

# Quenching of hadron spectra in heavy ion collisions at the LHC

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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.

## 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  $p_{\perp}$

### 1. Why hadron quenching ?

- hadrons = particles
  - ▶ in a sense much simpler than jets
- very precise data at the LHC

## 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  $p_{\perp}$

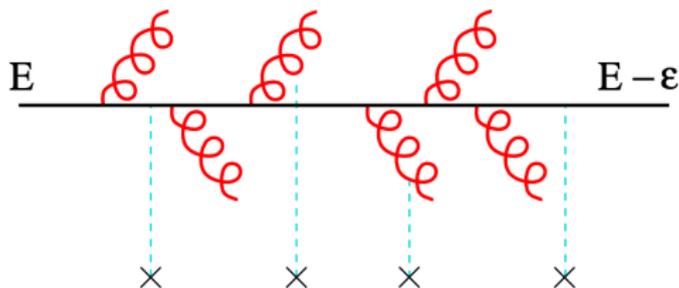
## 2. Why large transverse momentum ?

- cold nuclear matter effects weaken/vanish when  $p_{\perp} \gg Q_s$
- other hot medium effects 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 cross section has simple power-law behavior  $\sigma^{pp} \propto p_{\perp}^{-n}$

# The model

Take the **simplest energy loss model** for production of particle  $i$

$$\frac{d\sigma_{AA}^i}{dy d\mathbf{p}_\perp} = A^2 \int_0^\infty d\epsilon \frac{d\sigma_{pp}^i(\mathbf{p}_\perp + \epsilon)}{dy d\mathbf{p}_\perp} P_i(\epsilon)$$



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## Hadronization

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

$$\frac{d\sigma_{AA}^h}{dy d\mathbf{p}_\perp} = A^2 \sum_k \int_0^1 dz D_k^h(z) \int_0^\infty d\epsilon \frac{d\hat{\sigma}_{PP}^k(\mathbf{p}_\perp/z + \epsilon/z)}{dy d\mathbf{p}_\perp} \frac{1}{z} P_k(\epsilon/z)$$

- 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 swapping integrals

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$$\frac{d\sigma_{AA}^h}{dy d\mathbf{p}_\perp} = A^2 \int_0^\infty d\epsilon \frac{d\sigma_{pp}^h(\mathbf{p}_\perp + \langle \mathbf{z} \rangle \epsilon)}{dy d\mathbf{p}_\perp} P_i(\epsilon)$$

## 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

$$P(\epsilon) = \frac{1}{\omega_c} \bar{P}\left(\frac{\epsilon}{\omega_c}\right)$$

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

# The model

Take the **simplest energy loss model** for production of particle  $i$

$$\frac{d\sigma_{AA}^h}{dy d p_{\perp}} \simeq A^2 \int_0^{\infty} dx \frac{d\sigma_{PP}^h(p_{\perp} + \bar{\omega}_c x)}{dy d p_{\perp}} \bar{P}(x)$$

## pp production cross section

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

$$\frac{d\sigma_{PP}^i}{dy d p_{\perp}} \propto p_{\perp}^{-n}$$

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

# Nuclear modification factor $R_{AA}$

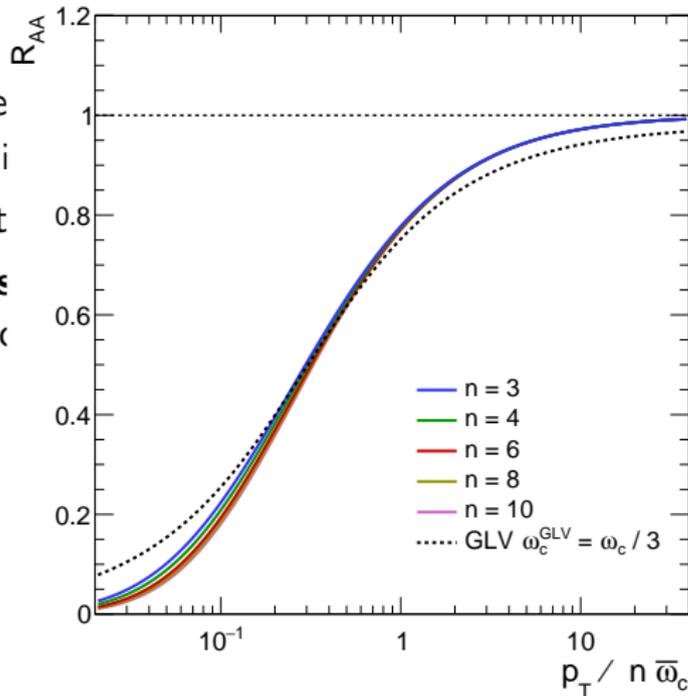
$$R_{AA}^h(p_{\perp}) = \int_0^{\infty} dx \left(1 + x \frac{\bar{\omega}_c}{p_{\perp}}\right)^{-n} \bar{P}(x) \simeq \int_0^{\infty} dx \exp\left(-x \frac{n \bar{\omega}_c}{p_{\perp}}\right) \bar{P}(x)$$

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

# Nuclear modification factor $R_{AA}$

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- $R_{AA}$  unique  
▶ determi
- Approximat
- **Universal** s  
hadron spec

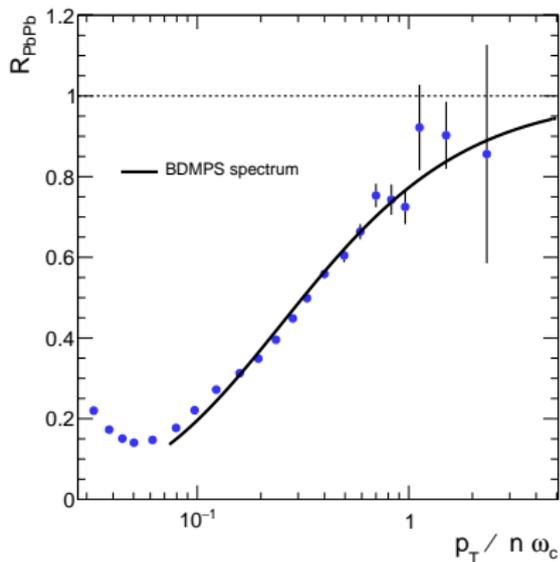
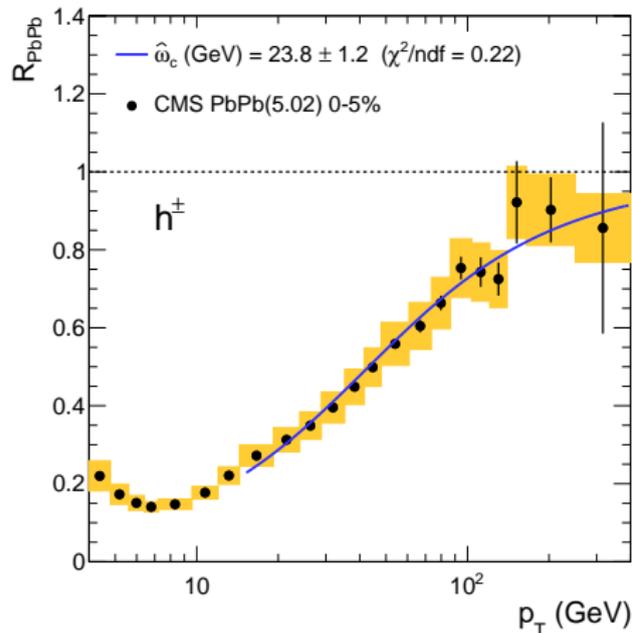


known

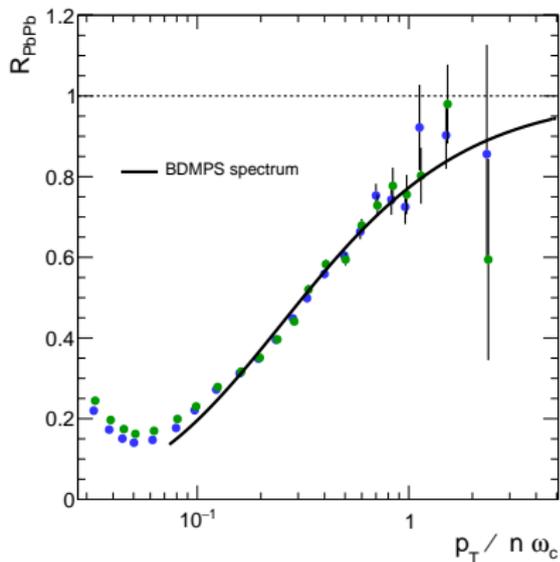
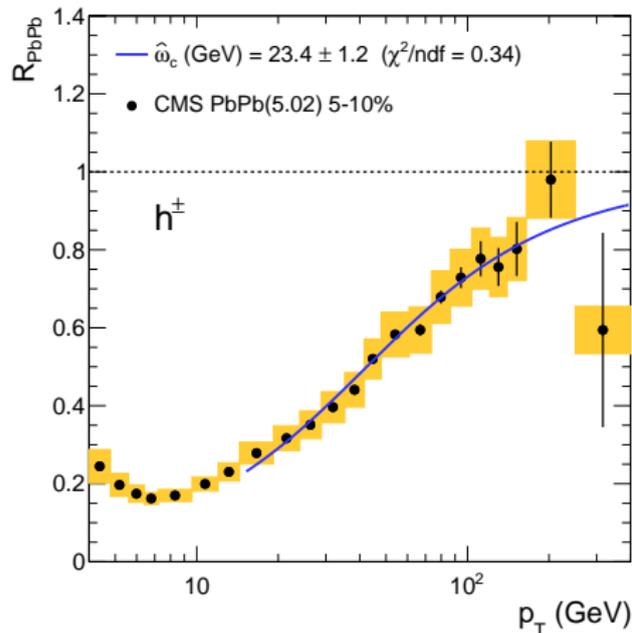
ion energies,

- Model with least number of assumptions and parameters
- Check **universality of quenching**
- Extract robust and ideally **model-independent estimates** of parton energy loss in a **data-driven approach**
- Start with charged hadrons  $R_{AA}$  at  $\sqrt{s} = 5$  TeV

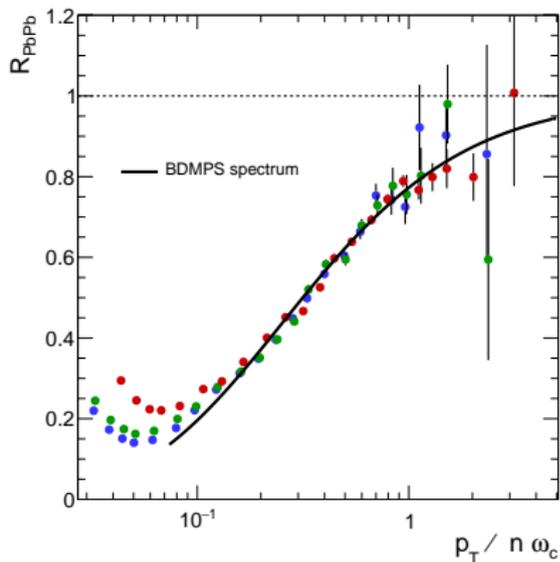
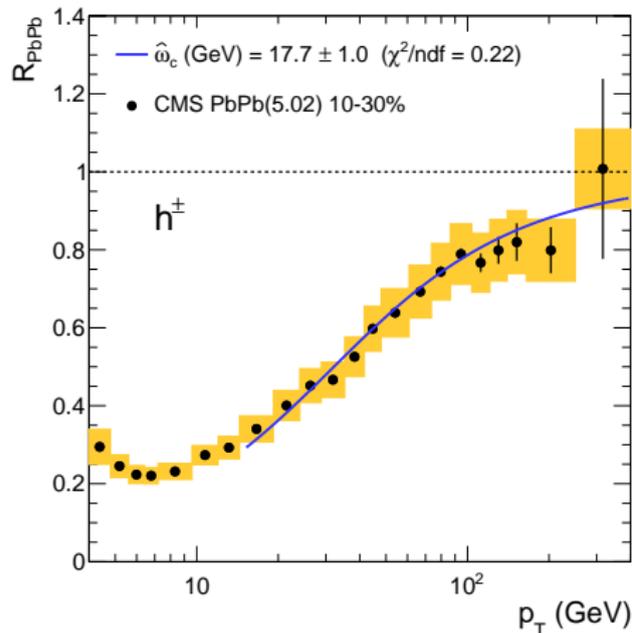
## Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV



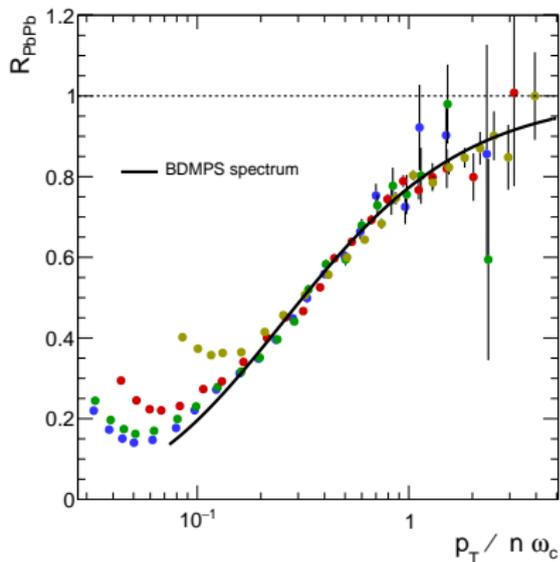
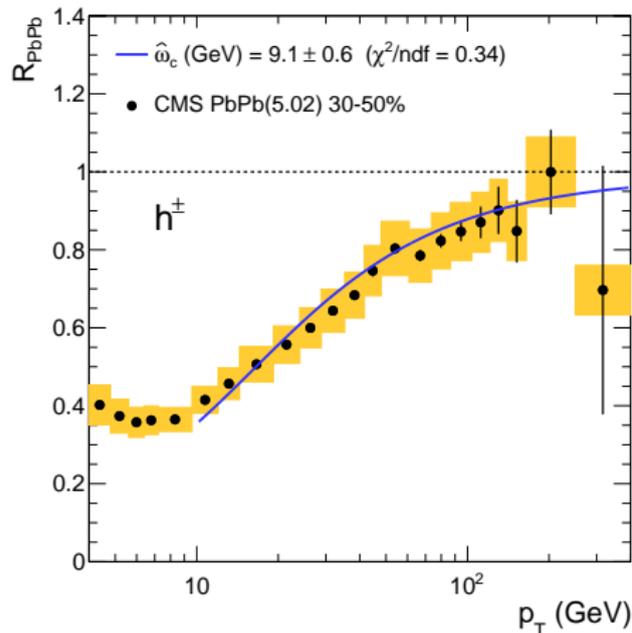
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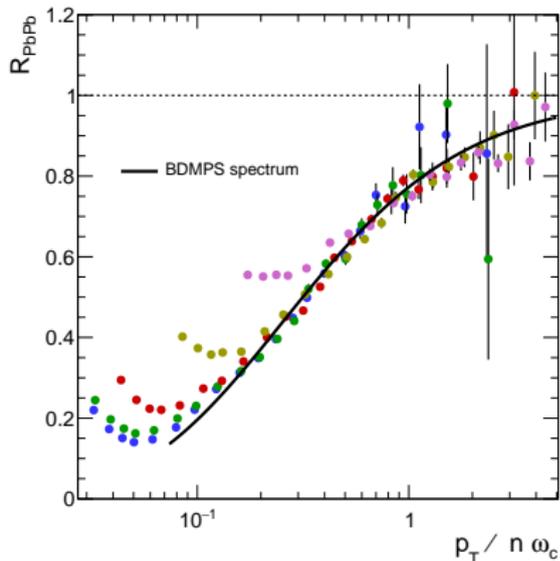
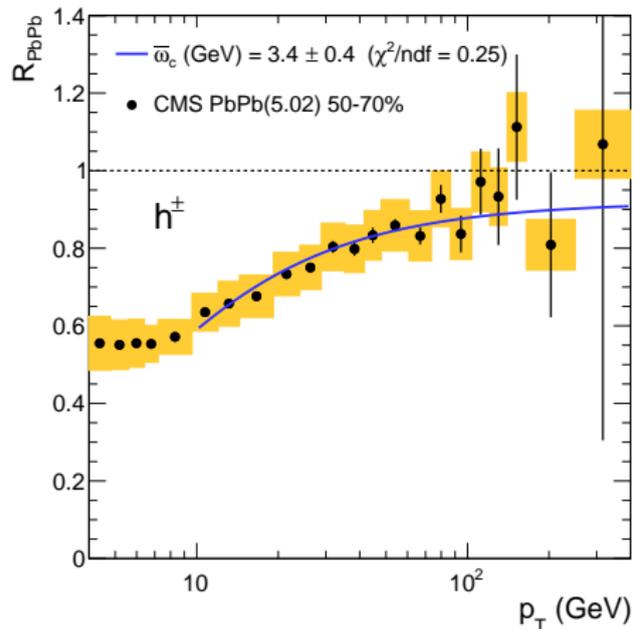
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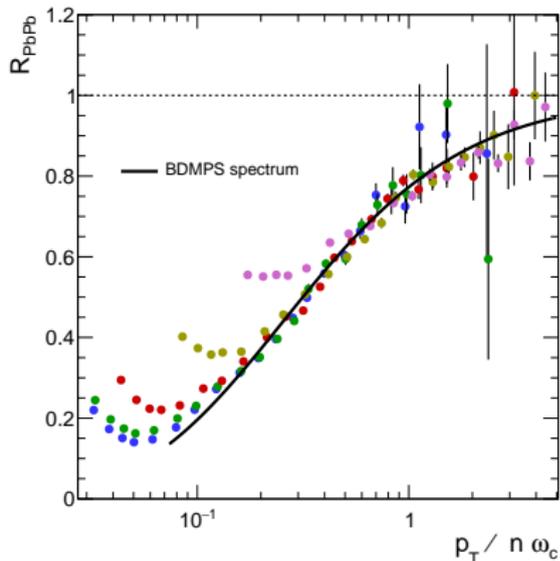
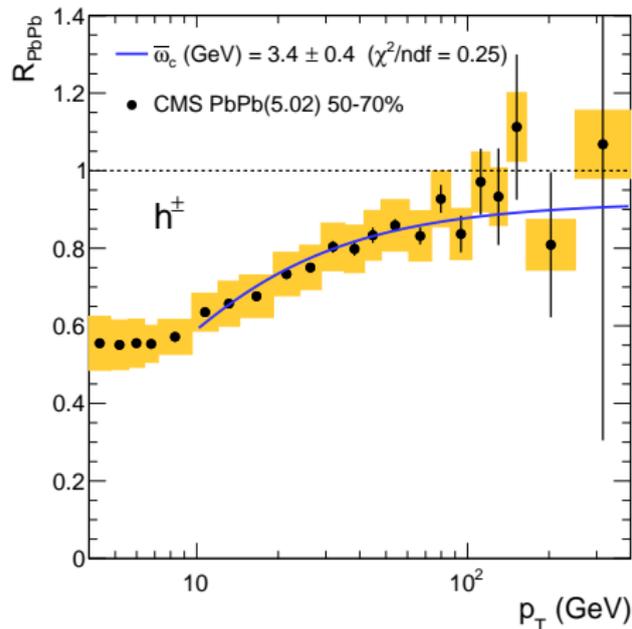
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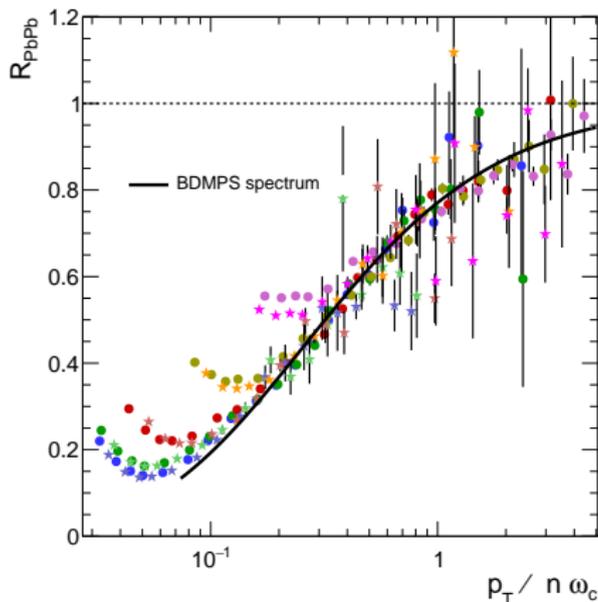


## Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV



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

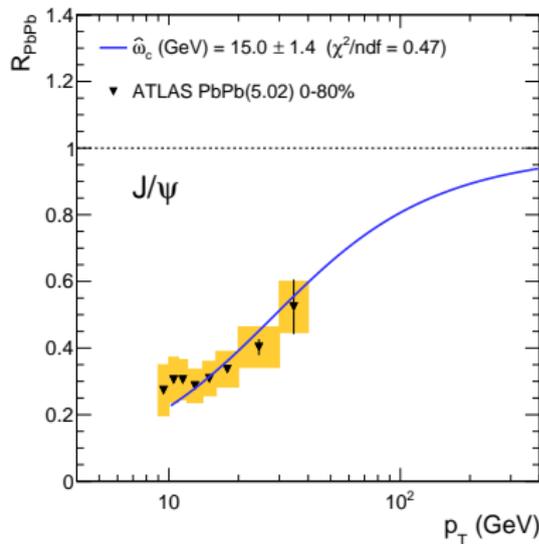
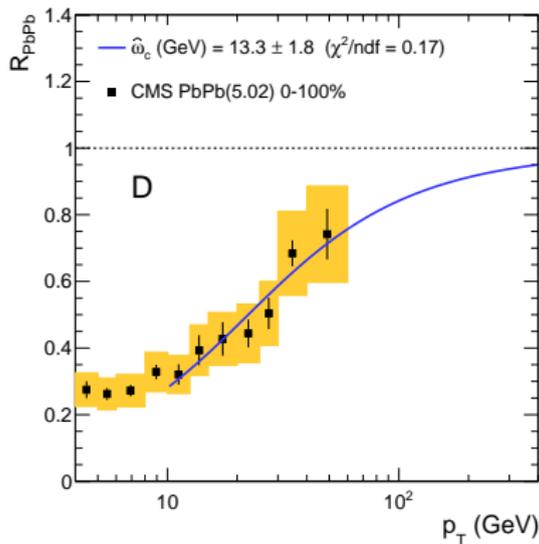
# Scaling



- Predicted scaling nicely observed at 2 energies and in 5 centrality bins
- Shape of  $R_{AA}$  consistent with BDMPS model ( $\chi^2/\text{ndf} \simeq 1$ )
- Scaling violations at low  $p_{\perp} \lesssim 10$  GeV (other process at work?)
- Most peripheral data do not follow the systematics

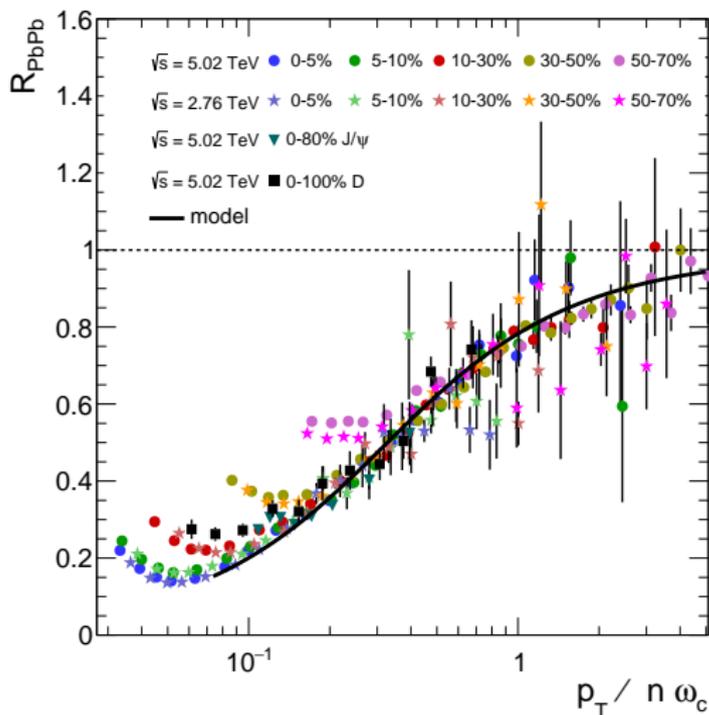
# Heavy hadrons into the game

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



- Fit to D &  $J/\psi$  using the same BDMPS (massless) quenching weight
- $R_{\text{AA}}$  of heavy hadrons follow the same trend
  - ▶ need for more precise data, more centrality & even larger  $p_{\perp}$

# Heavy hadrons into the game



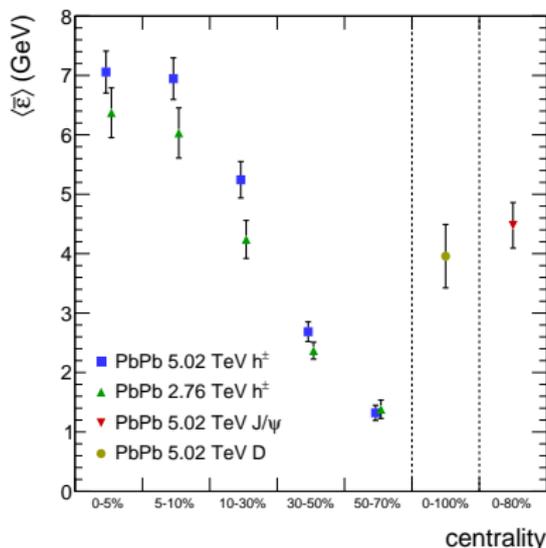
- Energy loss possibly only process relevant for  $J/\psi$  with  $p_{\perp} \gtrsim 10$  GeV
  - ▶ maybe not for excited states ?

# 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 pQCD indicates  $\langle z \rangle \simeq 0.5$  for  $h^\pm$ , larger for D &  $J/\psi$
  - ▶ could be computed from the (fractional) moments of the FF
- $\langle \epsilon \rangle =$  mean energy loss of the fragmenting parton, averaged over geometry
  - ▶ could be computed e.g. from hydrodynamics

# Mean energy loss



- **Drop** from  $\langle \bar{E} \rangle \simeq 7$  GeV to 1 GeV, from central to peripheral
- $\langle \bar{E} \rangle \simeq 4-5$  GeV from D &  $J/\psi$  in min bias collisions
  - ▶ need to analyze same centralities for better comparison with  $h^\pm$
- **10-20% increase** of  $\langle \bar{E} \rangle$  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
- **Taylor expansion** of the pp production cross section in  $\epsilon/p_{\perp}$  leads to

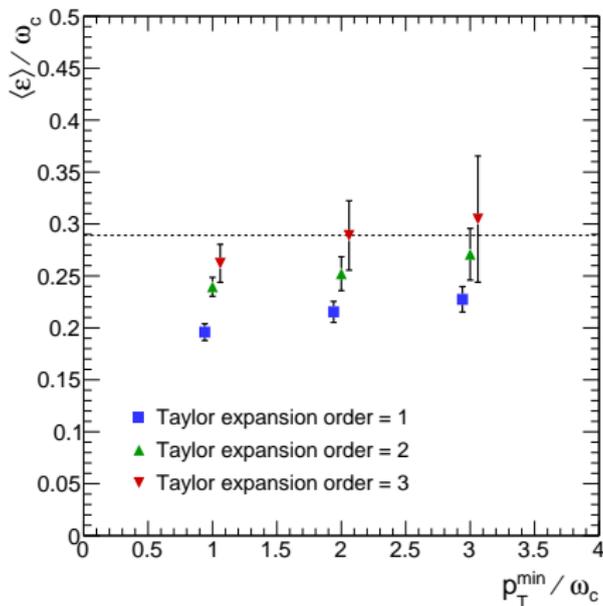
$$R_{AA}(p_{\perp}) = 1 - n \frac{\langle \epsilon \rangle}{p_{\perp}} + \frac{n(n+1)}{2} \frac{\langle \epsilon^2 \rangle}{p_{\perp}^2} + \dots$$

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

### Procedure

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

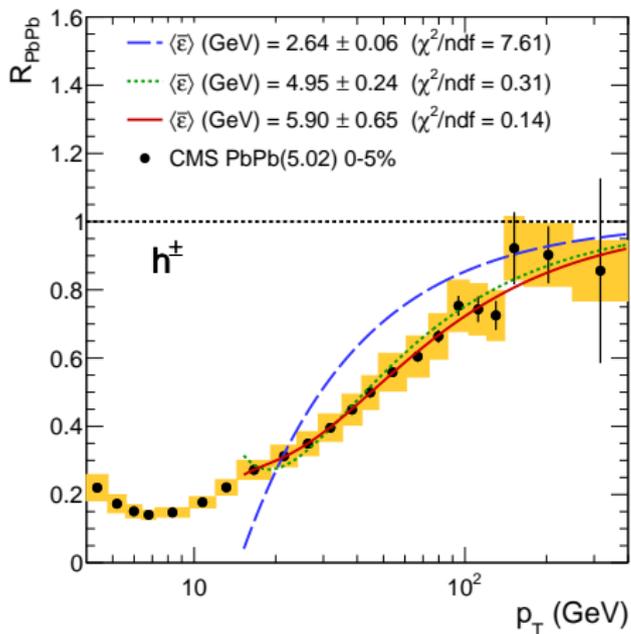
# Extracting first moment



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

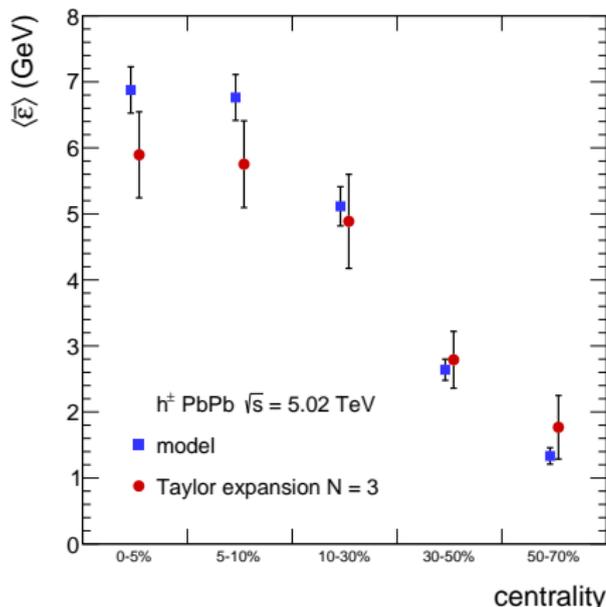
# Extracting moments from data

## Testing the procedure with charged hadron CMS data



- Good fits at all centralities

# Extracting moments from data



- Good agreement between the BDMPS and the 'agnostic' estimates
- Larger uncertainties because of the 3 parameters

# Summary

- **Simple energy loss model revisited** in light of the recent LHC data
- Measured  $R_{AA}$  exhibit a universal shape (scaling)
  - ▶ at different centralities and at both energies
  - ▶ D and  $J/\psi$  follow the same behavior
  - ▶ scaling violations below  $p_{\perp} \lesssim 10$  GeV
- Energy loss scales extracted for all centralities
  - ▶ **10%–20% increase** from 2.76 to 5 TeV
- **Data-driven procedure to extract moments** of the quenching weight
  - ▶ results consistent with estimates from the BDMPS model
- Outlook
  - ▶ Adding 2018 PbPb data, including XeXe results
  - ▶ Relating the energy loss with particle multiplicity

[Arleo, Falmagne, in preparation]

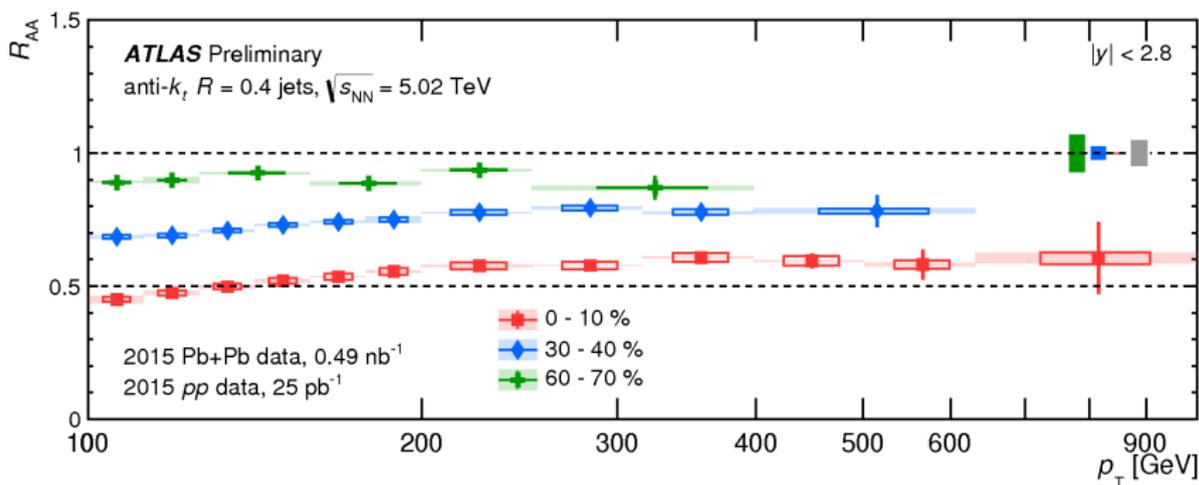
## What about jets ?

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

# What about jets ?

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## 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 !**

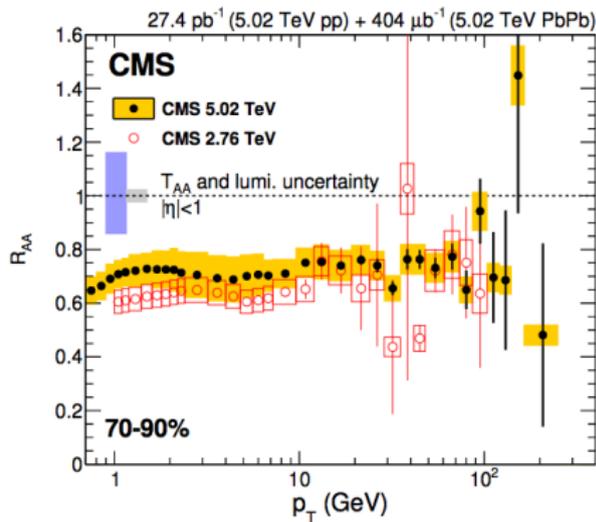
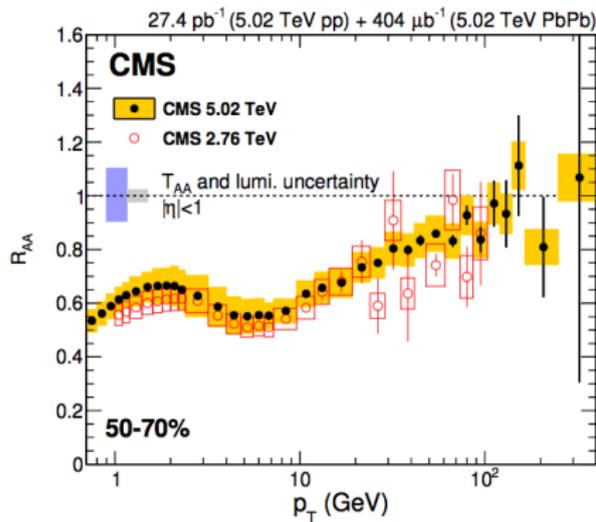
## Bias in the measurement

- 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 ?

# Peripheral collisions



- Probably due to a bias in the selection of peripheral events, producing ‘apparent’ suppression

[Loizides Morsch 2017]