **Both of these effects were recently seen in the data** (see EPJC 77 (2017) 379, ATLAS-CONF-2017-009).

The EQ model allows to understand the flatness of jet $R_{AA}$ near the TeV scale which was recently measured by ATLAS. The result of the minimization with respect to 5.02 TeV data is shown in Fig.7. The quenching is larger by about 10% in 5.02 TeV Pb+Pb collisions compared to 2.76 TeV collisions.