Quenching of hadron spectra in heavy ion collisions at the LHC

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

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
  - ...including heavy quark dynamics !
- Gluon emission off multi-particle antennas
- Jet fragmentation in a realistic medium, etc.

This talk

Here, looking for simpler things

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

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Why hadron quenching ?

- hadrons = particles
  - in a sense much simpler than jets
- very precise data at the LHC
  - two energies 2.76 TeV and 5.02 TeV
  - wide kinematical coverage: $p_\perp \lesssim 300$ GeV (ATLAS, CMS)
  - different hadron species
  - for the first time, $R_{\rm AA}$ reaches almost unity at very large $p_\perp$

This talk

Here, loo

I discuss a ... iative

energy loss ... e $p_\perp$

Why hadr

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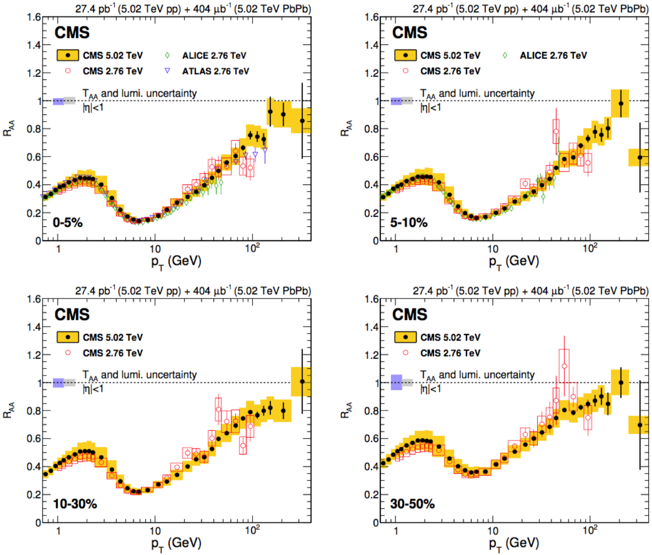

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Why large transverse momentum ?

- cold nuclear matter effects (nPDF/saturation, energy loss in nuclei, Cronin effect) expected to weaken/vanish when $p_\perp \gg Q_s$
- hot medium effects (e.g. coalescence processes or collisional energy loss) only play a role at not too large $p_\perp$
- radiative energy loss likely to be the only (or dominant) physical process at work
- pp production section exhibits simple power-law behavior $\sigma^{pp} \propto p_\perp^{-n}$

This talk

Here, looking for simpler things

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

Goals

- compare data to a model with the least number of assumptions and parameters
- check universality of quenching for different particle species, collision centralities and c.m. energies
- extract robust and ideally model-independent estimates of parton energy loss in a data-driven approach

The model

Take the simplest energy loss model for production of particle i

$$\frac{d\sigma^i_{\rm AA}(p_\perp)}{dy\, dp_\perp} = A^2 \int_0^\infty d\epsilon\ \frac{d\sigma^i_{\rm pp}(p_\perp + \epsilon)}{dy\, dp_\perp}\ P_i(\epsilon)$$

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Hadronization

- Particle losing energy $\neq$ detected particle
- Introducing FF D_k^h and summing over partonic channels:

$$\frac{d\sigma^h_{\mathrm{AA}}(p_\perp)}{dy\, dp_\perp} = A^2 \sum_k \int_0^1 dz\, D_k^h(z) \int_0^\infty d\epsilon\, \frac{d\hat{\sigma}^k_{\mathrm{pp}}(p_\perp/z + \epsilon/z)}{dy\, dp_\perp}\, \frac{1}{z}\, P_k(\epsilon/z)$$

- Assume that only one parton flavour to fragment (e.g. $g \rightarrow h^\pm$)
- Approximate $1/z\ P(\epsilon/z) \simeq 1/\langle z\rangle\ P(\epsilon/\langle z\rangle)$ and intertwine integrals

The model

Take the simplest energy loss model for production of hadron h

$$\frac{d\sigma^h_{\rm AA}(p_\perp)}{dy\,dp_\perp} = A^2 \int_0^\infty d\epsilon\ \frac{d\sigma^h_{\rm pp}(p_\perp + \langle z \rangle \epsilon)}{dy\,dp_\perp}\ P_i(\epsilon)$$

Quenching weight

- In BDMPS, the quenching weight depends on a single energy loss scale $\omega_c = 1/2\,\hat{q}\,L^2$ at high parton energy

$$P(\epsilon) = \frac{1}{\omega_c}\,\bar{P}(\epsilon/\omega_c)$$

- Computed numerically from the BDMPS (and GLV) gluon spectrum
- Because of hadronization, the energy loss scale accessible from data is $\bar{\omega}_c \equiv \langle z \rangle\,\omega_c$

The model

Take the simplest energy loss model for production of hadron h

$$\frac{d\sigma^h_{\rm AA}(p_\perp)}{dy\,dp_\perp} \simeq A^2 \int_0^\infty dx\, \frac{d\sigma^h_{\rm pp}(p_\perp + \bar{\omega}_c\, x)}{dy\,dp_\perp}\, \bar{P}(x)$$

pp production cross section

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

$$\frac{d\sigma^i_{\rm pp}(p_\perp)}{dy\,dp_\perp} \propto p_\perp^{-n}$$

- Power law index $n = n(h, \sqrt{s}) \simeq 5 - 6$ fitted from pp data
- Absolute magnitude of the cross section irrelevant when computing nuclear modification factor $R_{\rm AA}$

Nuclear modification factor R_{AA}

$$R^h_{AA}(p_\perp) = \int_0^\infty dx \left(1 + x\,\frac{\bar{\omega}_c}{p_\perp}\right)^{-n} \bar{P}(x) \simeq \int_0^\infty dx\, \exp\left(-x\,\frac{n\,\bar{\omega}_c}{p_\perp}\right) \bar{P}(x)$$

- R_{AA} uniquely predicted once the only parameter $\bar{\omega}_c$ is known
  - determined from a fit to R_{AA} data
- R_{AA} scaling function of $p_\perp/\bar{\omega}_c$ for a given $n(h, \sqrt{s})$
  - $R_{AA}(p_\perp, \bar{\omega}_c, n) = f(p_\perp/\bar{\omega}_c, n)$
  - Same **shape** of R_{AA} vs. $p_\perp$, for all centralities

Nuclear modification factor $R_{\rm AA}$

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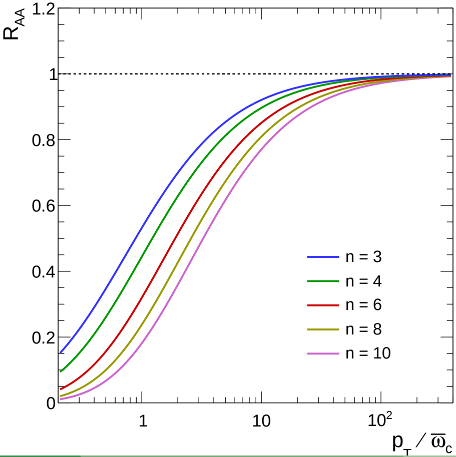
- $R_{\rm AA}$ uniquely … is known
  - determin…
- $R_{\rm AA}$ scaling f…
  - $R_{\rm AA}(p_\perp,$ …
  - Same **sh**…



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  - determined from a fit to $R_{\rm AA}$ data
- $R_{\rm AA}$ scaling function of $p_\perp/\bar{\omega}_c$ for a given $n(h, \sqrt{s})$
  - $R_{\rm AA}(p_\perp, \bar{\omega}_c, n) = f(p_\perp/\bar{\omega}_c, n)$
  - Same **shape** of $R_{\rm AA}$ vs. $p_\perp$, for all centralities
- Approximate scaling: $R_{\rm AA}(p_\perp, \bar{\omega}_c, n) = f(p_\perp/n\,\bar{\omega}_c)$
  - allows for comparing different hadron species or c.m. energies

Nuclear modification factor $R_{\rm AA}$

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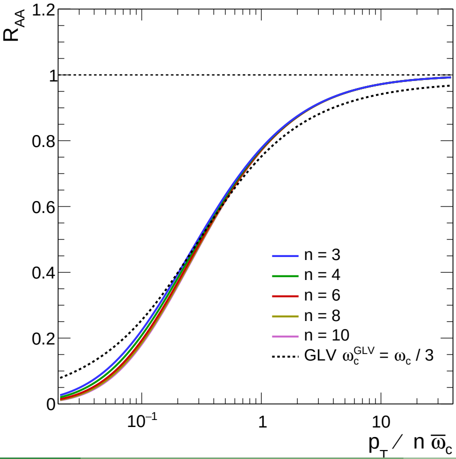
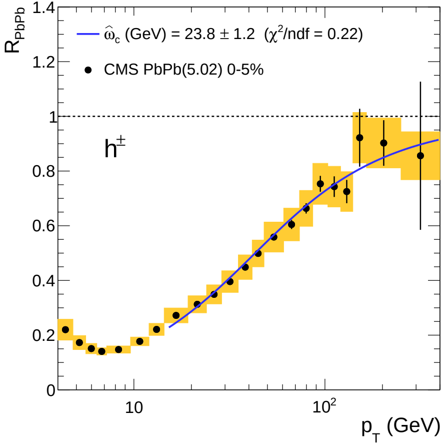


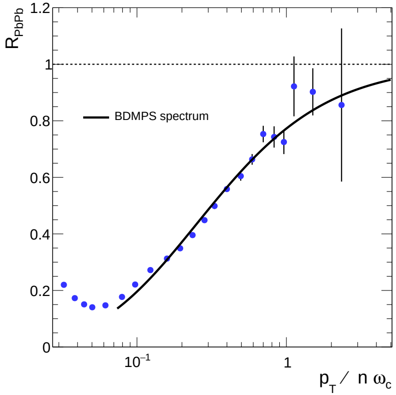
Strategy

- Check if the $p_\perp$ dependence of $R_{\rm AA}$ is indeed **universal**
  - shape independent of centrality, energy, and hadron species
- Discuss the values of $\bar{\omega}_c$ extracted from all the fits
- Start with CMS measurements of charged hadrons in PbPb at $\sqrt{s} = 5$ TeV

Analysis

Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV





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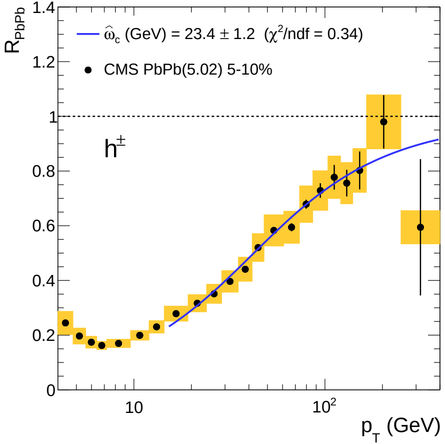

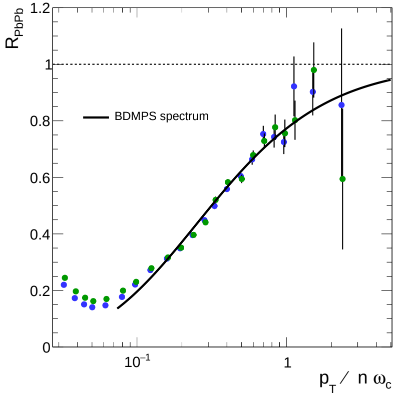

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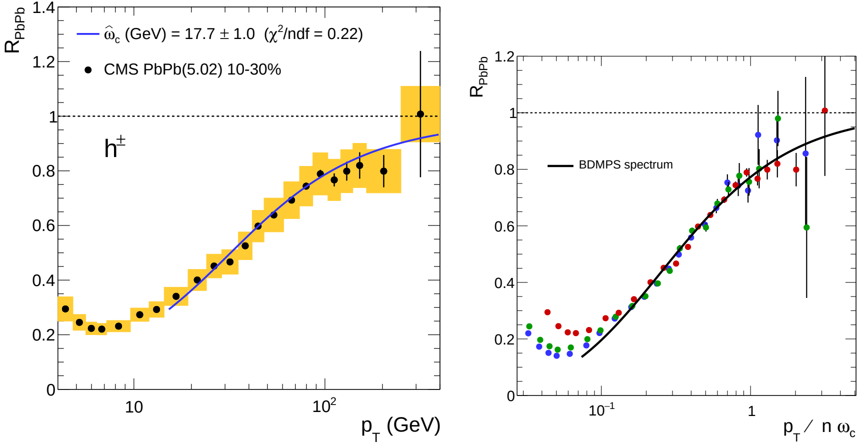

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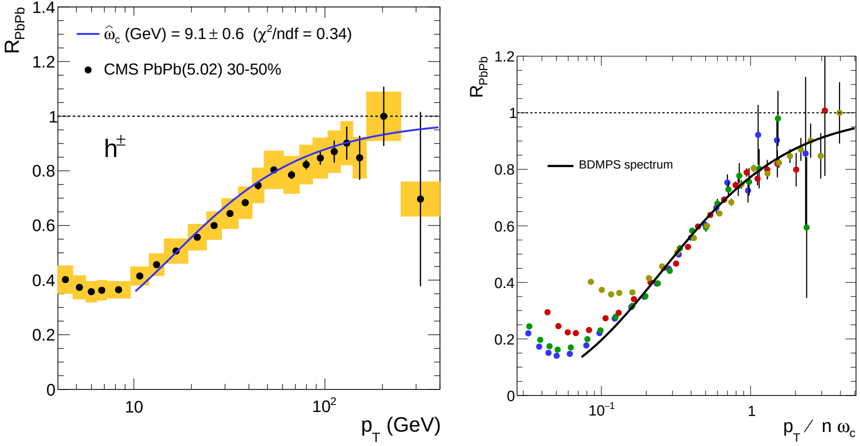

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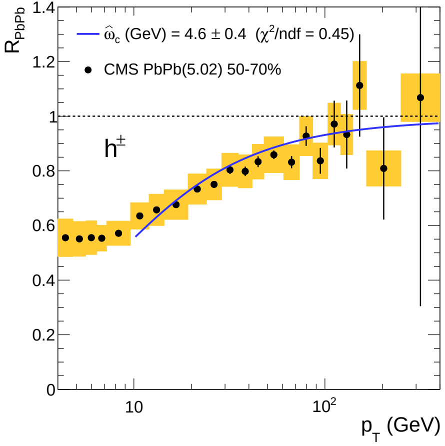

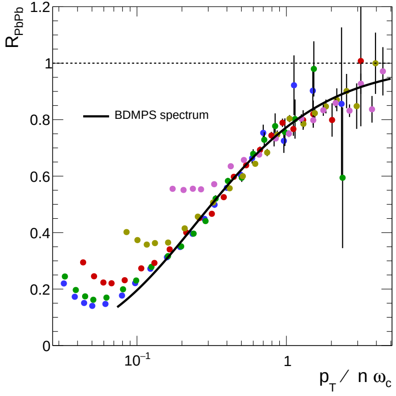

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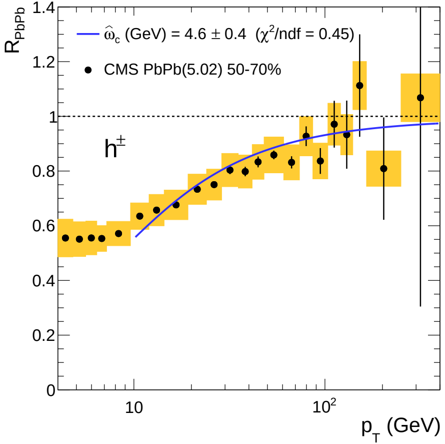
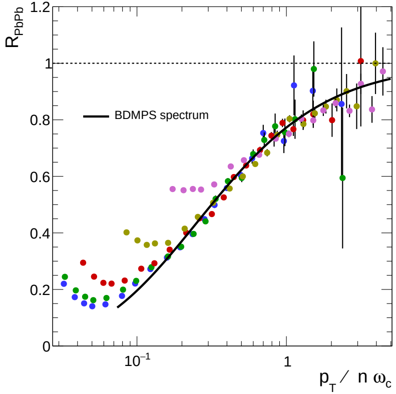
Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV & $\sqrt{s} = 2.76$ TeV





. . . now adding PbPb CMS data at $\sqrt{s} = 2.76$ TeV

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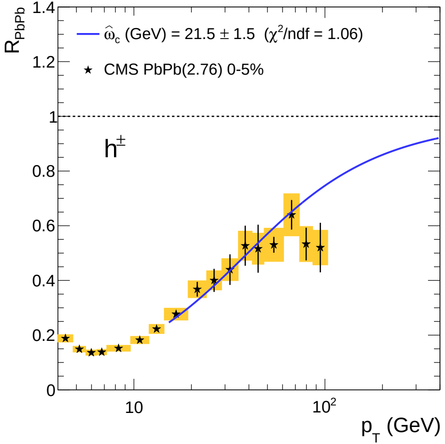

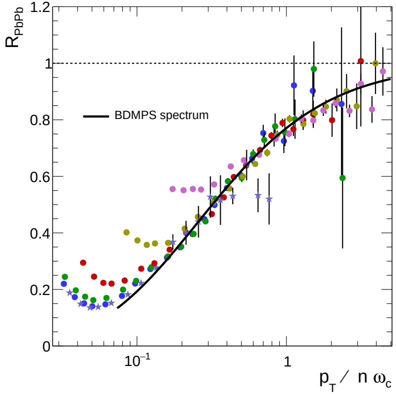

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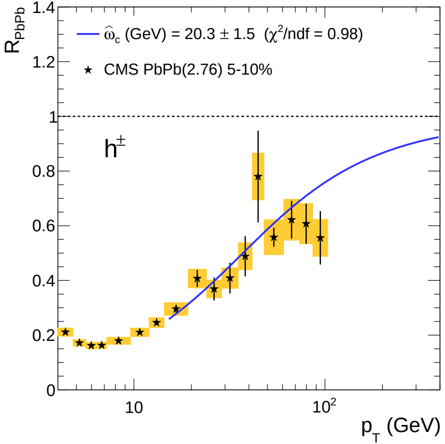

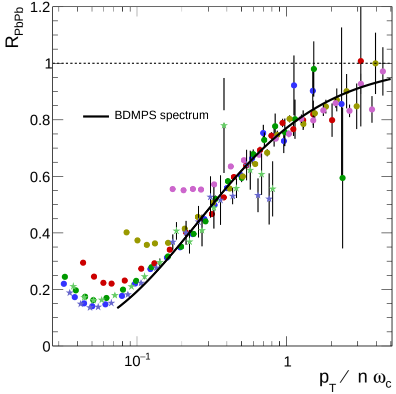

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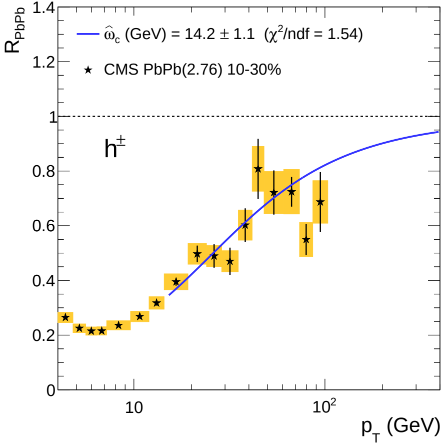

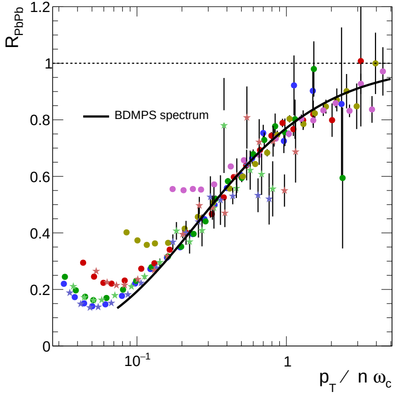

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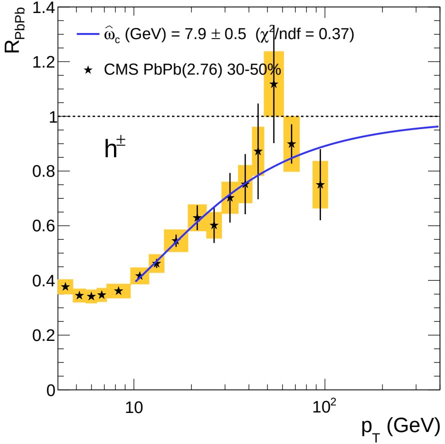

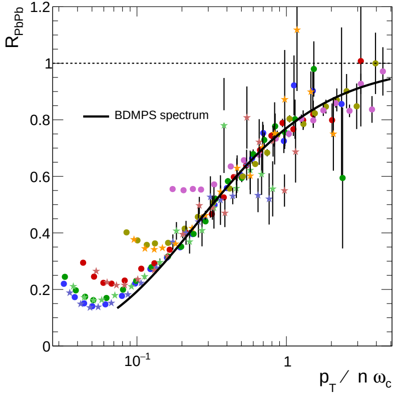

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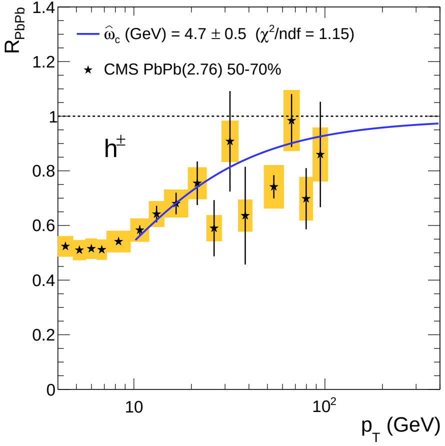

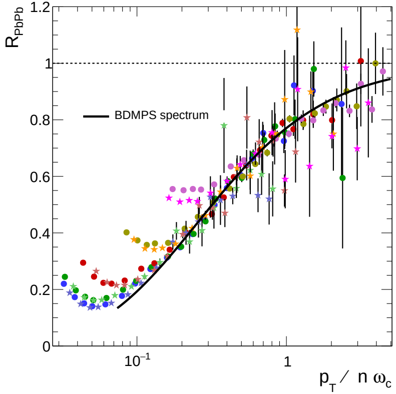

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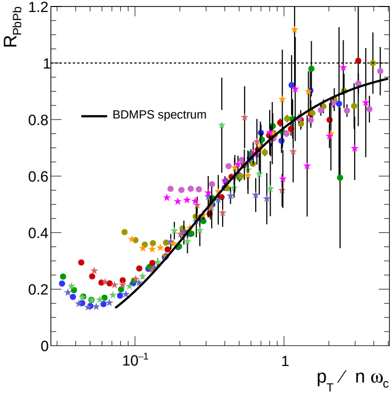

- Predicted scaling nicely observed at 2 energies and in 5 centrality bins
- Shape of $R_{\rm AA}$ nicely consistent with the simple model ($\chi^2/\text{ndf} \simeq 1$)
- Scaling violations at low $p_\perp \lesssim 10$ GeV
  - onset of another phenomenon below this scale ?

Heavy hadrons into the game

At large $p_\perp \gg m_h$, production of heavy hadrons (D/B, heavy quarkonia) should also proceed from the collinear fragmentation of a single parton

- $R_{\rm AA}$ of heavy hadrons might as well follow the same trend
- Fit to the D and J/ψ $R_{\rm AA}$ using the same BDMPS quenching weight (yet initially for massless partons)

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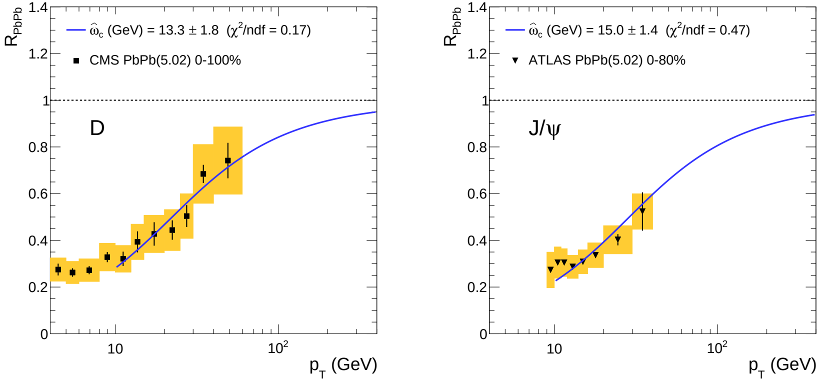
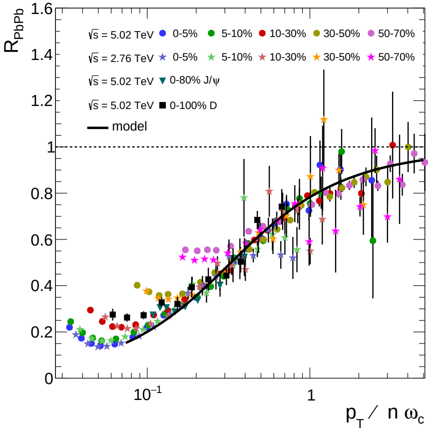


Heavy hadrons into the game



- Within uncertainties, D and J/ψ seem to follow the predicted trend
  - need for more precise data, more centrality & even larger $p_\perp$ to confirm
- Energy loss possibly only process relevant for J/ψ with $p_\perp \gtrsim 10$ GeV
  - maybe not for excited states ?

Mean energy loss

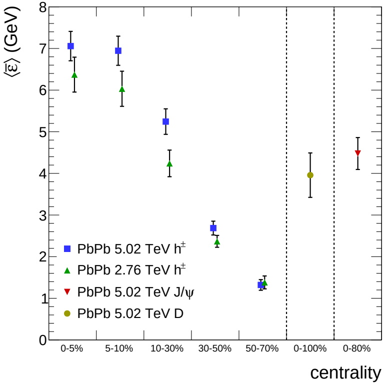
Fits allow for computing $\langle\bar{\epsilon}\rangle = \langle z\rangle \times \langle\epsilon\rangle$

- ...and $\langle\epsilon\rangle$ if $\langle z\rangle$ is known
  - NLO calculations indicate $\langle z\rangle \simeq 0.5$ for light hadrons
  - $\langle z\rangle$ slightly larger for D & J/ψ
  - could be computed from the fractional moments of the FF

$$\langle z\rangle \simeq \int dz\ z^{n+1}\ D_k^h(z) \Big/ \int dz\ z^n\ D_k^h(z)$$

- $\langle\epsilon\rangle$ should be understood as the mean energy loss of the fragmenting parton, averaged over production point and directions of propagation
  - could be computed e.g. from hydrodynamics

Mean energy loss



- Drop from $\langle\bar{\epsilon}\rangle \simeq$ 6–7 GeV to 1 GeV, from central to peripheral classes
- $\langle\epsilon\rangle \simeq$ 4–5 GeV from D & J/ψ in centrality integrated collisions
  - need to analyze same centralities for better comparison with $h^{\pm}$
- 10–20% increase of $\langle\bar{\epsilon}\rangle$ from 2.76 to 5 TeV
  - consistent with the increase of particle multiplicity measured by ALICE

Towards a purely data driven approach

- Still some model dependence because a specific quenching weight is assumed
- How to extract the mean energy loss without assuming anything on the quenching weight ?

Taylor expansion of the pp production cross section in $\epsilon/p_\perp$

$$\frac{d\sigma_{\rm pp}(p_\perp+\epsilon)}{dy\,dp_\perp} = \frac{d\sigma_{\rm pp}(p_\perp)}{dy\,dp_\perp} + \epsilon\,\frac{\partial}{\partial p_\perp}\frac{d\sigma_{\rm pp}(p_\perp)}{dy\,dp_\perp} + \dots$$

Integrating over $P(\epsilon)\,d\epsilon$ leads to

$$R_{\rm AA}(p_\perp) = 1 - n\frac{\langle\epsilon\rangle}{p_\perp} + \frac{n\,(n+1)}{2}\,\frac{\langle\epsilon^2\rangle}{p_\perp^2} + \dots = \sum_{i=0}^{N}(-1)^i\,\frac{\Gamma(n+i)}{\Gamma(i+1)\,\Gamma(n)}\,\frac{\langle\epsilon^i\rangle}{p_\perp^i}$$

Idea : take the first moments $\langle\bar\epsilon^j\rangle$ as free parameters !

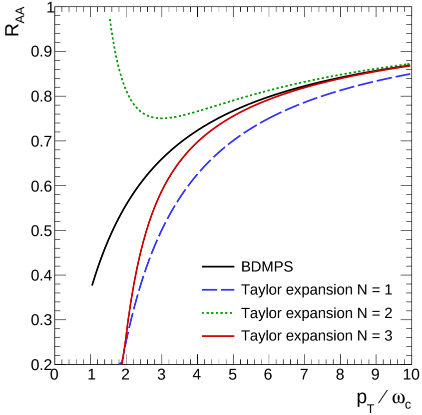
Extracting moments

Procedure

1. Check the convergence from a known quenching weight (here, BDMPS)
2. Generate pseudo-data according to the known quenching weight and check that the first moments can be retrieved from a fit to the pseudo-data

Extracting moments

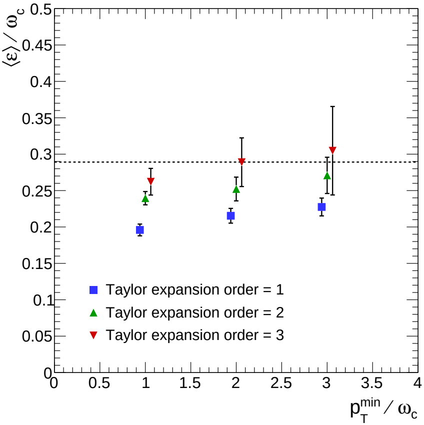
Convergence of the Taylor series



- Failure of the 1st order expansion at all $p_\perp$
- 2nd and 3rd order fits reproduce well the input $R_{\rm AA}$ at 'large' $p_\perp$

Extracting moments

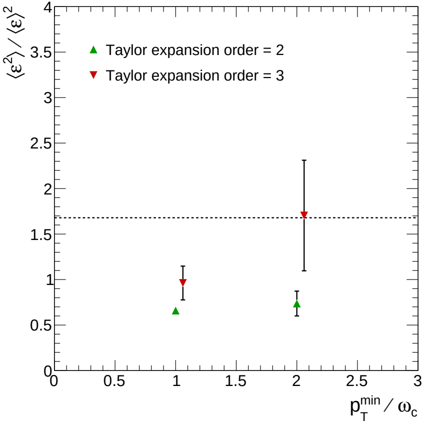
First moment



- First moment $\langle\epsilon\rangle$ can be extracted reliably if the $p_\perp$ range is large
- Larger uncertainties expected with 3rd order fits

Extracting moments

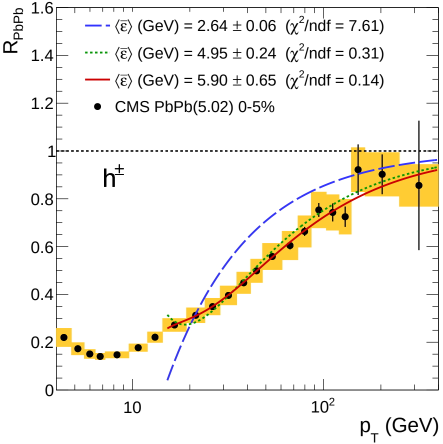
Second moment



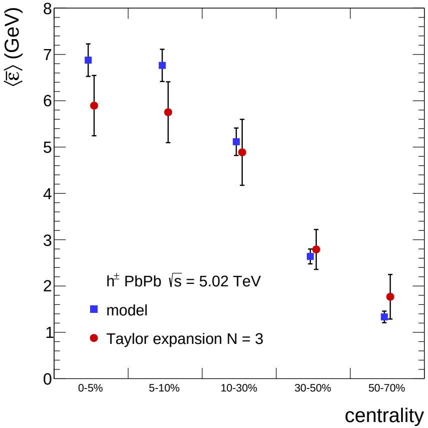
- Extracting the second moment (variance) is more delicate, yet not impossible
  - needs very precise data

Extracting moments from data

Testing the procedure with charged hadron CMS data



Extracting moments from data



- Good agreement between the BDMPS and the 'agnostic' estimates
- Larger uncertainties because of the 3 parameters (instead of 1 when assuming a given quenching weight)

Summary

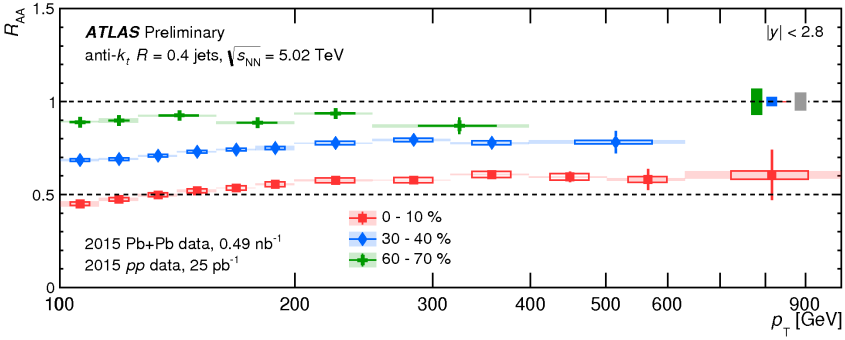
- Simple energy loss model revisited in light of the recent LHC data
- Measured R_{AA} exhibit a universal shape (scaling) for hadrons for different centralities and at both energies
  - heavy hadrons (including quarkonia) follow the same behavior
  - scaling violations for hadrons $p_\perp \leq 10$ GeV
- Energy loss scales extracted for all centralities
  - 10%–20% increase from 2.76 to 5 TeV consistent with that of particle multiplicity
- Data-driven procedure to extract moments of the quenching weight without any prior
  - results consistent with estimates from BDMPS

What about jets ?

Perhaps the most natural observable to test the model is $R_{\rm AA}$ of jets,
but. . .

What about jets ?

Perhaps the most natural observable to test the model is $R_{\rm AA}$ of jets, **but...**



How to understand this ?

- Rather flattish $R_{\rm AA}$
- $R_{\rm AA}$ never reaches unity even at extremely large energies !

What about jets ?

How to understand this ? No clue !

Bias in the measurement

- All measurements have been carefully cross-checked. . . so almost 1 TeV jets indeed seem significantly quenched !

Physical origin

- Energy lost by a jet in a medium should not necessarily be that of a single parton, nor that of a hadron
- Different scaling property of medium-induced energy loss for a jet ? Should $\langle \epsilon \rangle \propto \hat{q} L^2$ hold there too ? If not, why ?