Quenching of hadron spectra in heavy ion collisions at the LHC

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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 $p_\perp$

1. Why hadron quenching ?

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

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 $p_\perp$

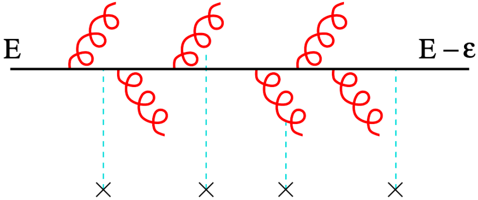
2. Why large transverse momentum ?

- 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

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



The model

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Hadronization

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

$$\frac{\mathrm{d}\sigma^{h}_{\mathrm{AA}}}{\mathrm{d}y\,\mathrm{d}p_\perp} = A^2 \sum_k \int_0^1 \mathrm{d}z\, D_k^h(z) \int_0^\infty \mathrm{d}\epsilon\, \frac{\mathrm{d}\hat{\sigma}^{k}_{\mathrm{pp}}(p_\perp/z + \epsilon/z)}{\mathrm{d}y\,\mathrm{d}p_\perp}\, \frac{1}{z}\, P_k(\epsilon/z)$$

- 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 swapping integrals

The model

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$$\frac{\mathrm{d}\sigma^{h}_{\mathrm{AA}}}{\mathrm{d}y\,\mathrm{d}p_{\perp}} = A^2 \int_0^{\infty} \mathrm{d}\epsilon\ \frac{\mathrm{d}\sigma^{h}_{\mathrm{pp}}(p_{\perp} + \langle z \rangle \epsilon)}{\mathrm{d}y\,\mathrm{d}p_{\perp}}\ P_i(\epsilon)$$

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 $\bar{\omega}_c \equiv \langle z \rangle\,\omega_c$

The model

Take the simplest energy loss model for production of particle i

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

pp production cross section

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

$$\frac{\mathrm{d}\sigma^i_{\mathrm{pp}}}{\mathrm{d}y\,\mathrm{d}p_\perp} \propto p_\perp^{-n}$$

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

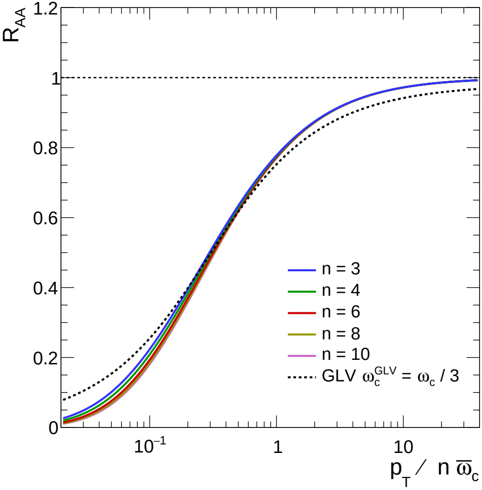
Nuclear modification factor R_{AA}

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

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

Nuclear modification factor R_{AA}

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



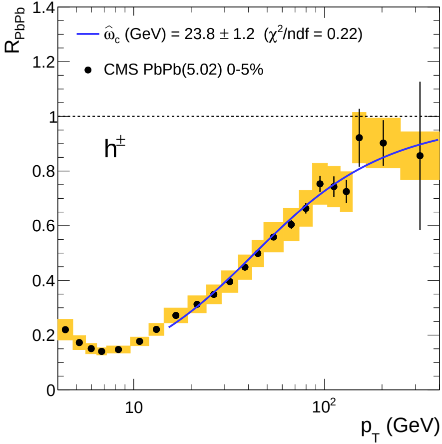
- R_{AA} unique … known
  - determi…
- Approximat…
- **Universal s…** … ion energies, hadron spec…

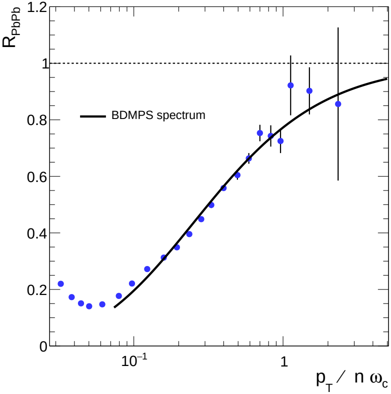
Strategy

- 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

Scaling

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





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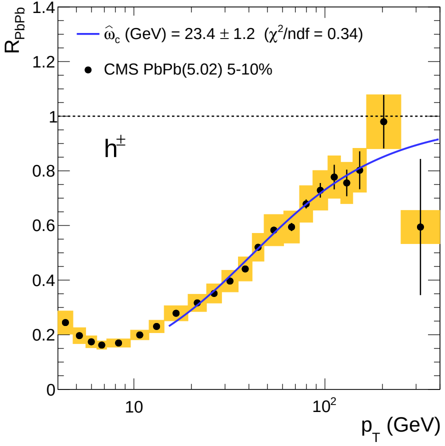

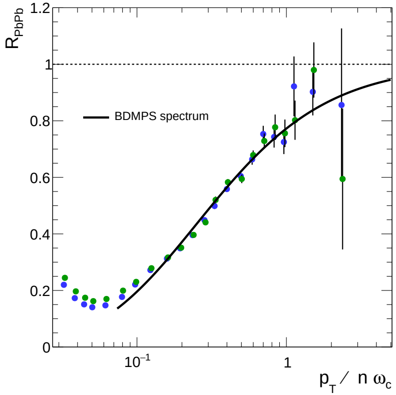

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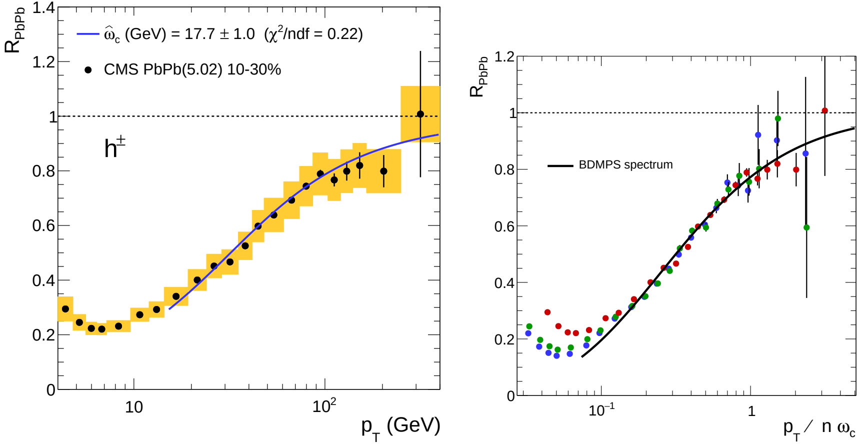

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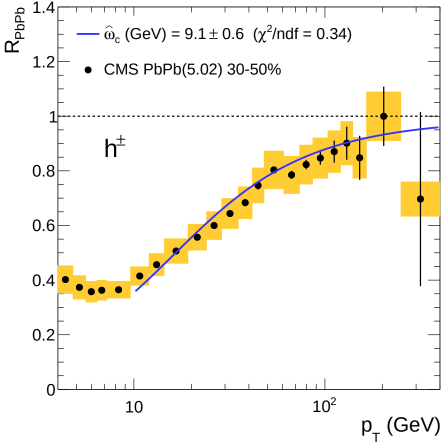

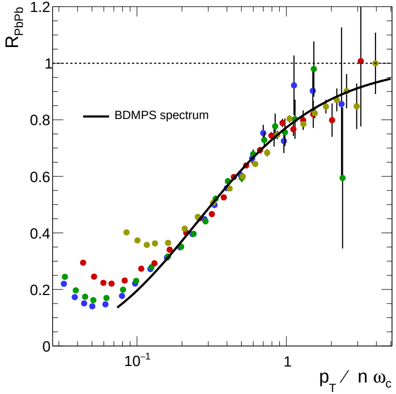

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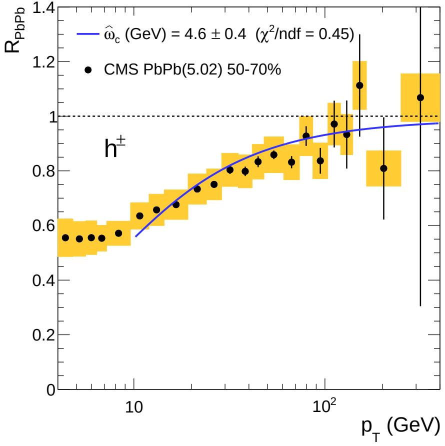

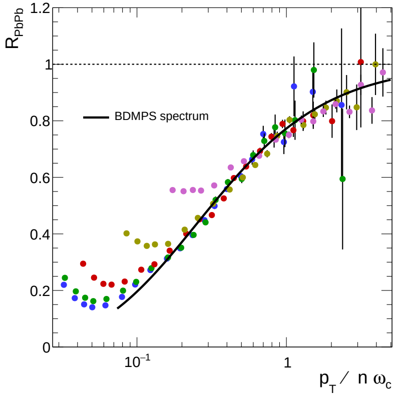

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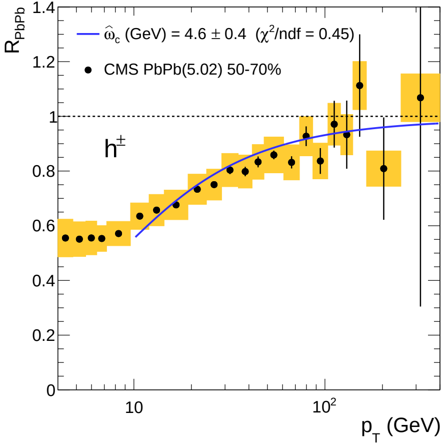
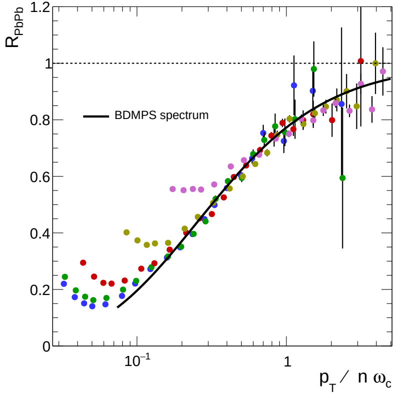
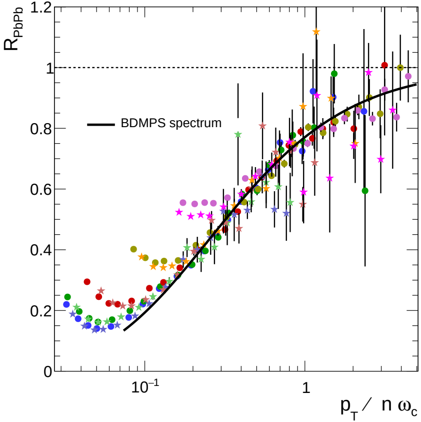




...now adding PbPb CMS data at $\sqrt{s} = 2.76$ TeV

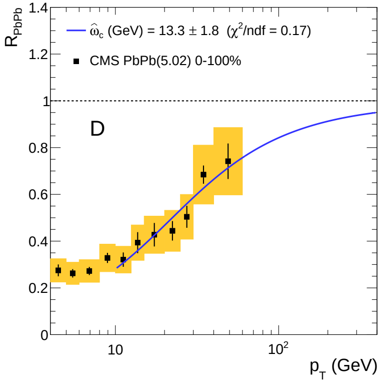
Scaling

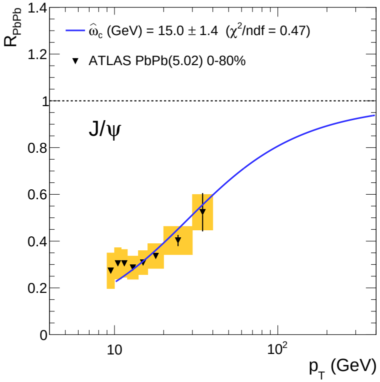


- Predicted scaling nicely observed at 2 energies and in 5 centrality bins
- Shape of R_{AA} consistent with BDMPS model (χ^2/ndf $\simeq 1$)
- Scaling violations at low $p_\perp \lesssim 10$ GeV (other process at work ?)
- Most peripheral data do not follow the systematics

Heavy hadrons into the game

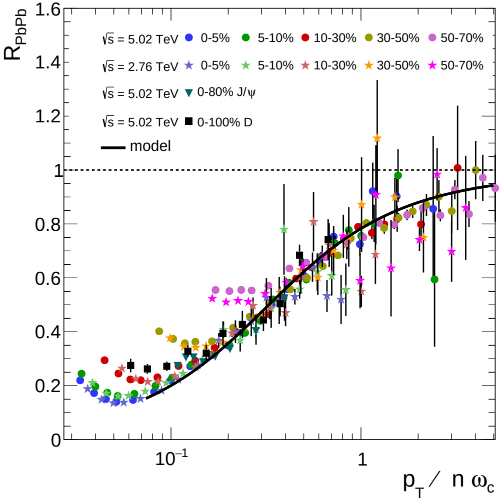
At large $p_\perp \gg M$, production of heavy hadrons (D/B, heavy quarkonia) should also proceed from the collinear fragmentation of a single parton





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

Heavy hadrons into the game



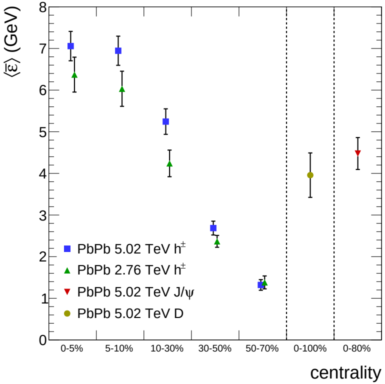
- Energy loss possibly only process relevant for J/ψ with $p_\perp \gtrsim 10$ GeV
  - maybe not for excited states ?

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 pQCD indicates $\langle z \rangle \simeq 0.5$ for $h^{\pm}$, larger for D & J/ψ
  - 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 $\langle\bar{\epsilon}\rangle \simeq 7$ GeV to 1 GeV, from central to peripheral
- $\langle\bar{\epsilon}\rangle \simeq$ 4–5 GeV from D & J/ψ in min bias 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
- Taylor expansion of the pp production cross section in $\epsilon/p_\perp$ leads to

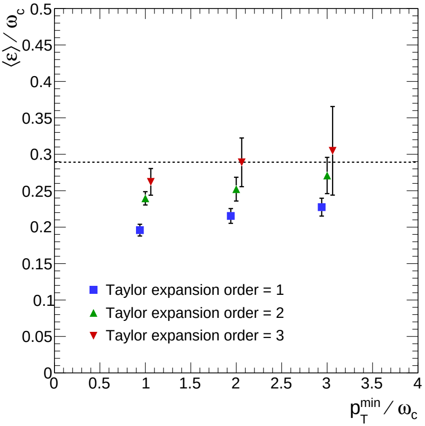
$$R_{\mathrm{AA}}(p_\perp) = 1 - n\frac{\langle\epsilon\rangle}{p_\perp} + \frac{n\,(n+1)}{2}\,\frac{\langle\epsilon^2\rangle}{p_\perp^2} + \ldots$$

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

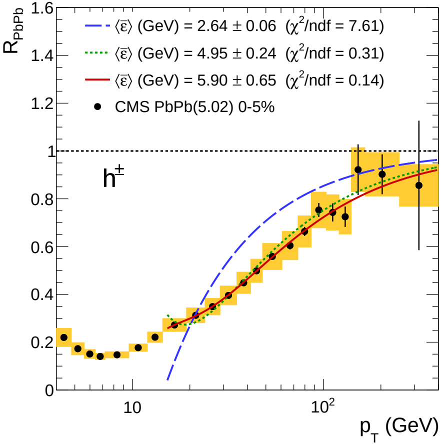
Extracting first moment



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

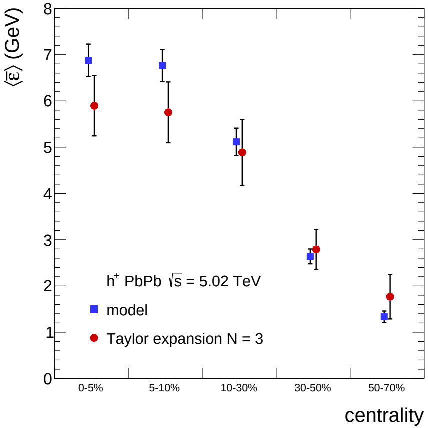
Extracting moments from data

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/ψ 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

Viens voir les physiciens

Charles Aznavour (1924-2018)

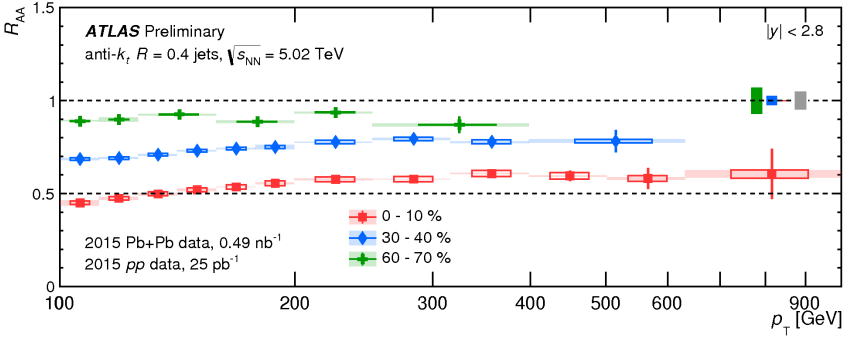
Thanks for your attention (and thank you Charles!)

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 $R_{\rm AA}$ 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 ?

Peripheral collisions