Quenching of hadron spectra in heavy ion collisions at the LHC

François Arleo

LLR Palaiseau

QGP France 2017 – Étretat, October 2017

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
- 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 $p_\perp$

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 $p_\perp$

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 $p_\perp$

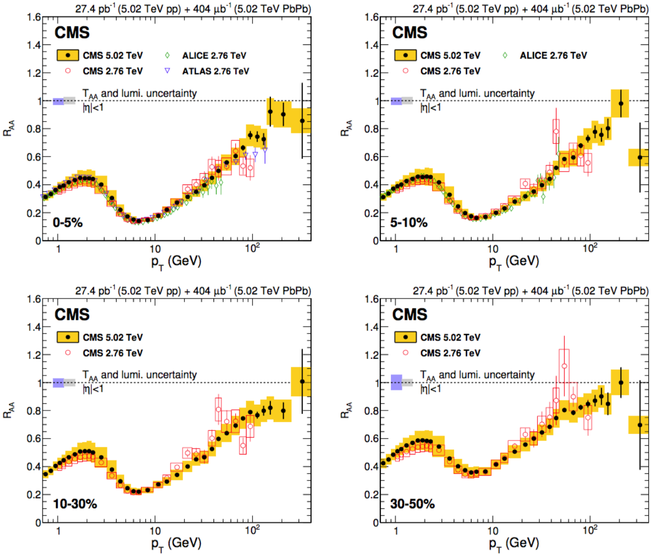
This talk

Here, loo

I discuss a iative
energy loss e $p_\perp$

Why hadr

- hadro
  - i
- very p
  - t
  - v
  - c
  - f



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 $p_\perp$

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

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

The model

Take the simplest energy loss model for production of particle i

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

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. $g \to h^\pm$)
- 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 $R_{\rm AA}$

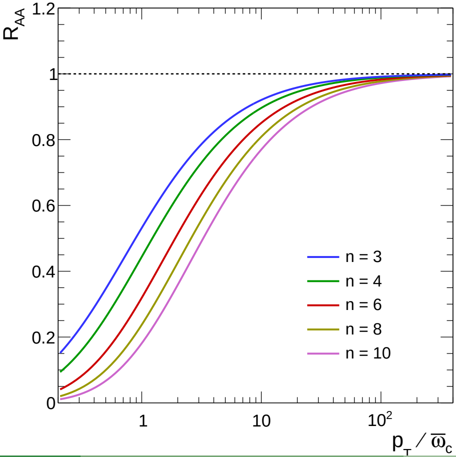
$$R^h_{\rm AA}(p_\perp) = \int_0^\infty dx \left(1 + x\,\frac{\bar\omega_c}{p_\perp}\right)^{-n} \bar P(x) \simeq \int_0^\infty dx\, \exp\left(-x\,\frac{n\,\bar\omega_c}{p_\perp}\right)\, \bar P(x)$$

- $R_{\rm AA}$ uniquely predicted once the only parameter $\bar\omega_c$ is known
  - 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

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



Nuclear modification factor $R_{\rm AA}$

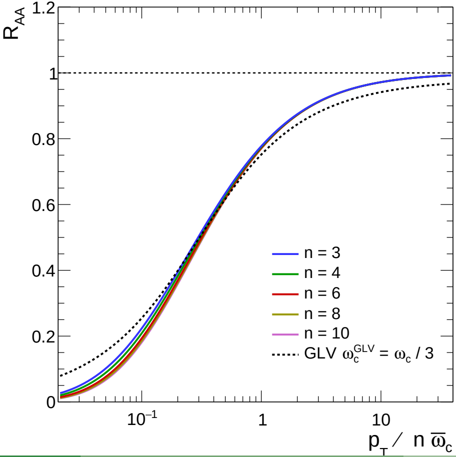
$$R^h_{\rm AA}(p_\perp) = \int_0^\infty dx \left(1 + x\,\frac{\bar\omega_c}{p_\perp}\right)^{-n} \bar{P}(x) \simeq \int_0^\infty dx\, \exp\left(-x\,\frac{n\,\bar\omega_c}{p_\perp}\right)\, \bar{P}(x)$$

- $R_{\rm AA}$ uniquely predicted once the only parameter $\bar\omega_c$ is known
  - 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_{AA}

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

- R_{AA} uniquely … is known
  - determin…
- R_{AA} scaling …
  - $R_{\mathrm{AA}}(p_\perp,$ …
  - Same **sh**…
- Approximate …
  - allows fo… . energies

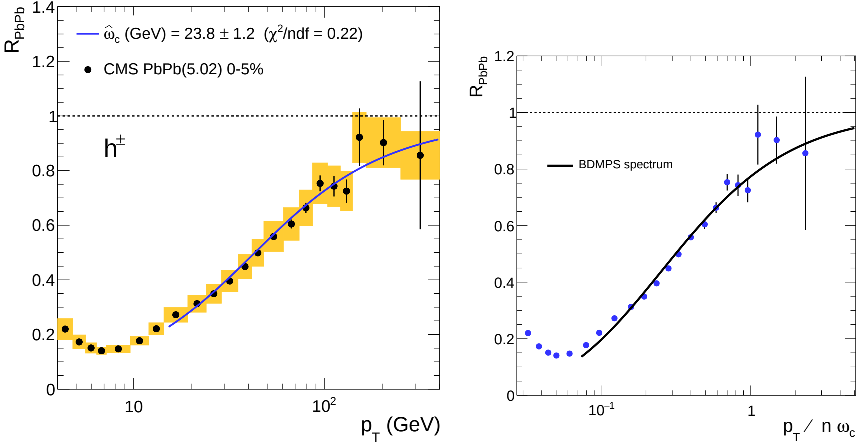


Strategy

- 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

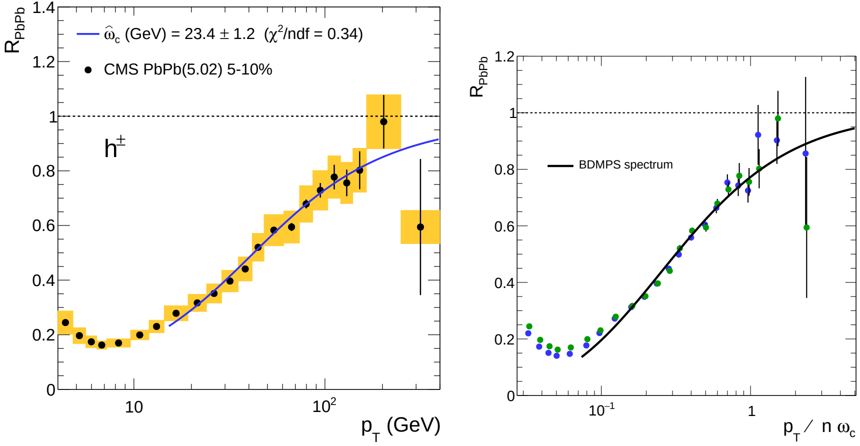
Analysis

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



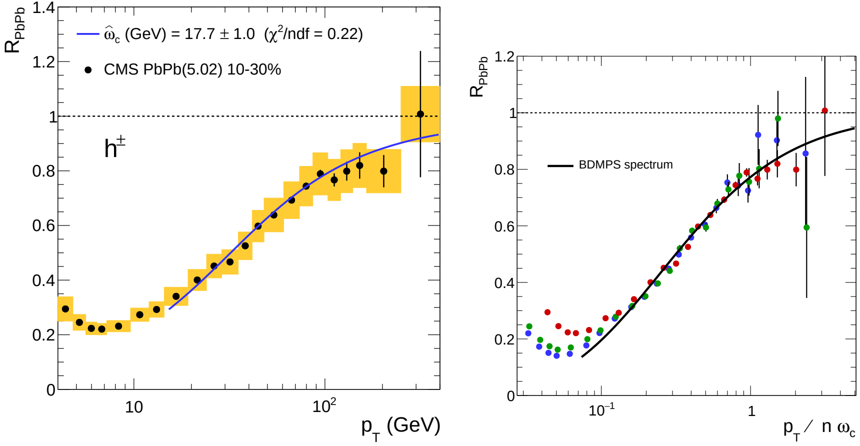
Analysis

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



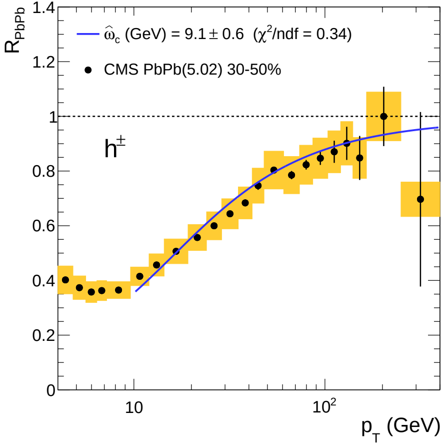
Analysis

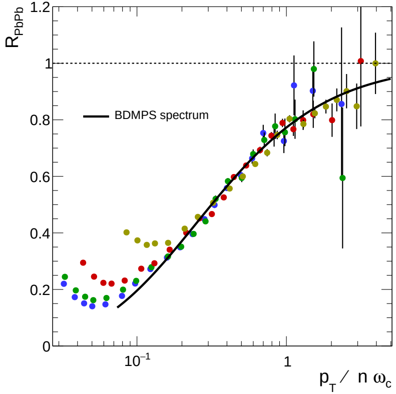
Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV



Analysis

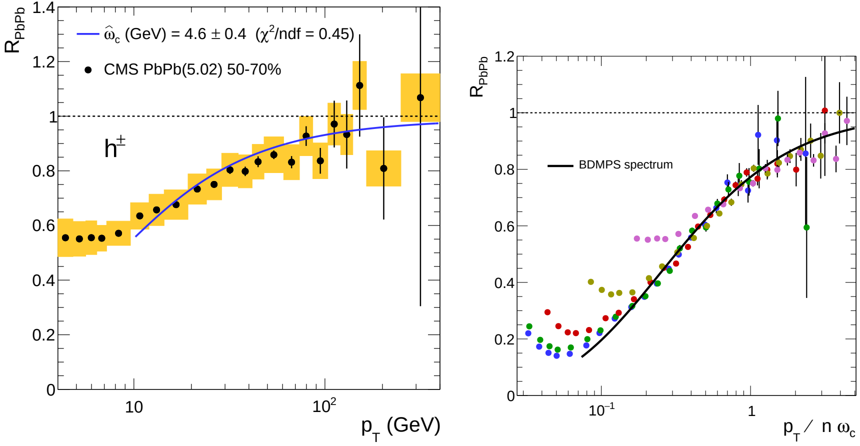
Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV





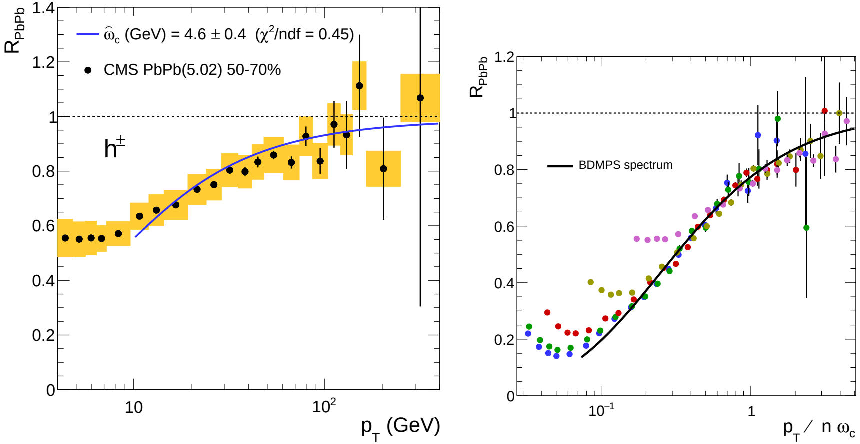
Analysis

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



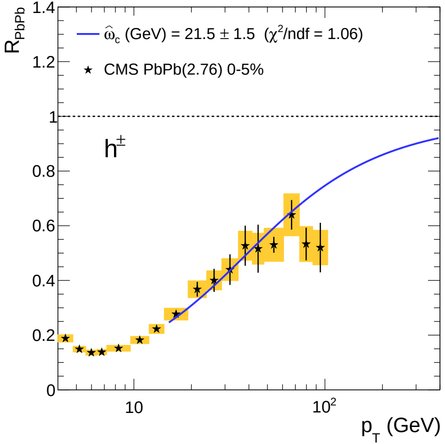
Analysis

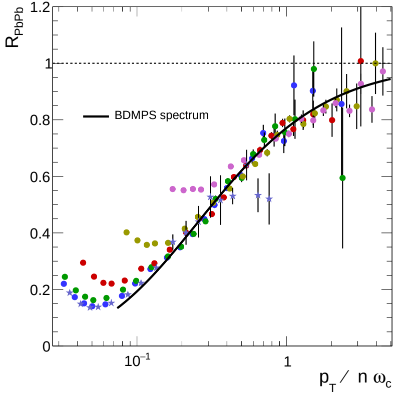
Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV & $\sqrt{s} = 2.76$ TeV



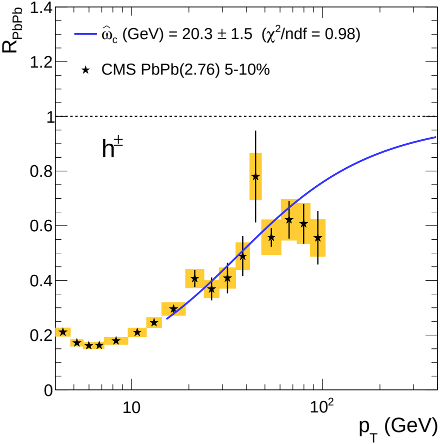
. . . now adding PbPb CMS data at $\sqrt{s} = 2.76$ TeV

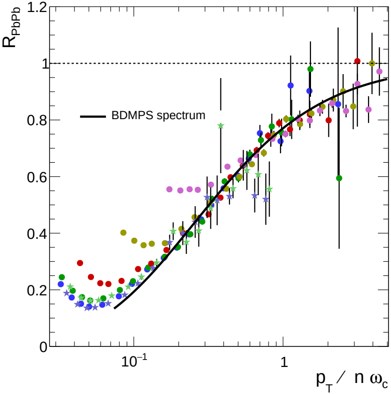
Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV & $\sqrt{s} = 2.76$ TeV





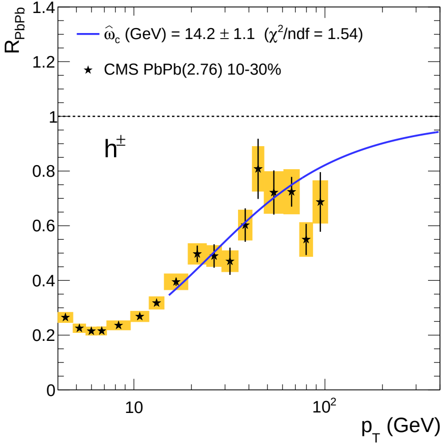
Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV & $\sqrt{s} = 2.76$ TeV

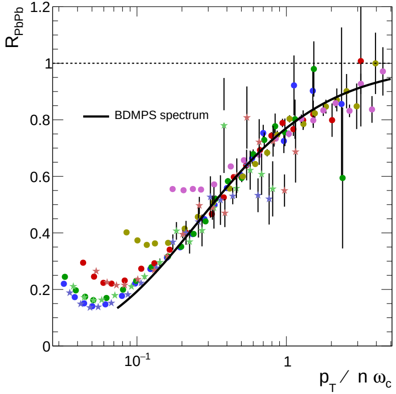




Analysis

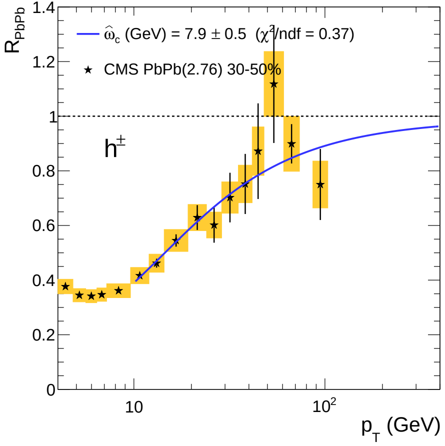
Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV & $\sqrt{s} = 2.76$ TeV

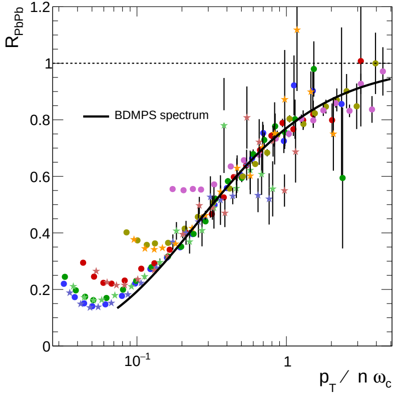




Analysis

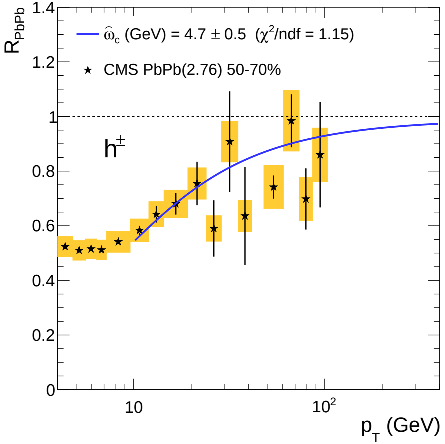
Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV & $\sqrt{s} = 2.76$ TeV

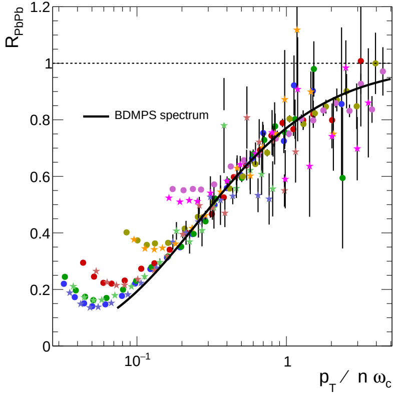




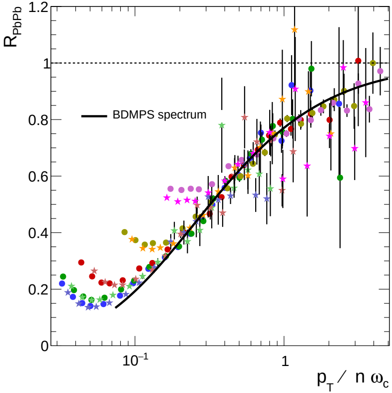
Analysis

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



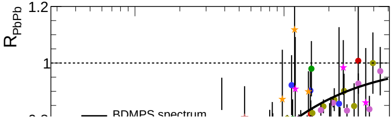


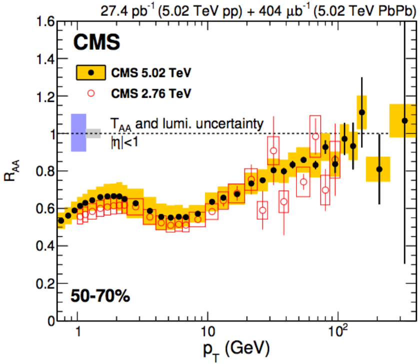
Analysis

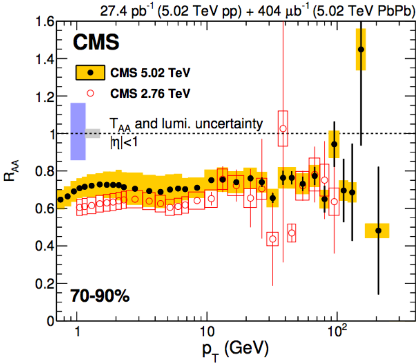


- Predicted scaling nicely observed at 2 energies and in 5 centrality bins
- Shape of $R_{\rm AA}$ nicely consistent with the simple model (χ^2/ndf $\simeq$ 1)
- Scaling violations at low $p_\perp \lesssim$ 10 GeV
  - onset of another phenomenon below this scale ?
- The most peripheral data set does not follow the systematics

Analysis







- Scaling violations at low $p_\perp \lesssim 10$ GeV
  - onset of another phenomenon below this scale ?
- The most peripheral data set does not follow the systematics

Heavy hadrons into the game

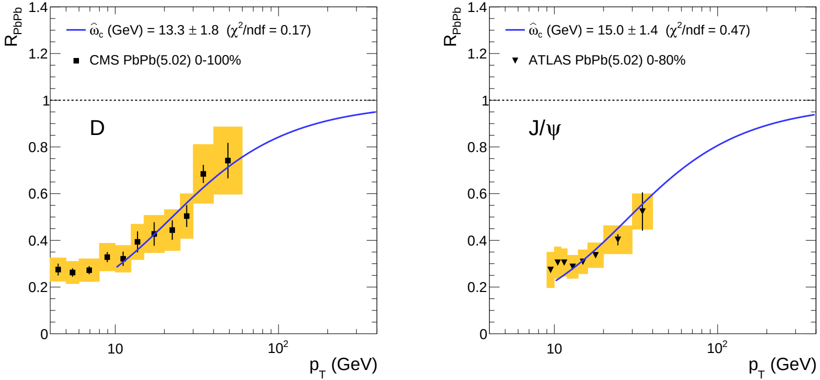
At large $p_\perp \gg m_h$, production of heavy hadrons (D/B, heavy quarkonia) should also proceed from the collinear fragmentation of a single parton

- $R_{\rm AA}$ 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)

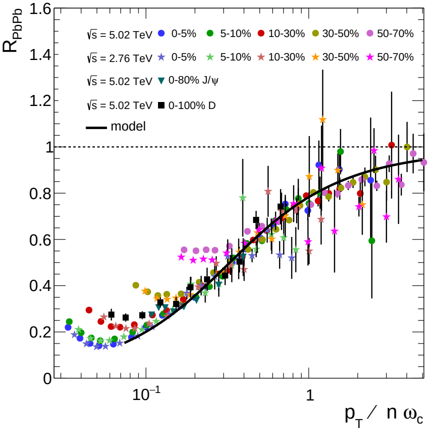
Heavy hadrons into the game

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



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

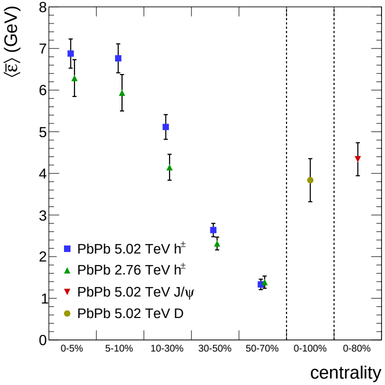
Fits allow for computing $\langle\bar{\epsilon}\rangle = \langle z\rangle \times \langle\epsilon\rangle$

- ... 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



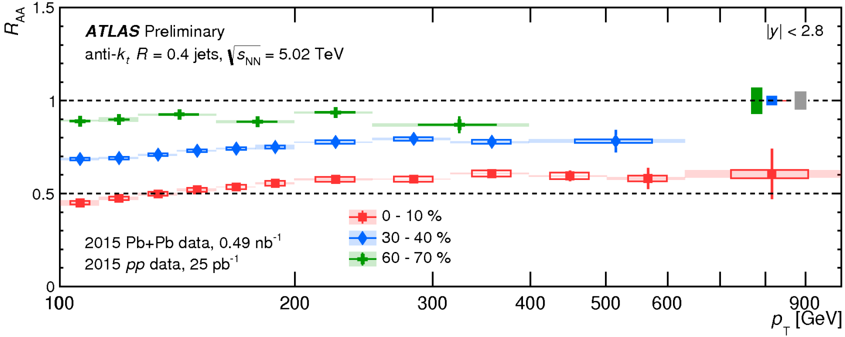
- Drop from $\langle\bar{\epsilon}\rangle \simeq$ 6–7 GeV to 1 GeV, from central to peripheral classes
- $\langle\epsilon\rangle \simeq$ 4–5 GeV from D & J/ψ in centrality integrated collisions
  - need to analyze same centralities for better comparison with $h^{\pm}$
- 10–20% increase of $\langle\bar{\epsilon}\rangle$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

What about jets ?

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

What about jets ?

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



How to understand this ?

- Rather flattish R_{AA}
- R_{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 ?

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 $\epsilon / p_\perp$

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

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

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

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

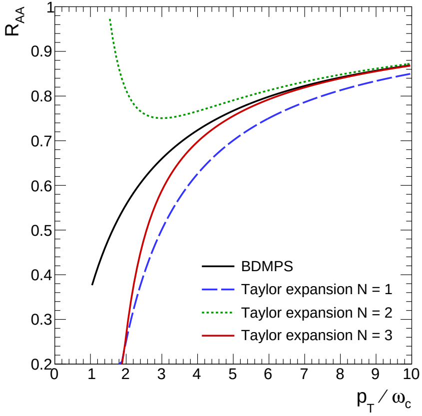
Extracting moments

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

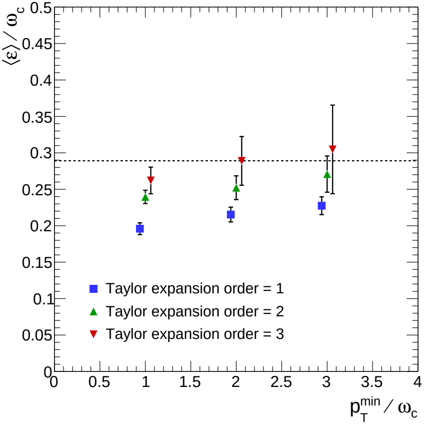
Convergence of the Taylor series



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

Extracting moments

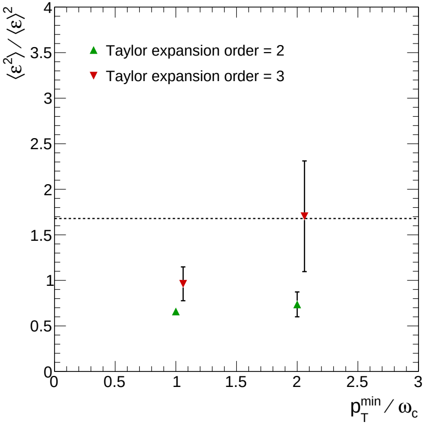
First moment



- 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

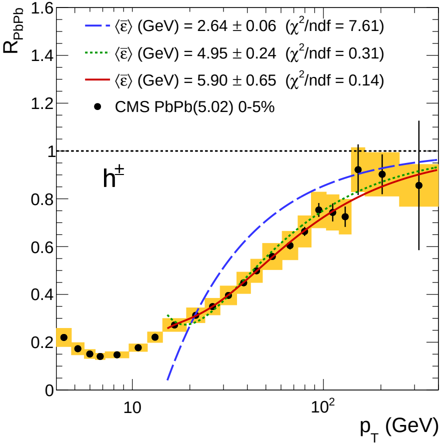
Second moment



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

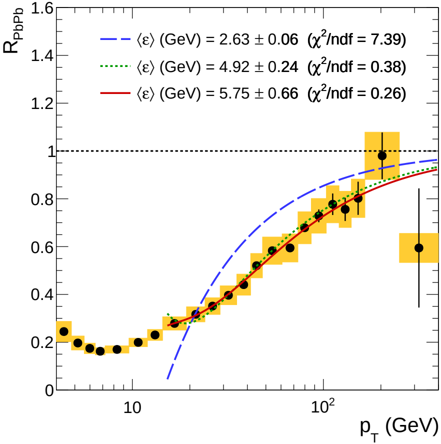
Extracting moments from data

Testing the procedure with charged hadron CMS data



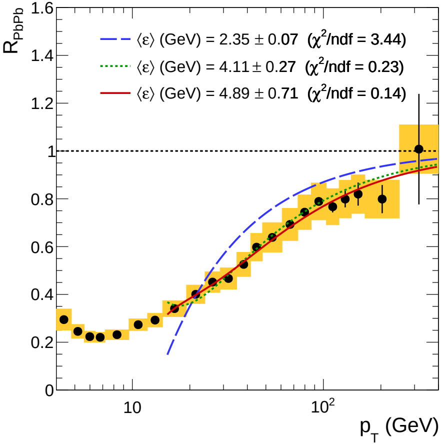
Extracting moments from data

Testing the procedure with charged hadron CMS data



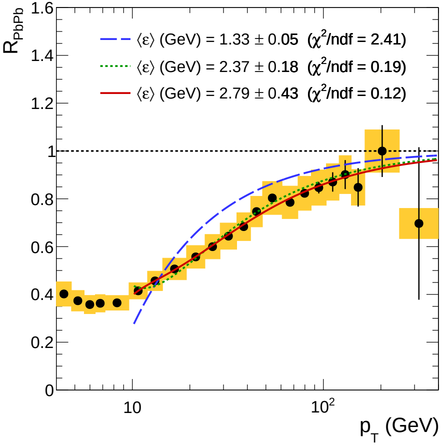
Extracting moments from data

Testing the procedure with charged hadron CMS data



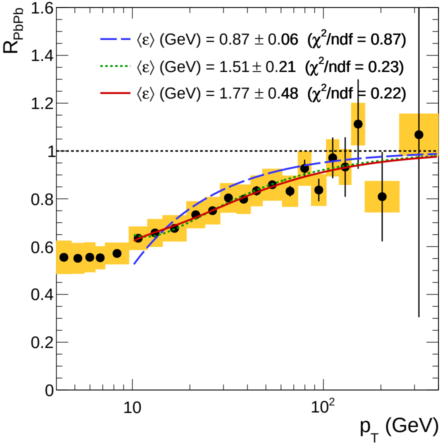
Extracting moments from data

Testing the procedure with charged hadron CMS data

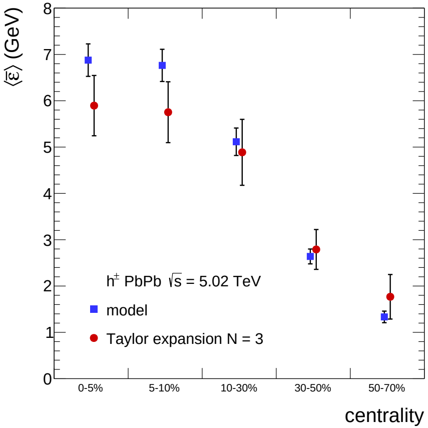


Extracting moments from data

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