Parton energy loss and charmonia suppression in heavy ion collisions

Martin Spousta

Charles University
Prague

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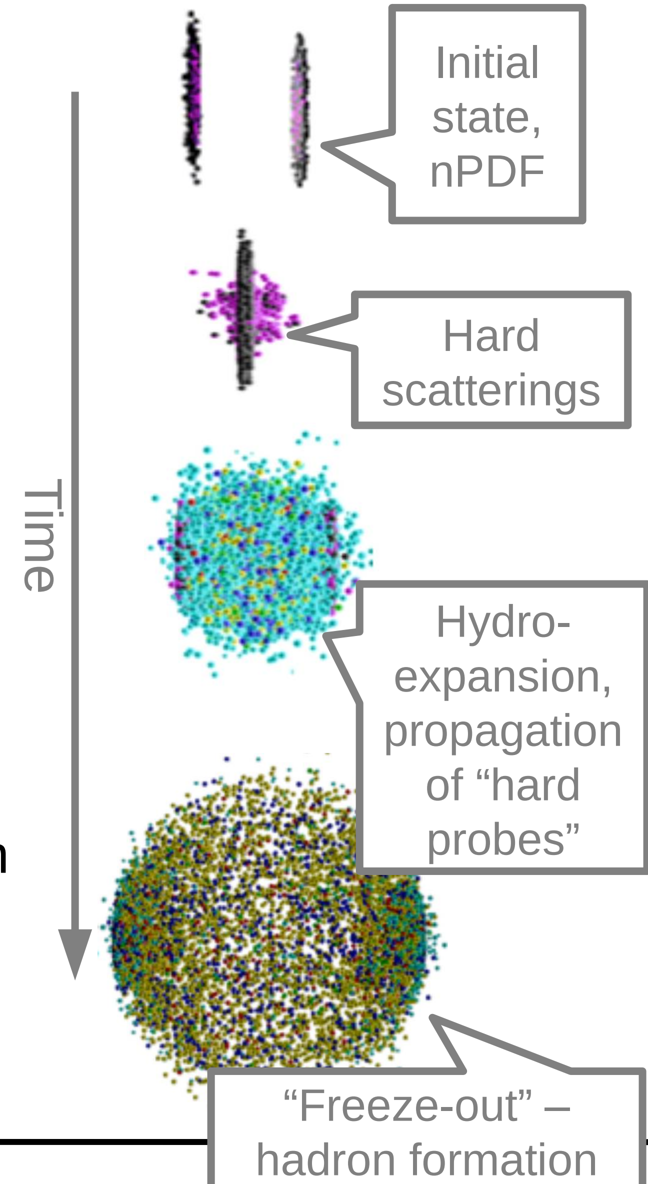
Introduction

Hot and dense **deconfined matter** is created in heavy ion collisions, called quark-gluon plasma (QGP). This matter allows to:

- Study **non-perturbative** aspects of QCD and **collective phenomena** connected with the strong interaction.
- Study the **phase transition** between quarks and gluons and hadrons.
- Study matter which is similar to the matter present in the **early stages of the universe.**

Strong suppression of jet and quarkonia production seen in heavy ion collisions. A lot of models on the market, but **can we understand basic aspects of the suppression**?



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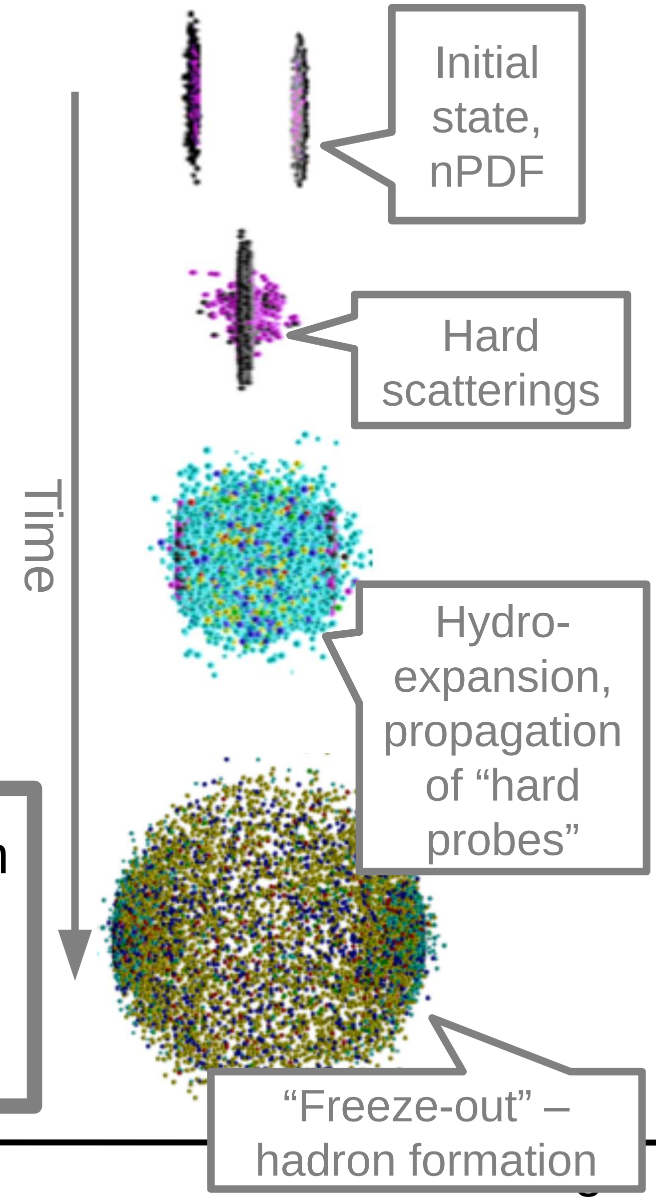


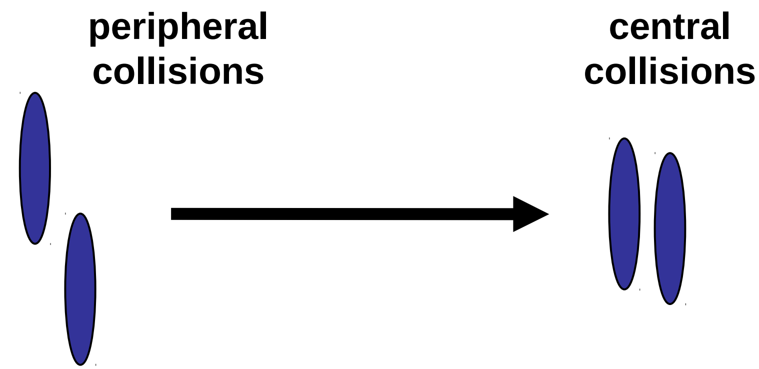
Strong suppression of jet and quarkonia production seen in heavy ion collisions. A lot of models on the market, but **can we understand basic aspects of the suppression**?

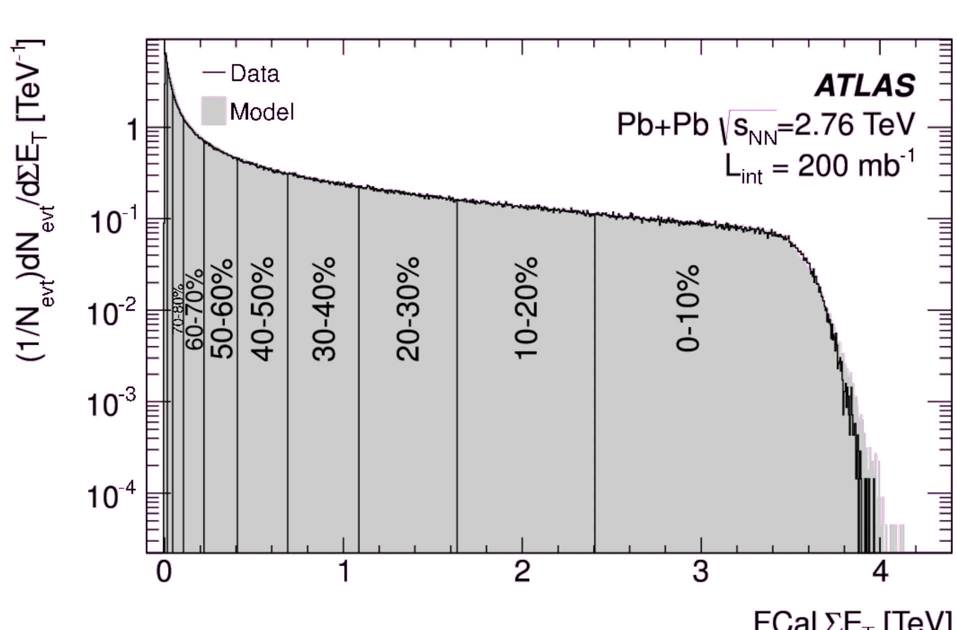
Warning

Strong suppression of jet and quarkonia production seen in heavy ion collisions. A lot of models on the market, but **can we understand basic aspects of the suppression**?

- This talk is neither an overview of theory status nor an exectutive summary of experimental measurement
- Goal: introduce basic features seen in the data + show one particular approach how to understand them
- Appropriate referencing in original publications:
  - M.S. and Brian Cole, **Interpreting single jet measurements** in Pb+Pb collisions at the LHC, **Eur. Phys. J. C76 (2016) no.2, 50**
  - M.S., On similarity of jet quenching and **charmonia suppression**, **Phys. Lett. B767 (2017) 10**

- Quantifies the **degree of overlap** of two colliding nuclei.
- More central collisions – higher deposited energy.
- Quantified typically by a measurement of signal in forward detectors.





Inclusive jet suppression in Pb+Pb collisions

$$R_{AA} = \frac{\left.\frac{1}{N_{\mathrm{evnt}}}\frac{\mathrm{d}^2 N_{\mathrm{jet}}^{PbPb}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right|_{\mathrm{cent}}}{\langle T_{\mathrm{AA}}\rangle_{\mathrm{cent}} \times \frac{\mathrm{d}^2\sigma_{\mathrm{jet}}^{pp}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}$$

Jet yield in heavy ion collisions

Mean nuclear tickness fuction

Jet cross-section in *pp* collisions

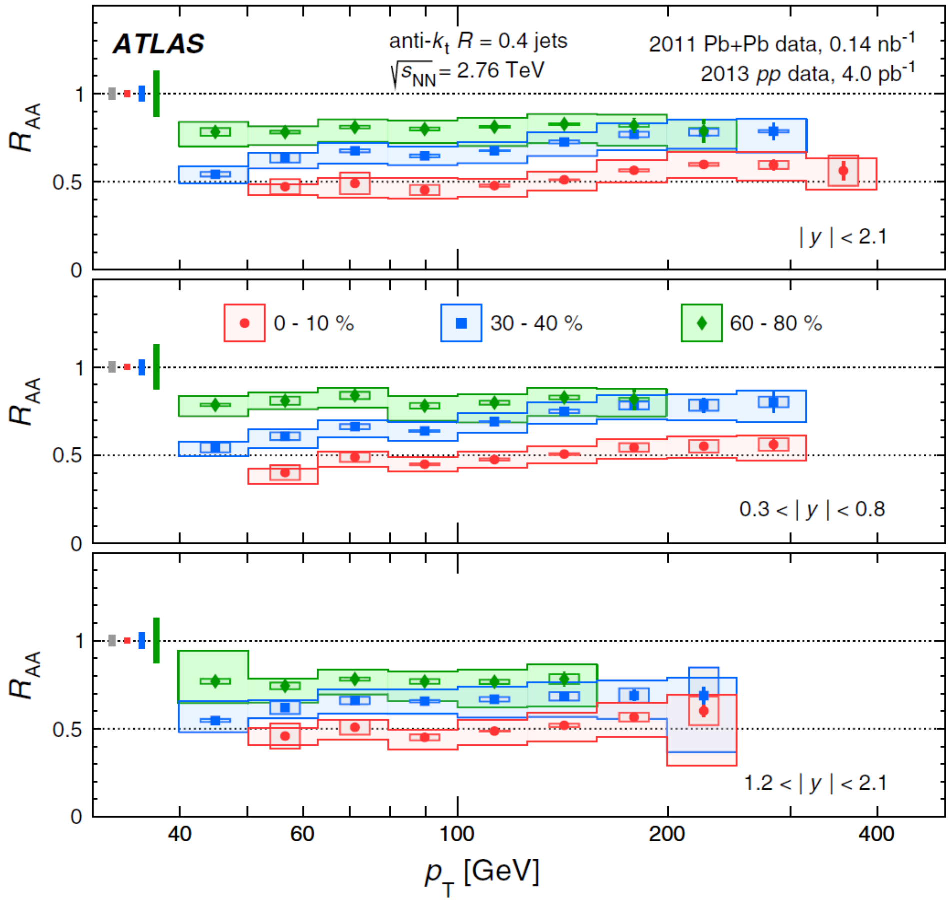
Expected jet yield in the case of no quenching

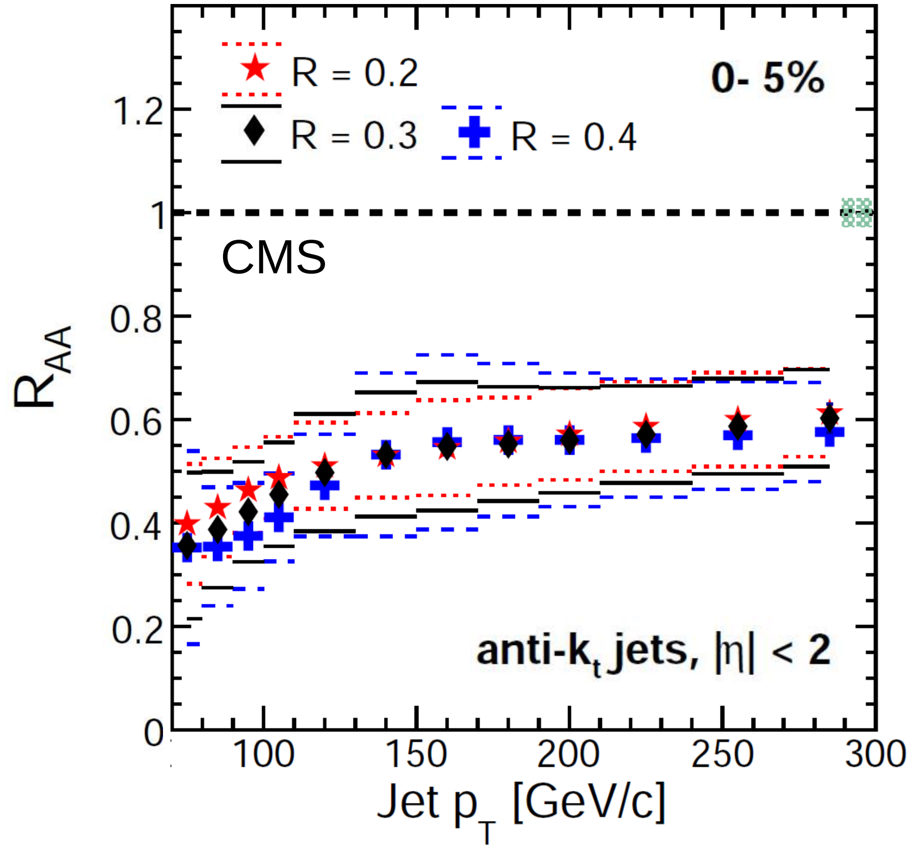
- R_{AA} … nuclear modification factor
- If heavy ion collision was a simple superposition of proton-proton collisions, then $R_{AA} = 1$

Inclusive jet R_{AA}

PRL 114 (2015) 072302

PRC 96 (2017) 015202





Strong jet quenching … suppression **by a factor of two**!

How does the QCD mechanism (~ in-medium gluon radiation) leads to a disappearance of "half of jets"?

Inclusive jet R_{AA}

PRL 114 (2015) 072302

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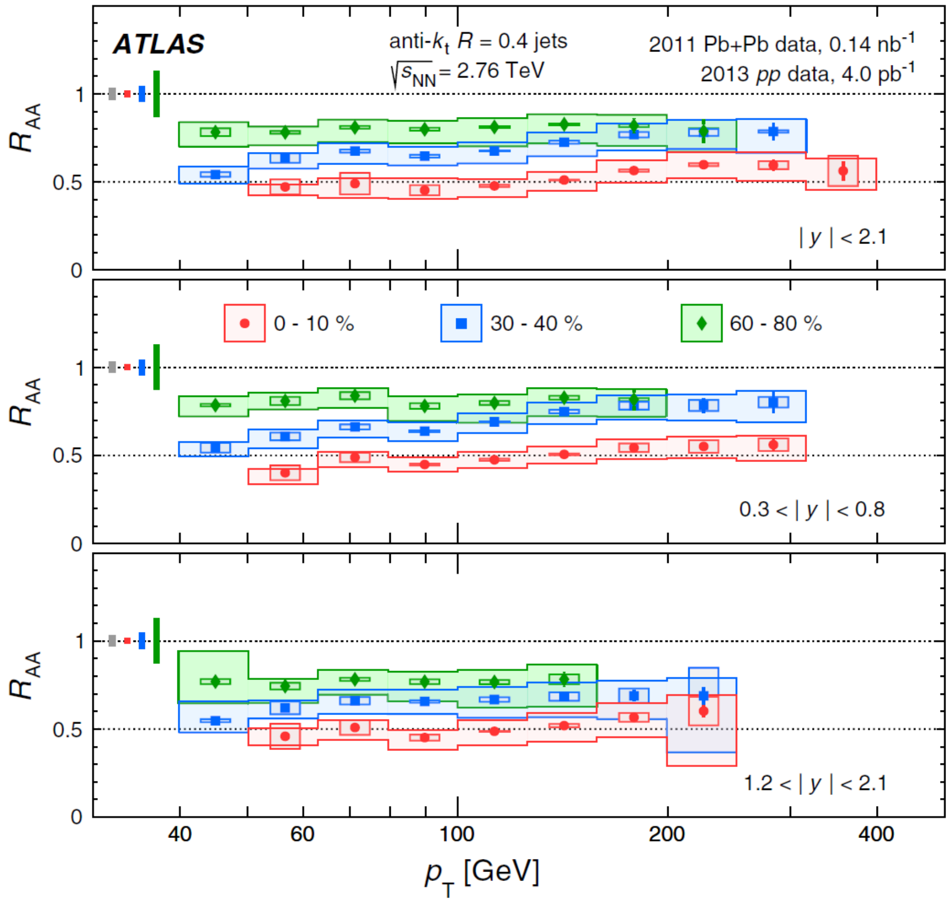
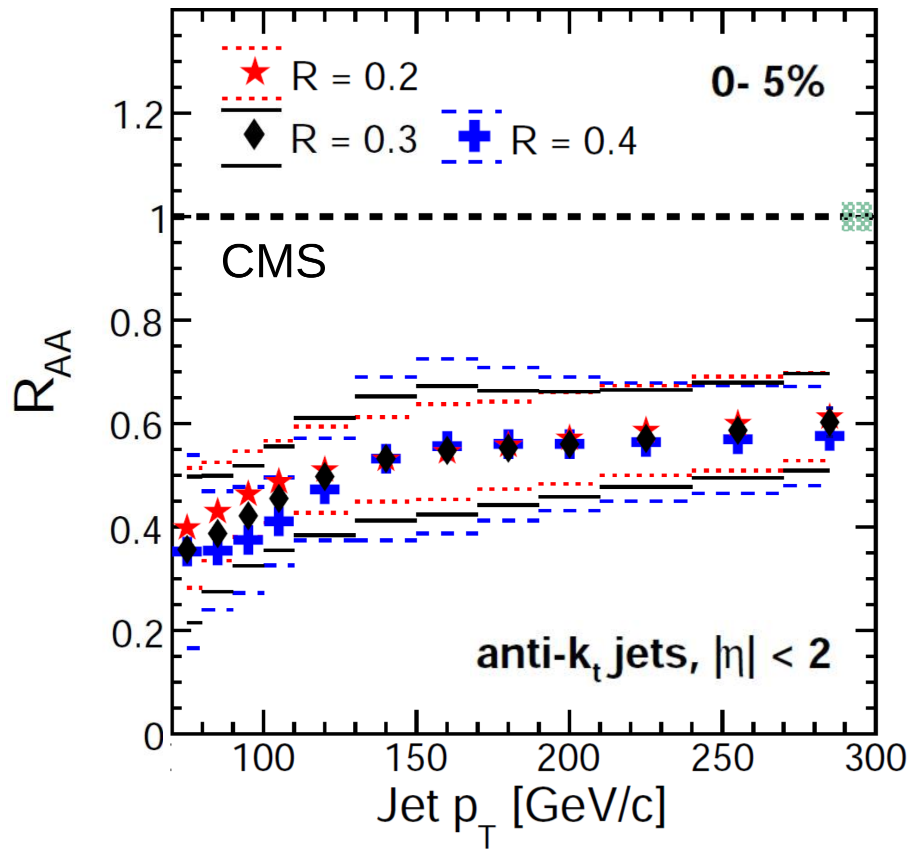
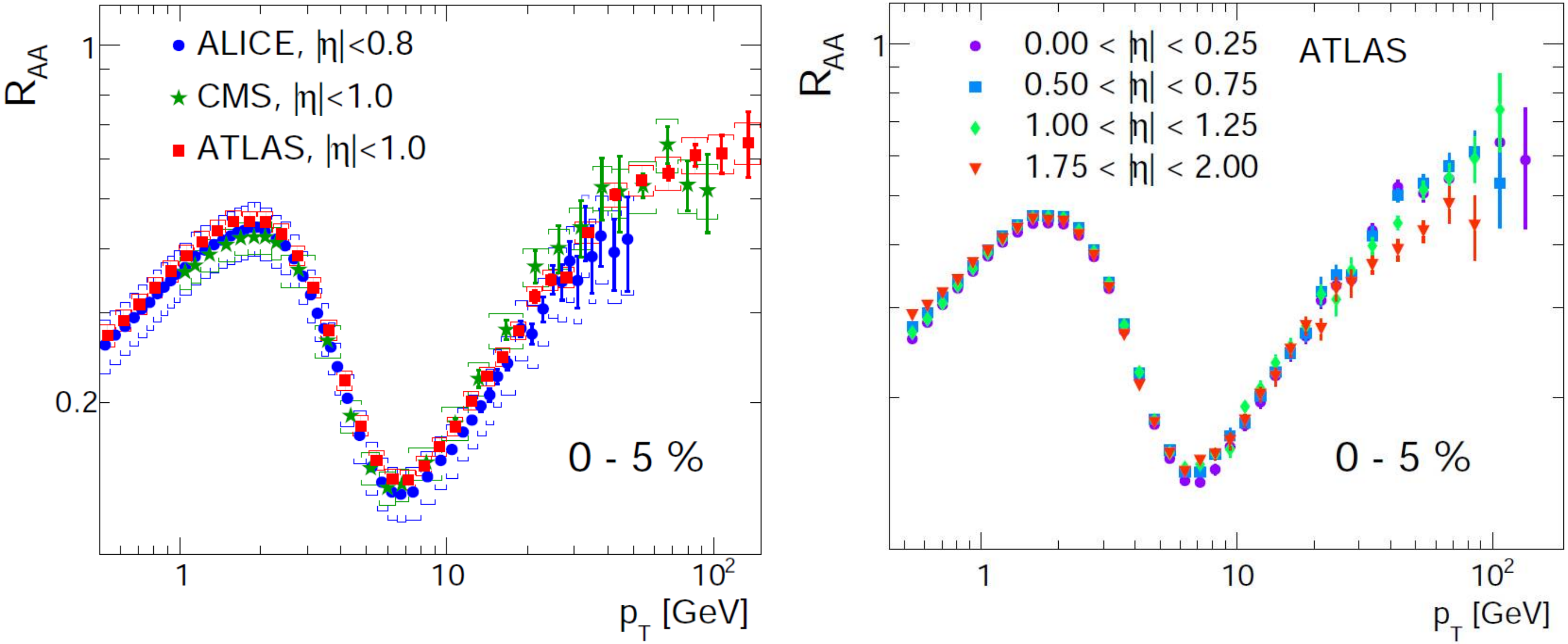




Features:

1) only modest (if any) rise with increasing jet p_T,
2) almost no rapidity dependence

Charged particle R_{AA}



… now inclusive charged particles ...

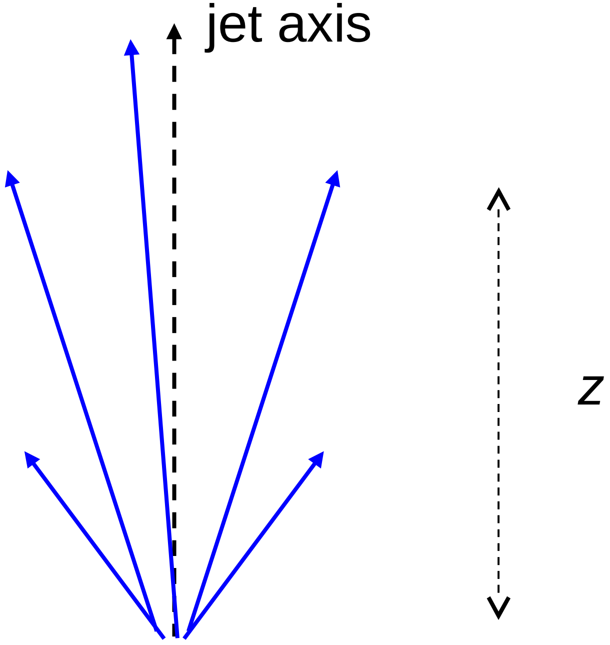
EPJC 72 (2012) 1945
PLB 720 (2013) 52
JHEP09 (2015) 050

Features:

1) steep increase for p_T>10 GeV,
2) almost no rapidity dependence

Charged particles in jets

… quantified by measuring fragmentation functions



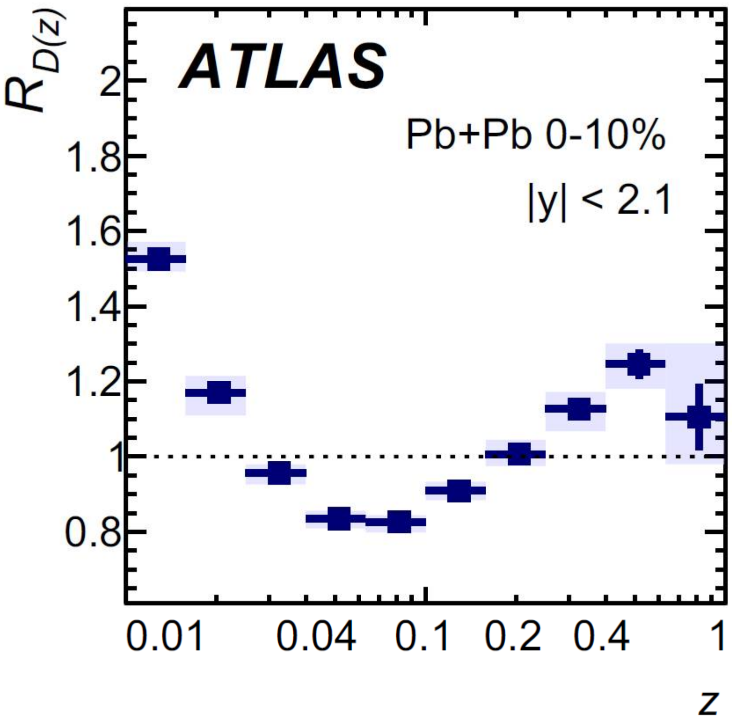
$$z = \frac{p_{\mathrm{T}}}{p_{\mathrm{T}}^{jet}} \cos \Delta R$$

$$D(z) = \frac{1}{N_{jet}} \frac{\mathrm{d}N}{\mathrm{d}z}$$

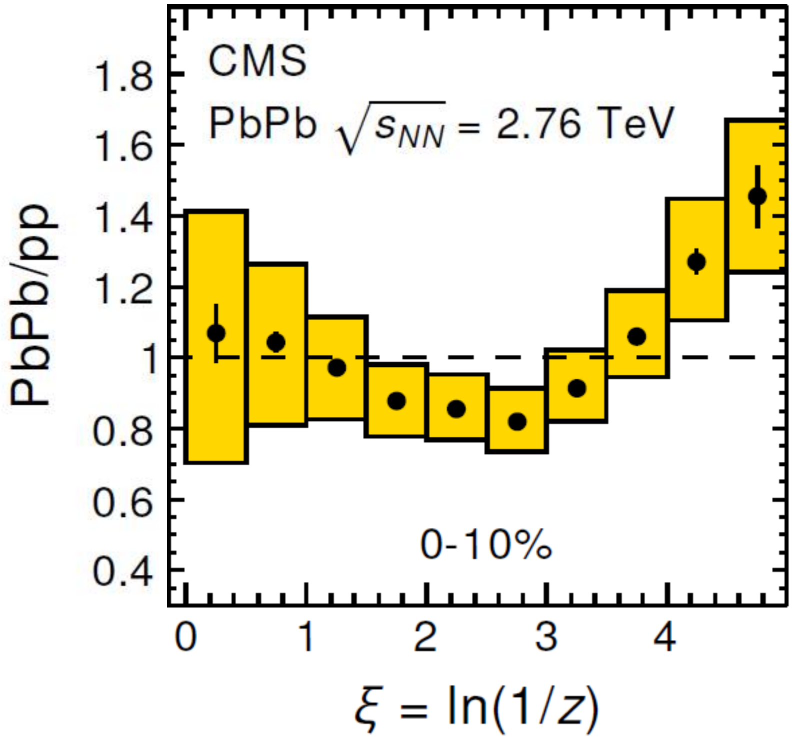
$$R_{D(z)} = \frac{D(z)|_{\mathrm{cent}}}{D(z)|_{pp}}$$

Charged particles in jets

PLB 739 (2014) 320
EPJC 77 (2017) no.6, 379



PRC 90 (2014) 024908

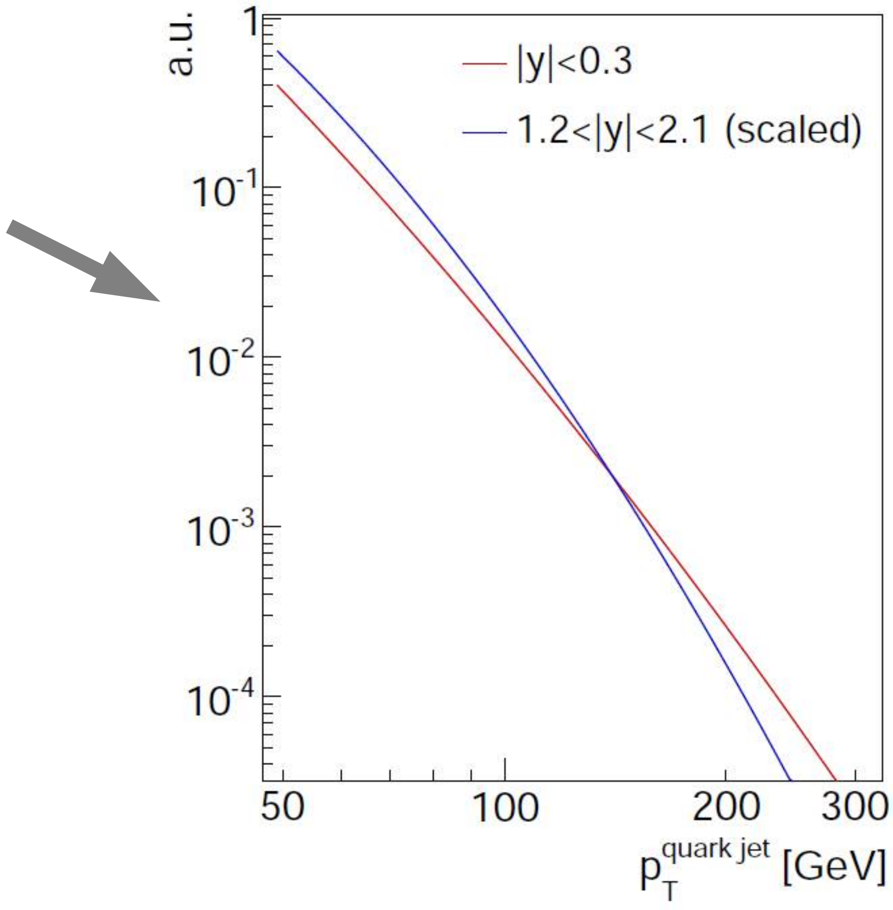


Features:

1) enhancement of soft particles, depletion at intermediate ξ (or *z*)
2) enhancement at high *z* (low ξ)

Jets and charged particles – some basic questions

- Why see **no rapidity dependence** in R_{AA} given quite different initial parton spectra and flavor composition at different rapidities?
- What is responsible for the **enhancement at high *z*** seen in the fragmentation?
- Can we find **connection among** charged particle R_{AA}, jet R_{AA} and jet fragmentation?



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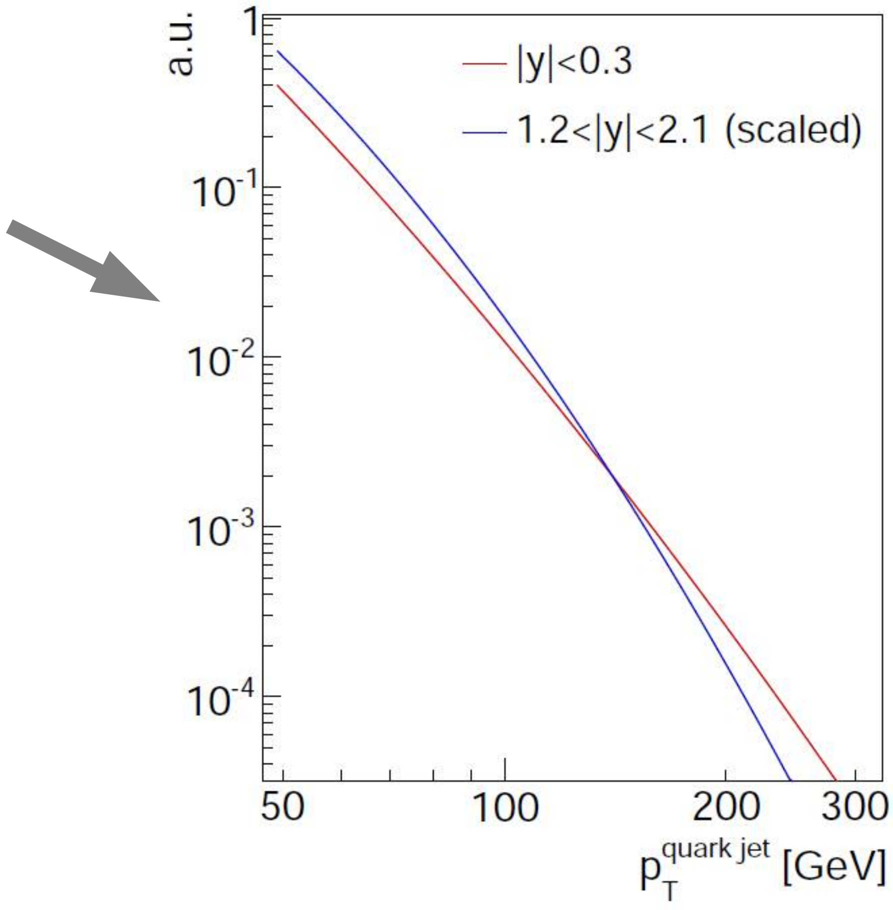


–> Use a simple model with **minimal assumptions** on the quenching physics to extract basic properties of the jet quenching

Effective quenching model: simple approach

$$\frac{dN}{dp_{\mathrm{T}}^{\mathrm{jet}}} = A\left[f_{q0}\left(\frac{p_{T0}}{p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{n_q} + (1-f_{q0})\left(\frac{p_{T0}}{p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{n_g}\right]$$

Jet spectra parameterized by a power law

Fraction of jets of a given flavor (i.e. quark or gluon initiated)

$$f_q\left(p_{\mathrm{T}}^{\mathrm{jet}}\right) = \frac{1}{1+\left(\frac{1-f_{q0}}{f_{q0}}\right)\left(\frac{p_{T0}}{p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{n_g-n_q}}$$

Effective quenching model: simple approach

$$\frac{dn_{\mathrm{Q}}(p_{\mathrm{T}}^{\mathrm{jet}})}{dp_{\mathrm{T}}^{\mathrm{jet}}} = \frac{dn\left(p_{\mathrm{T}}^{\mathrm{jet}} + S(p_{\mathrm{T}}^{\mathrm{jet}})\right)}{dp_{\mathrm{T}}^{\mathrm{jet}}} \times \left(1 + \frac{dS}{dp_{\mathrm{T}}^{\mathrm{jet}}}\right)$$

Yield of quenched jets of a given flavor at given pt

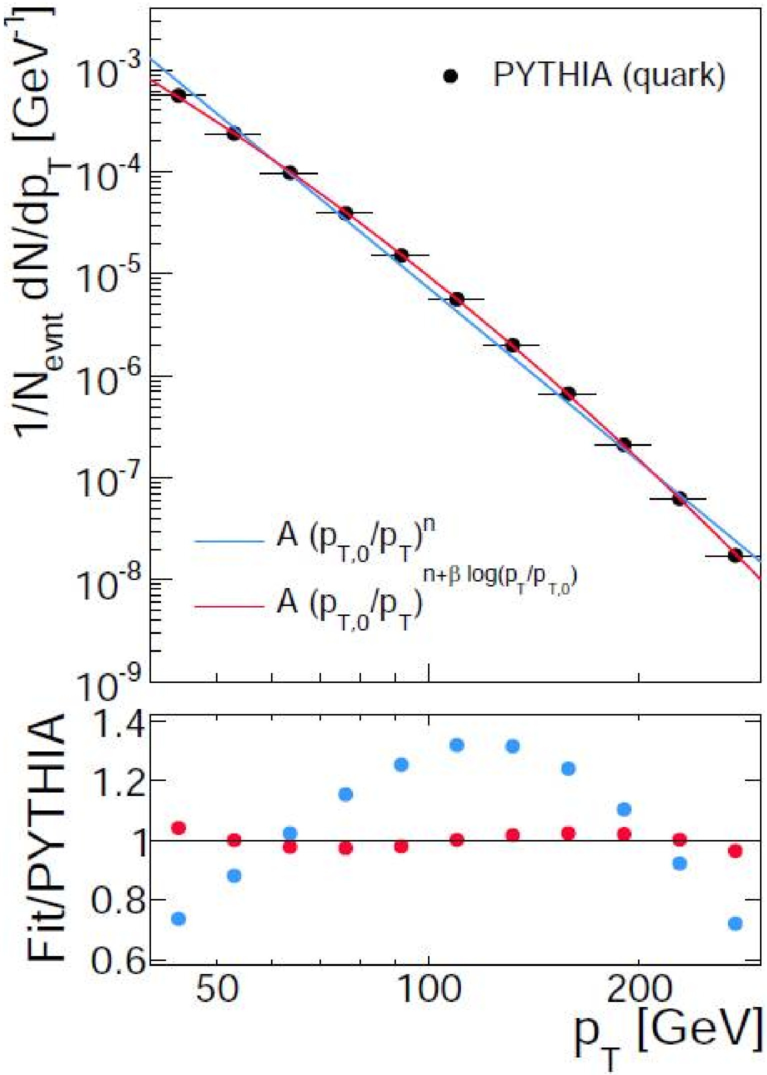
$$S_q \equiv s p_T$$
$$S_g = c_{\mathrm{F}} \times S_q$$

Fractional energy loss

R_{AA} in the approximation of fractional energy loss

$$R_{\mathrm{AA}} = f_q \left(\frac{1}{1 + S_q/p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{n_q} \times \left(1 + \frac{dS_q}{dp_T}\right) + (1 - f_q) \left(\frac{1}{1 + S_g/p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{n_g} \times \left(1 + \frac{dS_g}{dp_T}\right)$$

… a bit more precisely



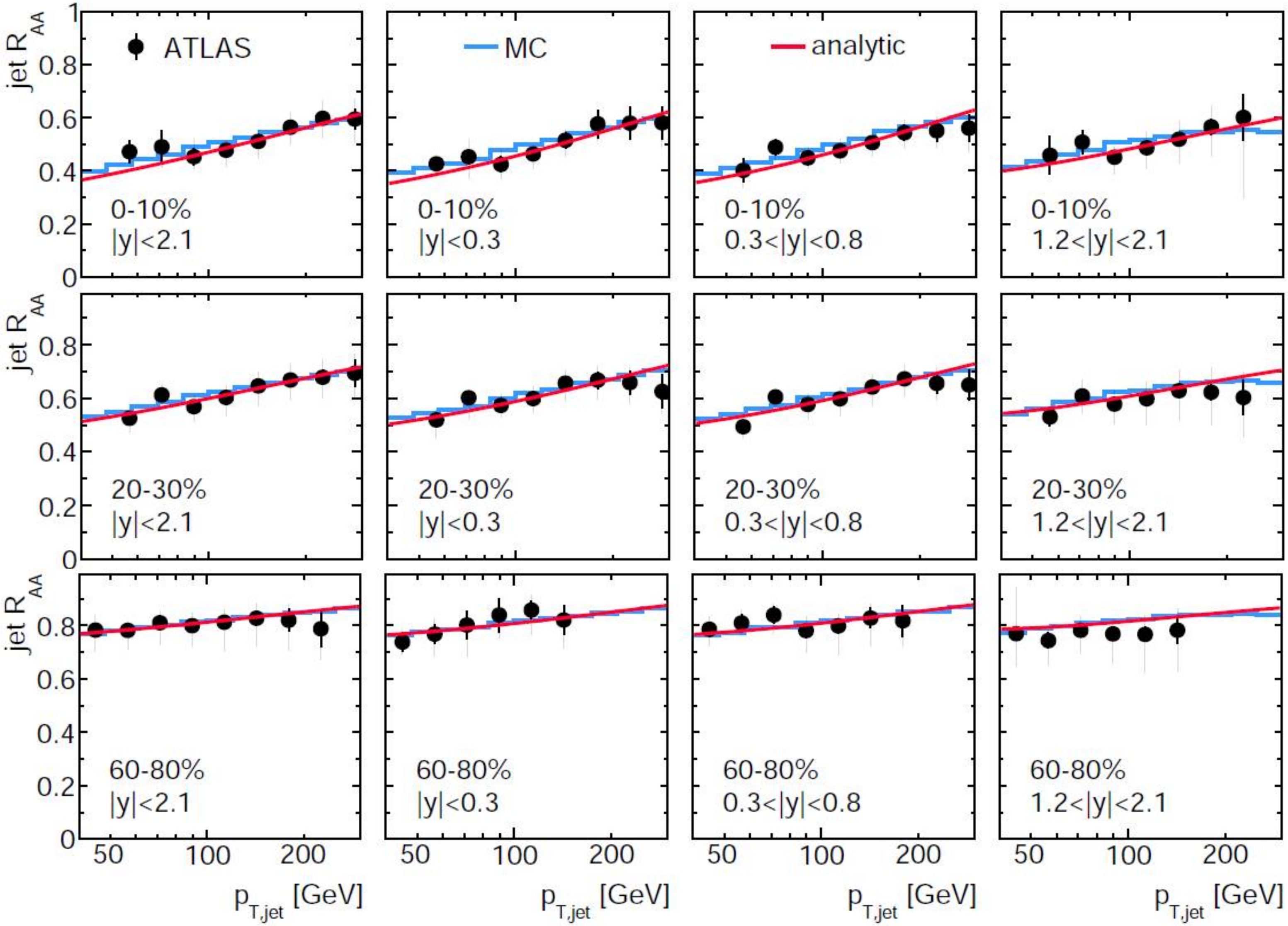
$$\frac{dn}{dp_{\mathrm{T}}^{\mathrm{jet}}} = A \left(\frac{p_{T0}}{p_{\mathrm{T}}^{\mathrm{jet}}} \right)^{n+\beta \log\left(p_T^{jet}/p_{T0}\right)}$$

More precise parameterization of input jet spectra

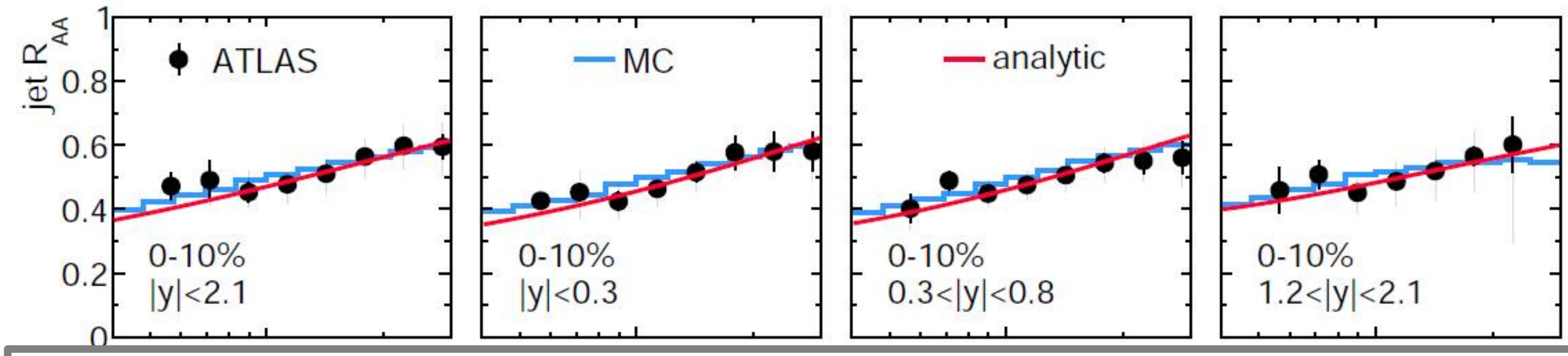
More general modeling of jet energy loss

$$S = s' \left(\frac{p_T^{\mathrm{jet}}}{p_{T0}} \right)^{\alpha}$$

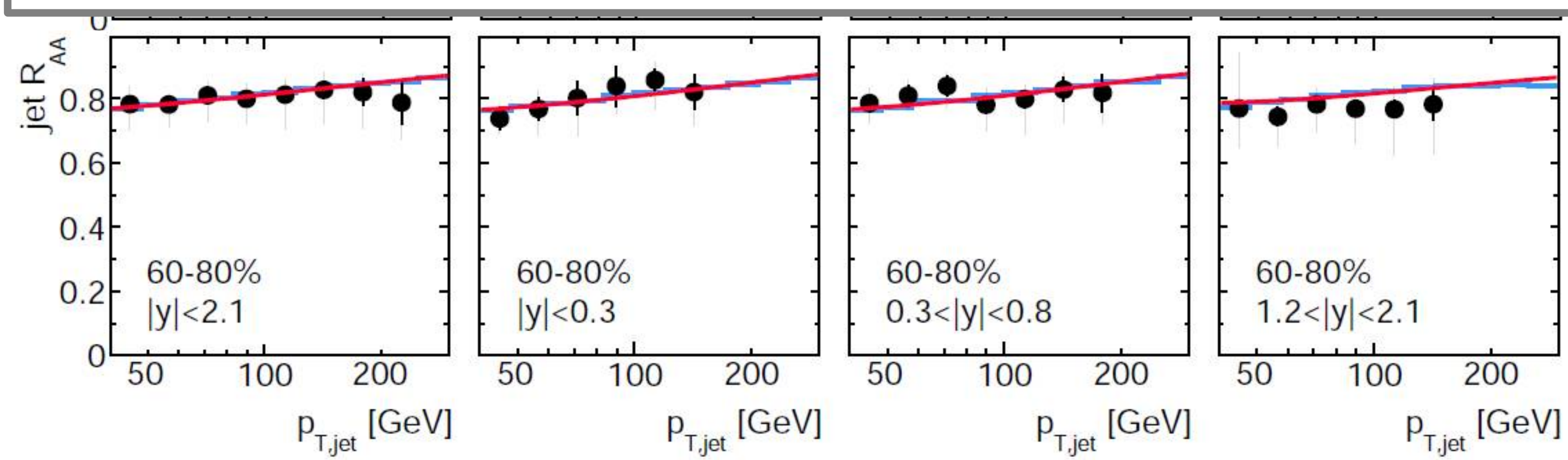
Jet R_{AA} in effective quenching model



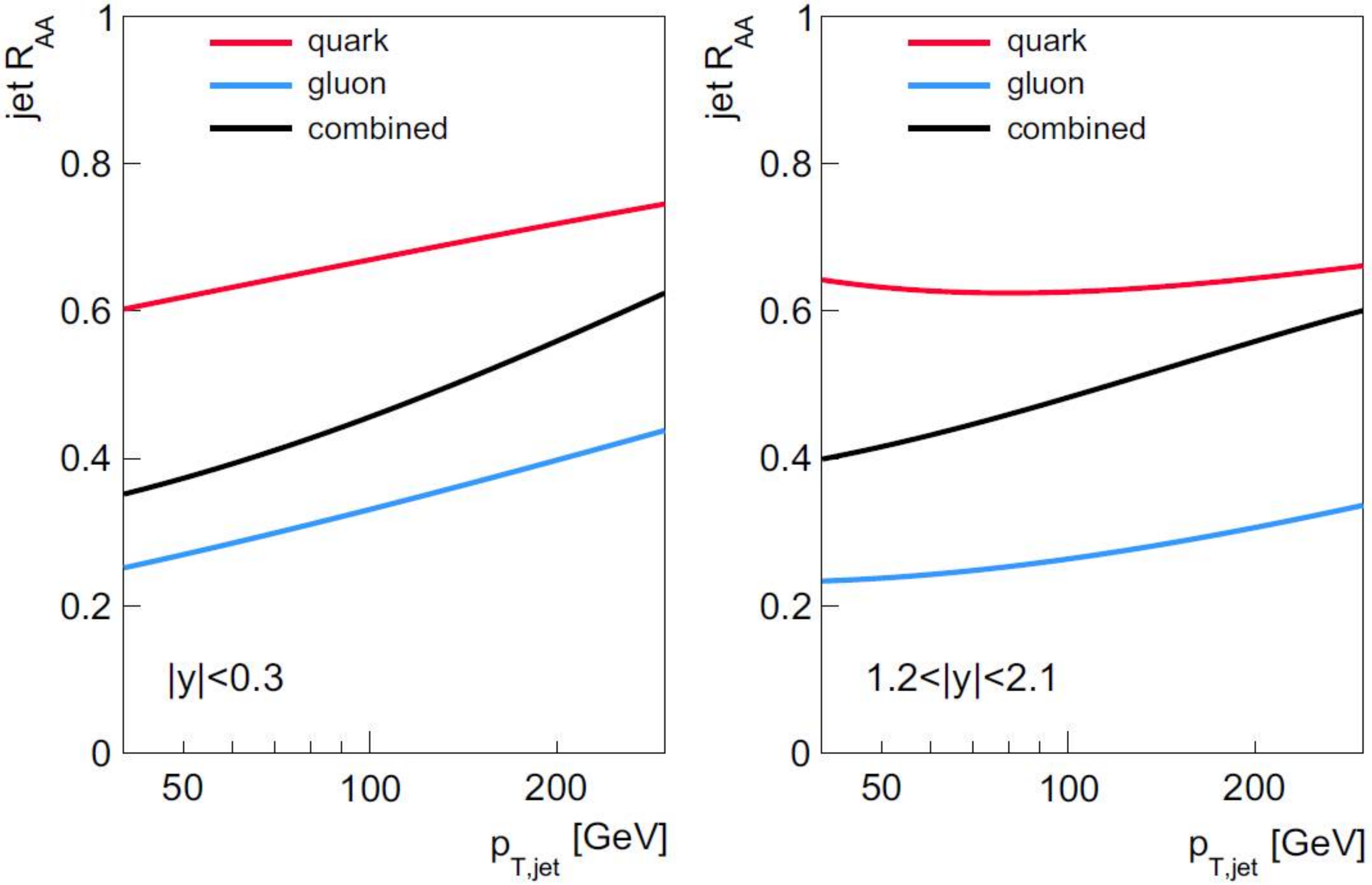
Jet R_{AA} in effective quenching model



–> Flatness and no rapidity dependence of jet R_{AA} can be explained as a consequence of different energy loss of quark and gluon initiated jets on top of steeply falling p_T spectra of initial partons



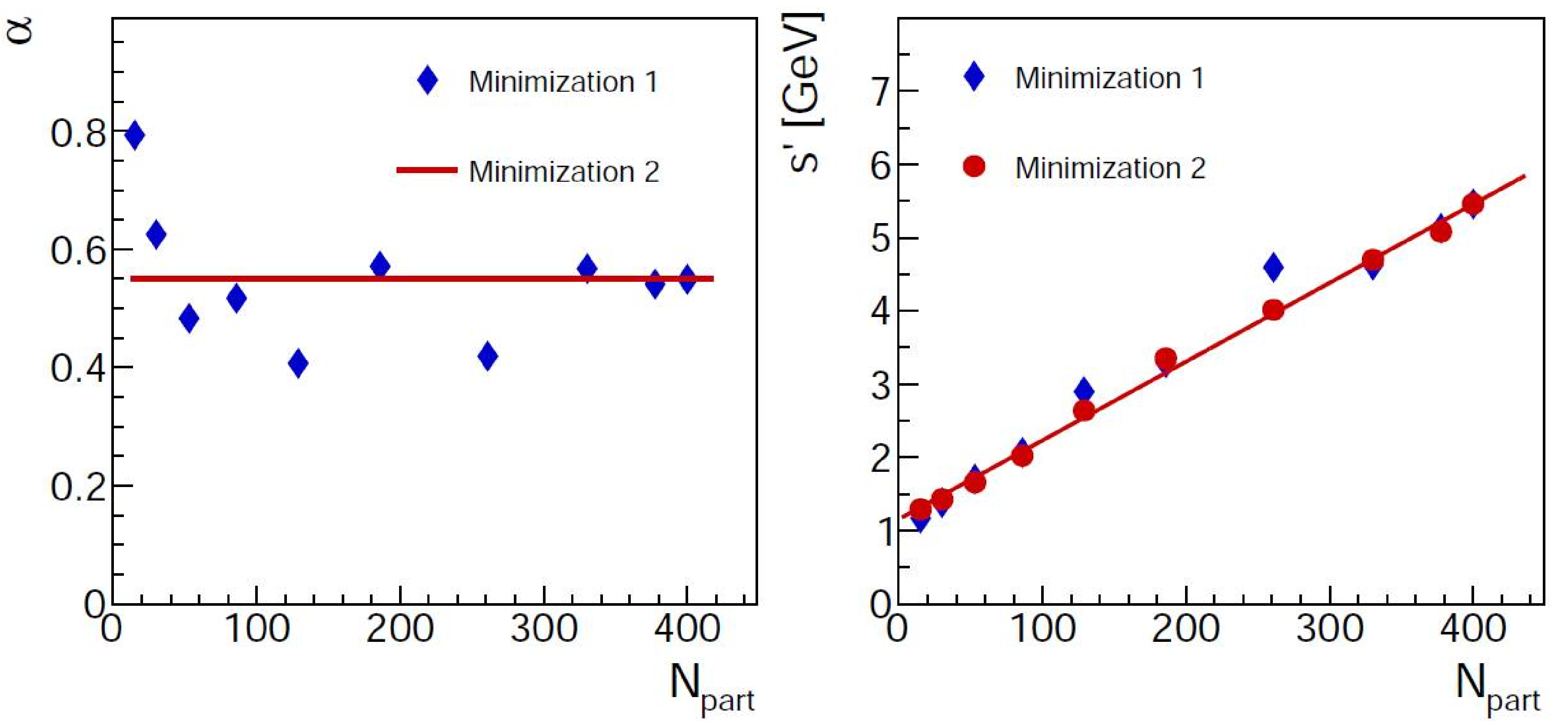
Jet R_{AA} in extended model



Quantifying the parton energy loss (I.)

$$S = s' \left(\frac{p_T^{\mathrm{jet}}}{p_{T0}} \right)^{\alpha}$$

Energy loss parameterized = encapsulated into two free parameters



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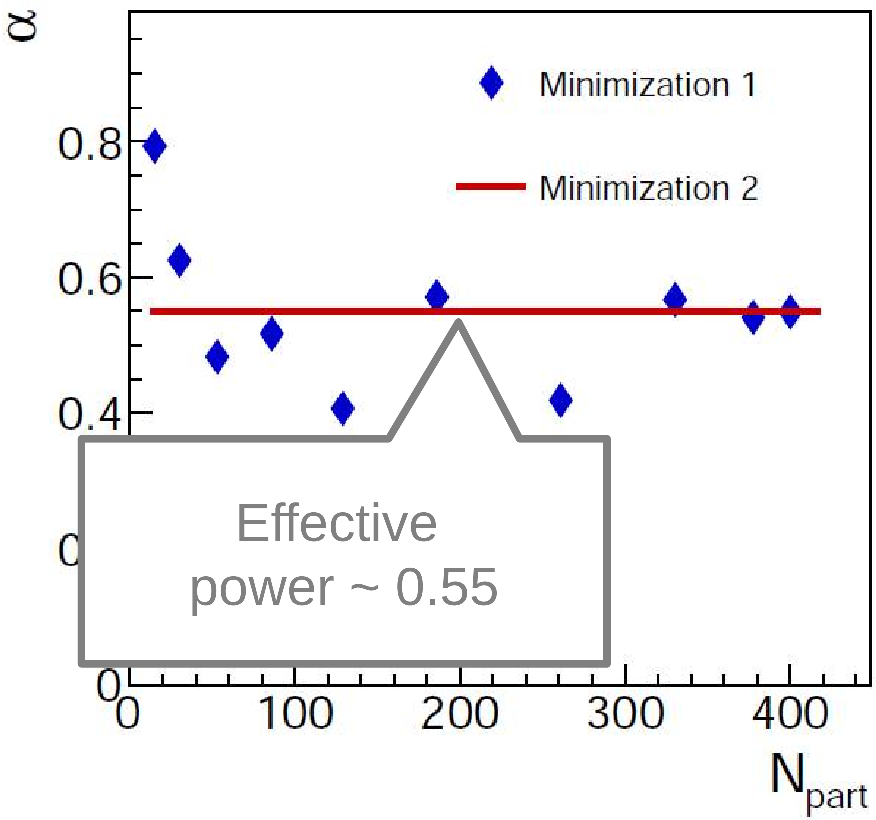
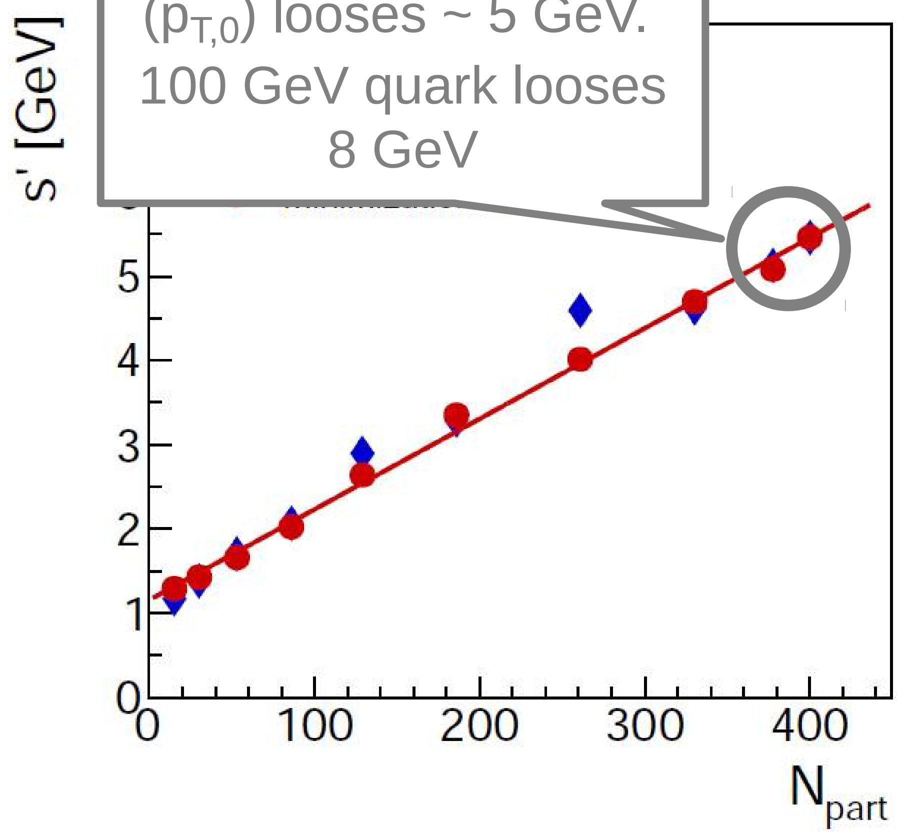
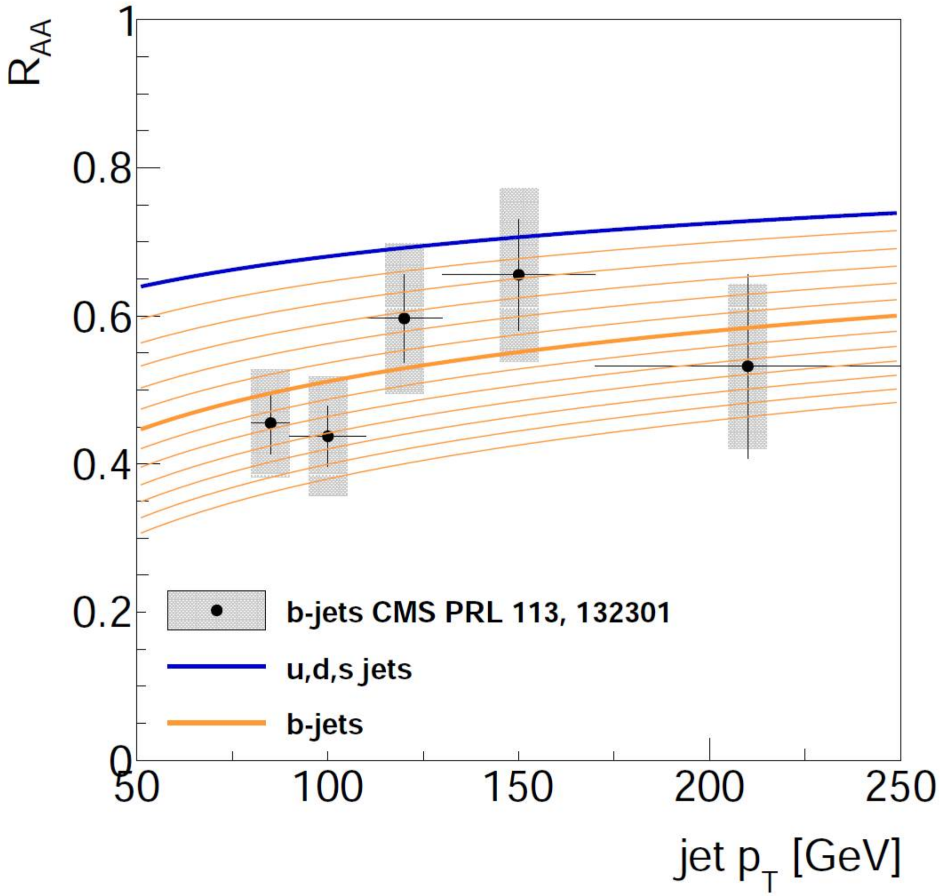


Effective power ~ 0.55



Quark with p_T=40 GeV ($p_{T,0}$) looses ~ 5 GeV. 100 GeV quark looses 8 GeV

b-jets suppression

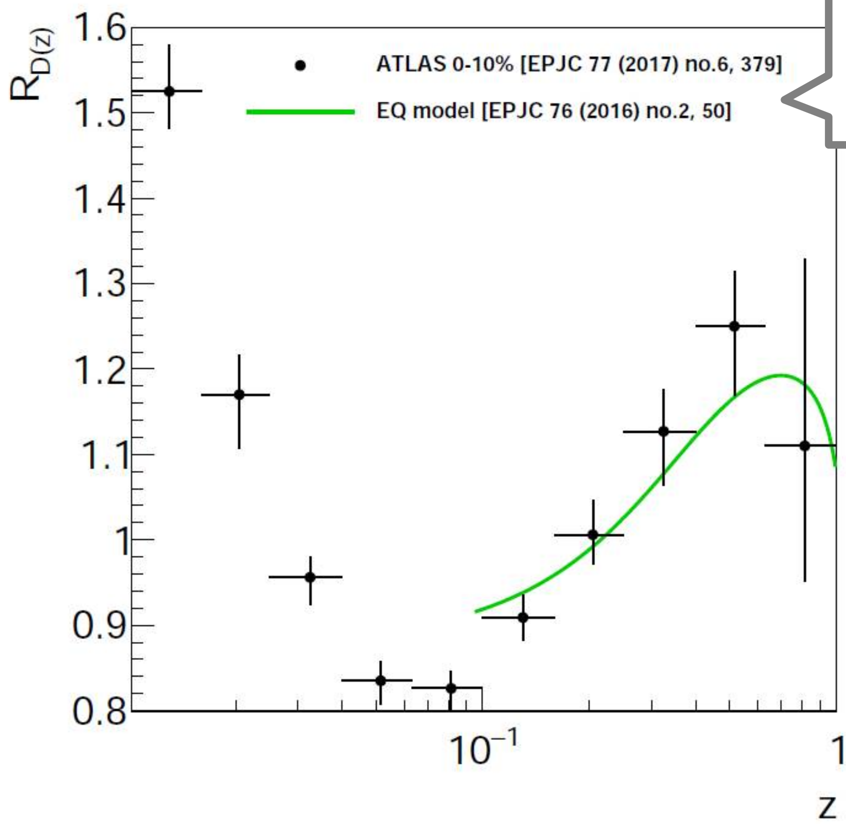


Realistic input b-jet spectra + quantification of E-loss for light-quark initiated jets … minimization wrt data

=> ***b*-jets are suppressed by 1.5±0.4 more** than light quark jets (role of gluon splitting included)
=> useful input for full theory calculations (?)

Modifications of fragmentation functions

–> Subtract the energy from the jet / initial parton and then let it fragment as in the vacuum (motivated by arguments of color coherent energy loss, e.g. PRL 106 (2011), PLB B725 (2013))



Pb+Pb to pp ratio of fragmentation functions

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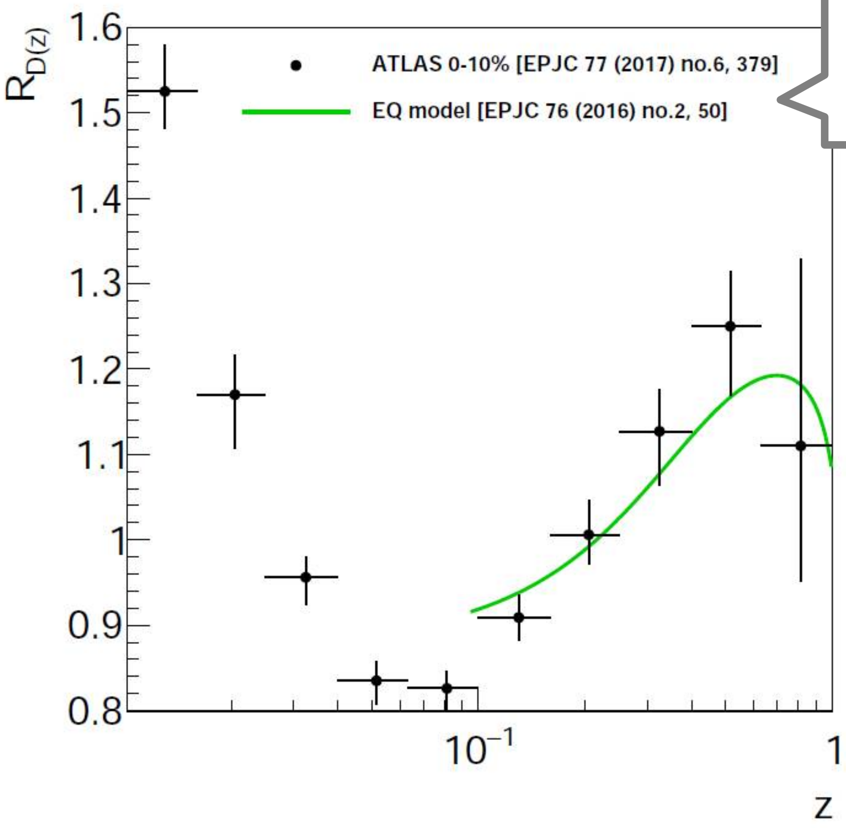
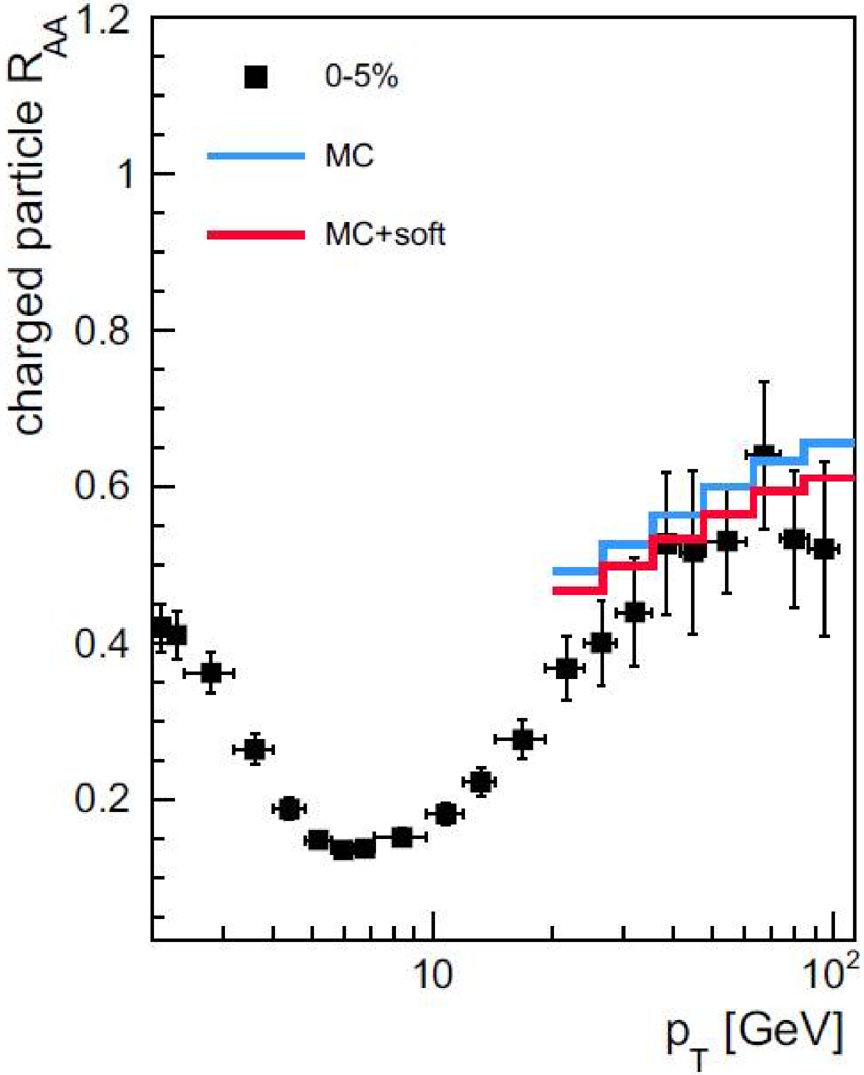


Pb+Pb to pp ratio of fragmentation functions

–> Structure seen at intermediate and high-z is due to the difference in quenching of quark and gluon initiated jets

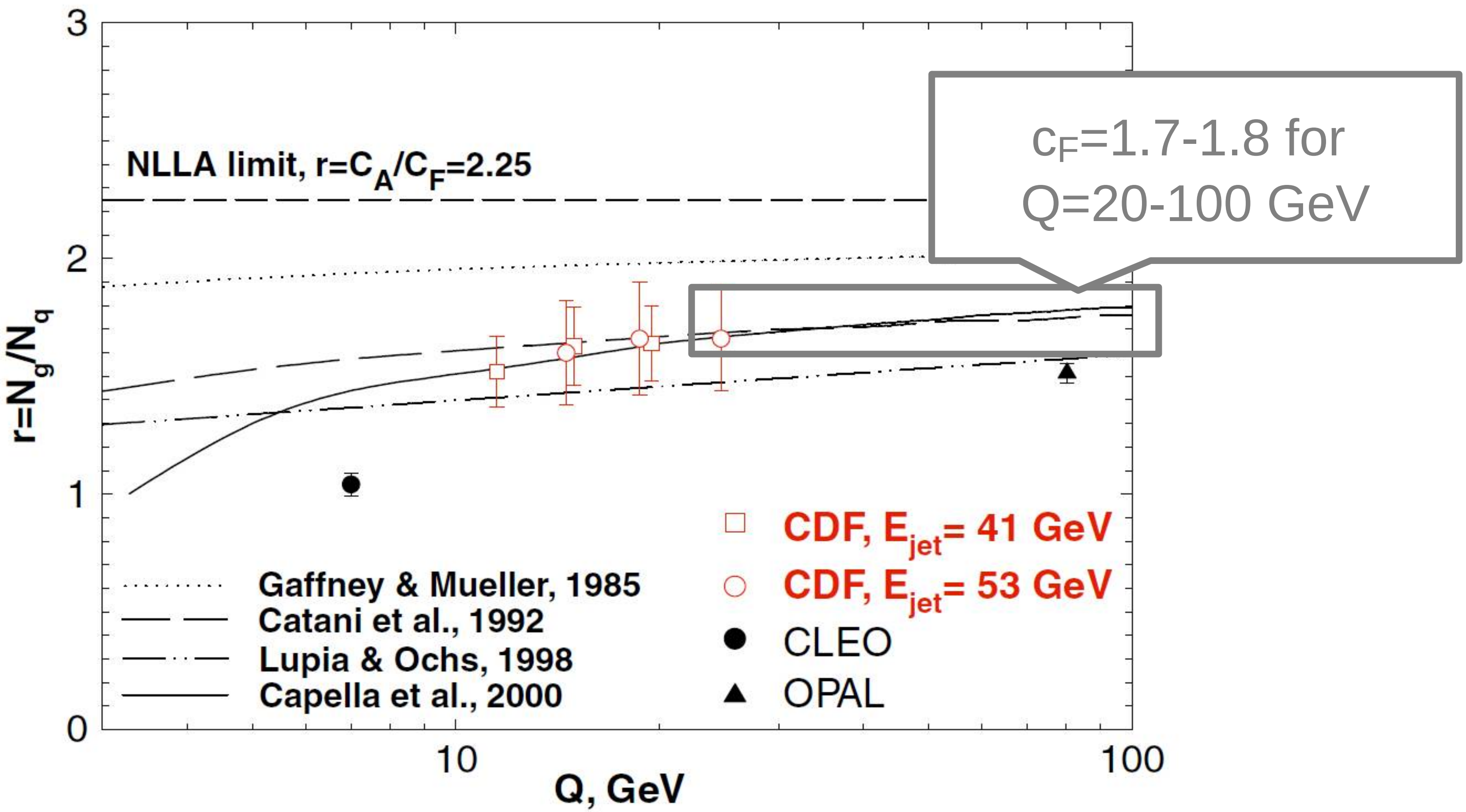
–> Direct verification of a presence of color coherence effects in the data

Charged particle R_{AA}?



- If one can reproduce jet R_{AA} and jet fragmentation one is automatically able to reproduce **charged particle R_{AA}**
- Below 20-30 GeV, the agreement with data is worse => the energy loss is **not dominantly coherent in the whole** kinematic range of the jet production

More precise quantification of parton energy loss



… vacuum value of c_F measured and calculated in pQCD (MLLA)

… can we go beyond the simple approximation of $c_F = 9/4$?

More precise quantification of parton energy loss

$$S_q = s' \left(\frac{p_T^{\mathrm{jet}}}{p_{T,0}} \right)^{\alpha} \qquad S_g = c_{\mathrm{F}} \times S_q$$

- Use rapidity differential jet R_{AA} measurement to perform a multidimensional fit and extract α, s' and **c_F simultaneously**
- Input spectra @ NLO (POWHEG+PYTHIA8 + 3 variations of PDFs)

–> Result:

$s' = x \cdot N_{\mathrm{part}} + y$	$x = (12.3 \pm 1.4) \cdot 10^{-3}$ GeV, $y = 1.5 \pm 0.2$ GeV
α	0.52 ± 0.02
c_{F}	1.78 ± 0.12

–> value of c_F consistent with the value in the vacuum

What about other objects?

Data tell us that the medium largely sees a jet as one object
=> what about other objects with a structure that are suppressed?

J/Ψ & $\Psi(2S)$

What about other objects?

Data tell us that the medium largely sees a jet as one object
=> what about other objects with a structure that are suppressed?

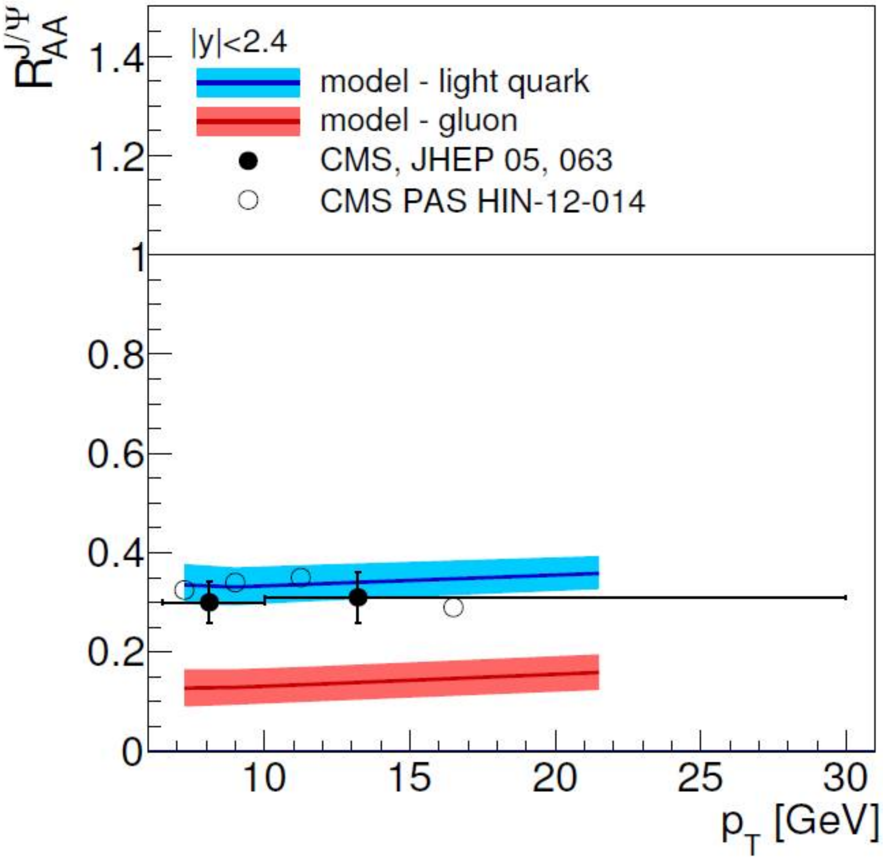
J/Ψ & Ψ(2S)

… check the differences between the suppression of jets and charmonia at high-p_T (at the LHC at mid-rapidity)

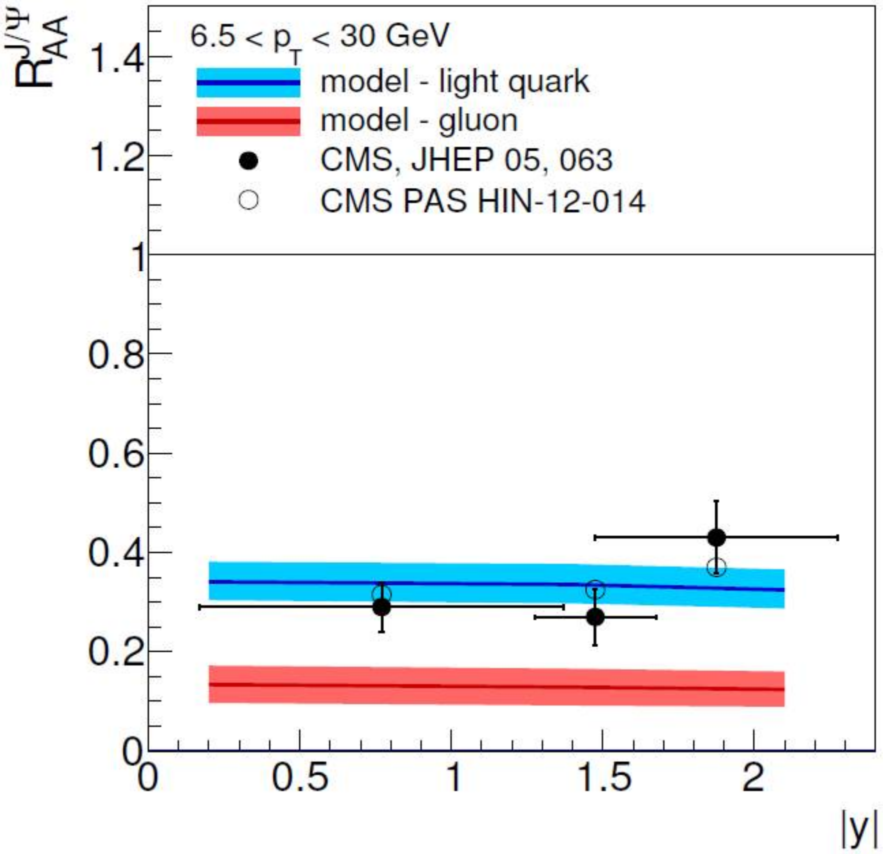
Input:

- Measured *pp* spectra of charmonia
- Energy loss extracted from jets

Charmonia

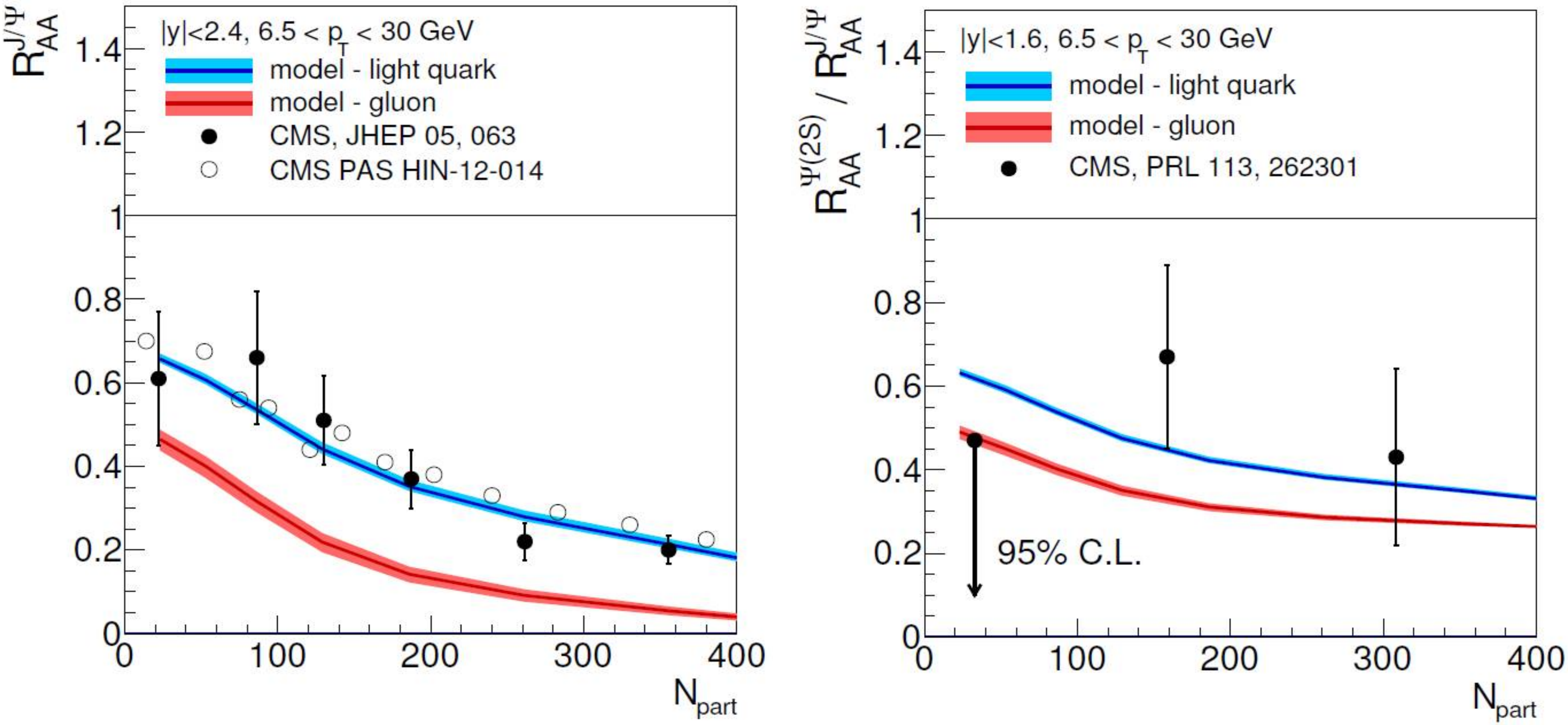


$R_{AA}^{J/\Psi}$
|y|<2.4
model - light quark
model - gluon
CMS, JHEP 05, 063
CMS PAS HIN-12-014
p_T [GeV]



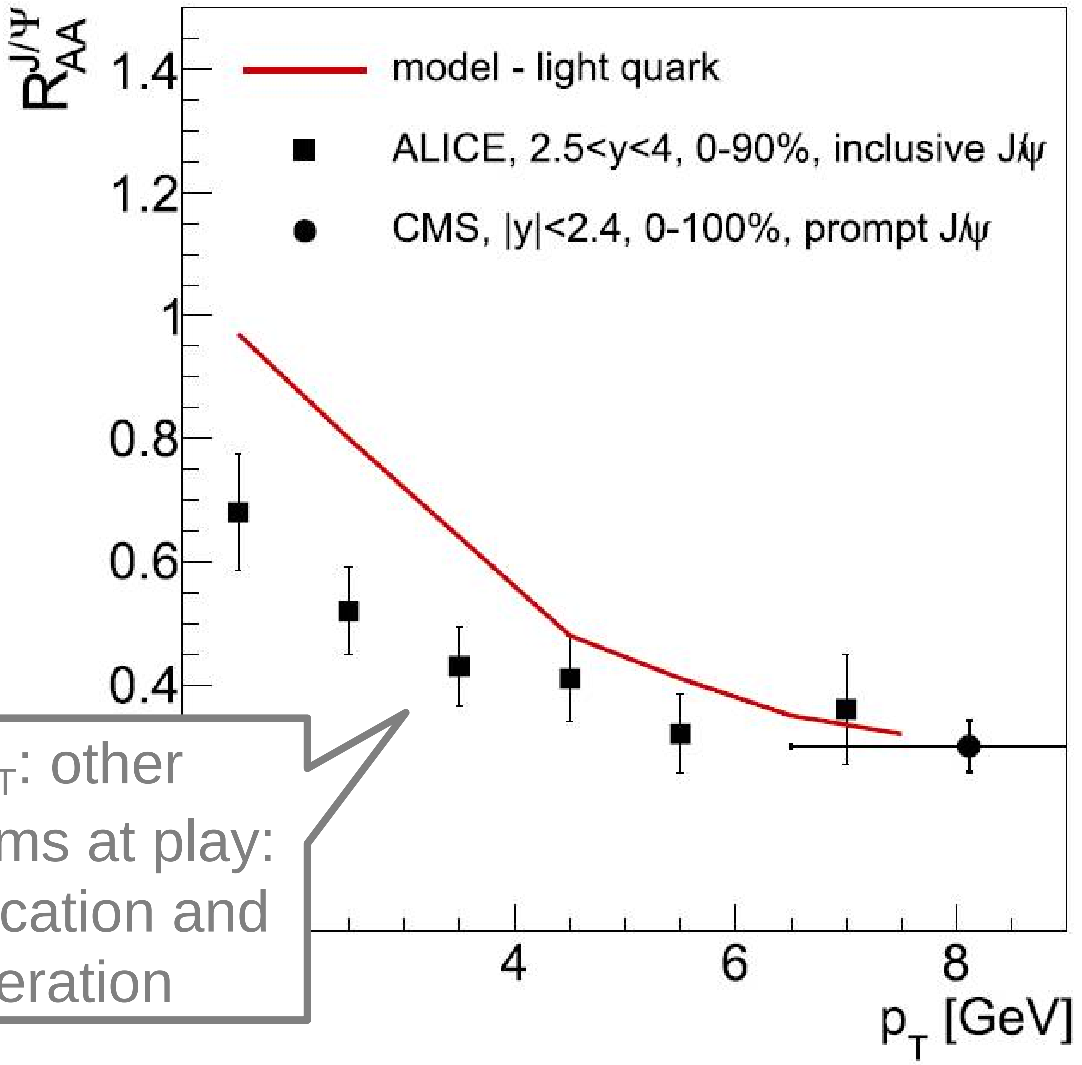
$R_{AA}^{J/\Psi}$
6.5 < p_T < 30 GeV
model - light quark
model - gluon
CMS, JHEP 05, 063
CMS PAS HIN-12-014
|y|

Charmonia



… suppression of both charmonia at p_T>6.5 GeV is similar to the suppression of light quark jets

Charmonia, where does the picture breaks?



Low-p_T: other mechanisms at play: e.g. dissocation and regeneration

Summary

- Quark/gluon dependence of the jet quenching drives quite a lot of what we see in the data.
- Color coherence effects are seen in the data.
- *b*-jets are quenched by 1.5±0.4 more than light quark jets.
- Average jet quenching can be quantified from the data as follows:

$s = x \cdot N_{\text{part}} + y$	$x = (12.3 \pm 1.4) \cdot 10^{-3}$ GeV, $y = 1.5 \pm 0.2$ GeV
α	0.52 ± 0.02
c_{F}	1.78 ± 0.12

$$S_q = s' \left(\frac{p_T^{\text{jet}}}{p_{T,0}} \right)^{\alpha}$$

… c_F seems vacuum-like

- Suppression of charmonia at p_T>6.5 GeV at midrapidity behaves like the suppression of light quark jets.

More general message

Jet quenching and charmonia suppression can teach us not only about the properties of QGP but also about hadron formation:

- space-time scales of the hadron formation via well defined space-time scales of QGP
- role of color: e.g. color-octet versus color-singlet production of charmonia, color coherence effects

Backup slides

Hard processes