Jet quenching and charmonia suppression from Effective Quenching model

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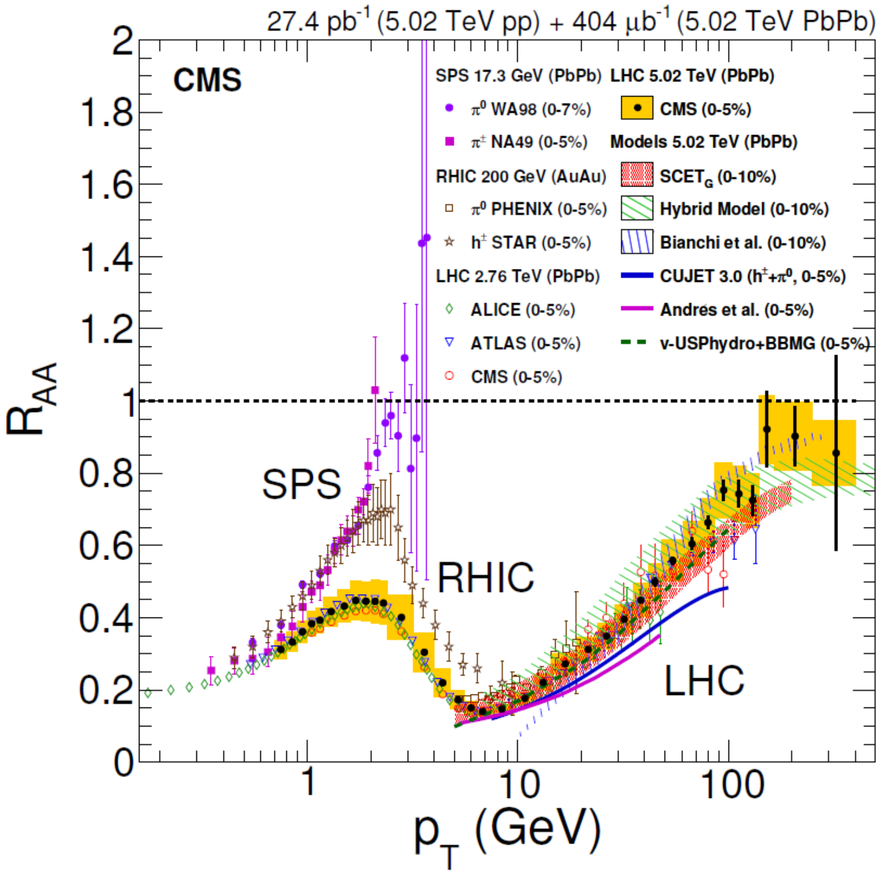
Introduction



- Physics of the suppression = **parton** energy loss in **fluctuating** hot nuclear matter
- => Some observables (I_{AA}, R_{AA} of particles, ...) result from a **complicated convolution** of: hard parton spectra, dependence of the loss on the flavor and parton shower shapes, path-length...
- => All observables are convolutions of (non-trivial) initial conditions and (non-trivial) energy loss

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- Be as realistic as one can:
  - MC generators
  - Model full evolution of medium (JETSCAPE Collaboration)
  - theory calculations of parton enegy loss

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Phys.Rev. Lett. 119 (2017) 062302

Phys.Lett B767 (2017) 10

Eur.Phys.J. C76 (2016) no.2, 50

arXiv:1702.01931

arXiv:1908+ε.XXXX

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This talk ...

… use a simple model with minimal assumptions on the quenching physics to extract basic properties of the jet quenching

The simplest modeling of parton energy loss

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

Jet spectra parameterized by a power law

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

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

The simplest parametric modeling of parton energy loss

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

Yield of quenched jets of a given flavor at given pt

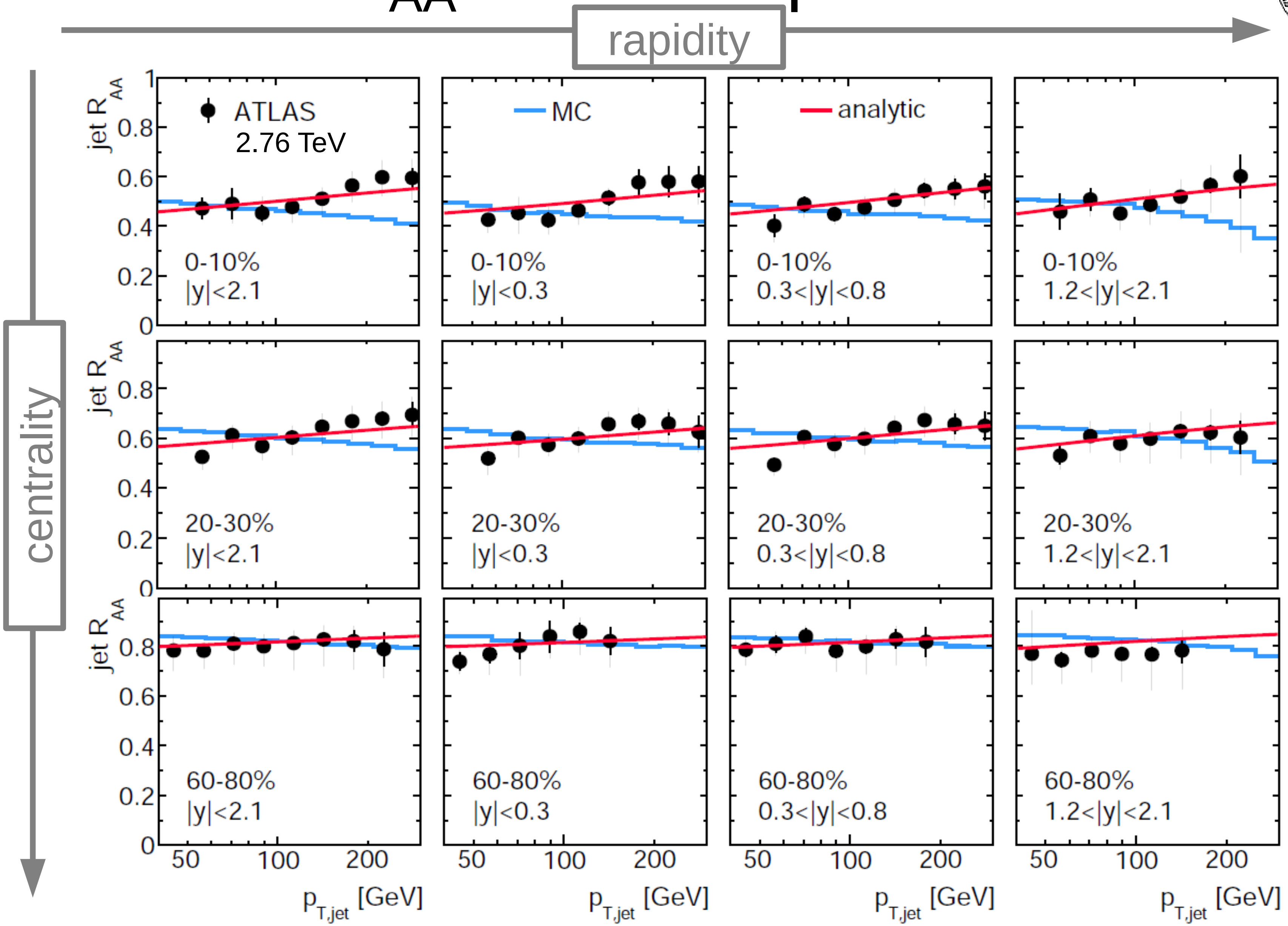
$$S_q \equiv s p_T$$
$$S_g = c_{\mathrm{F}} \times S_q$$

Fractional energy loss

R_{AA} in the approximation of fractional energy loss

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

Jet R_{AA} in the simplest model



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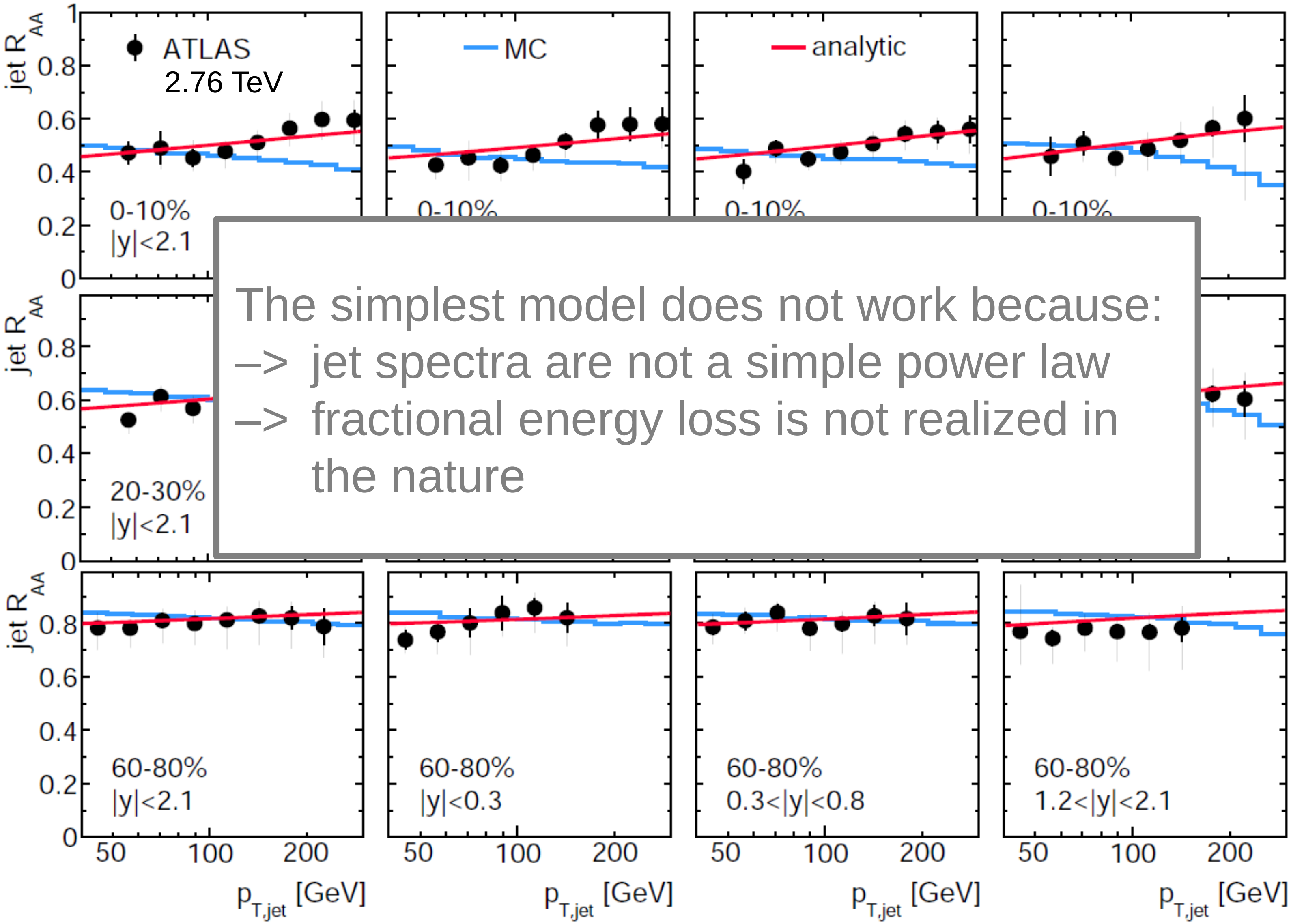
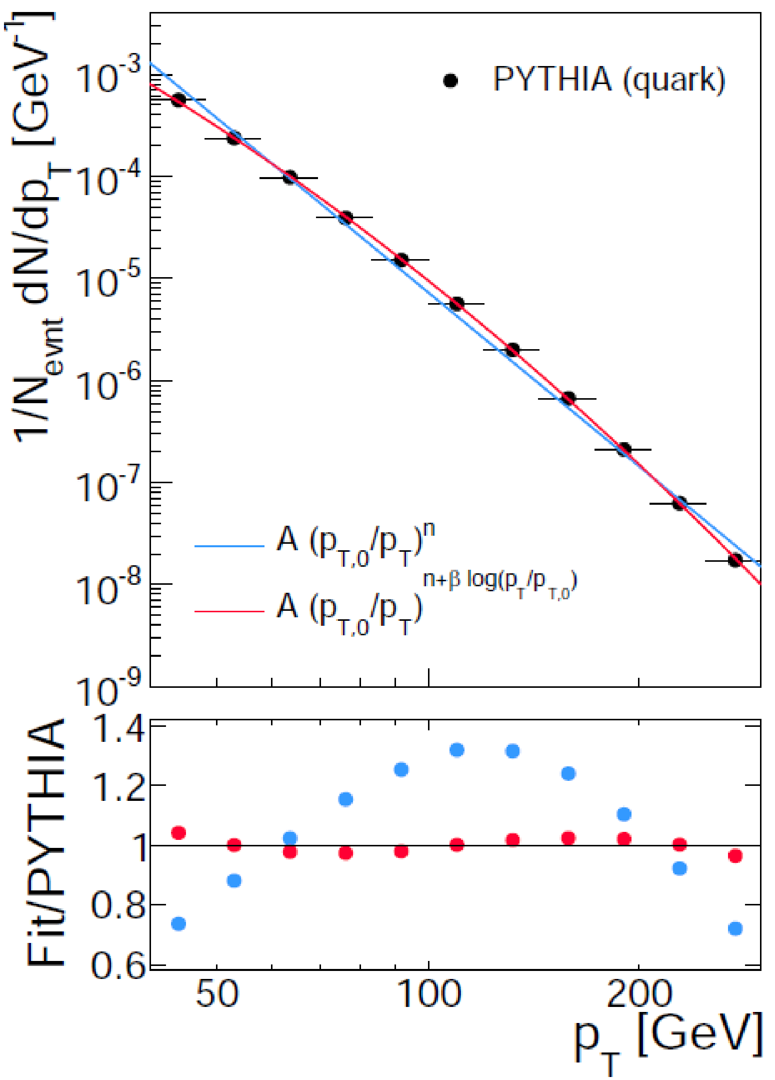


The simplest model does not work because:
–> jet spectra are not a simple power law
–> fractional energy loss is not realized in the nature

Realistic parametric model



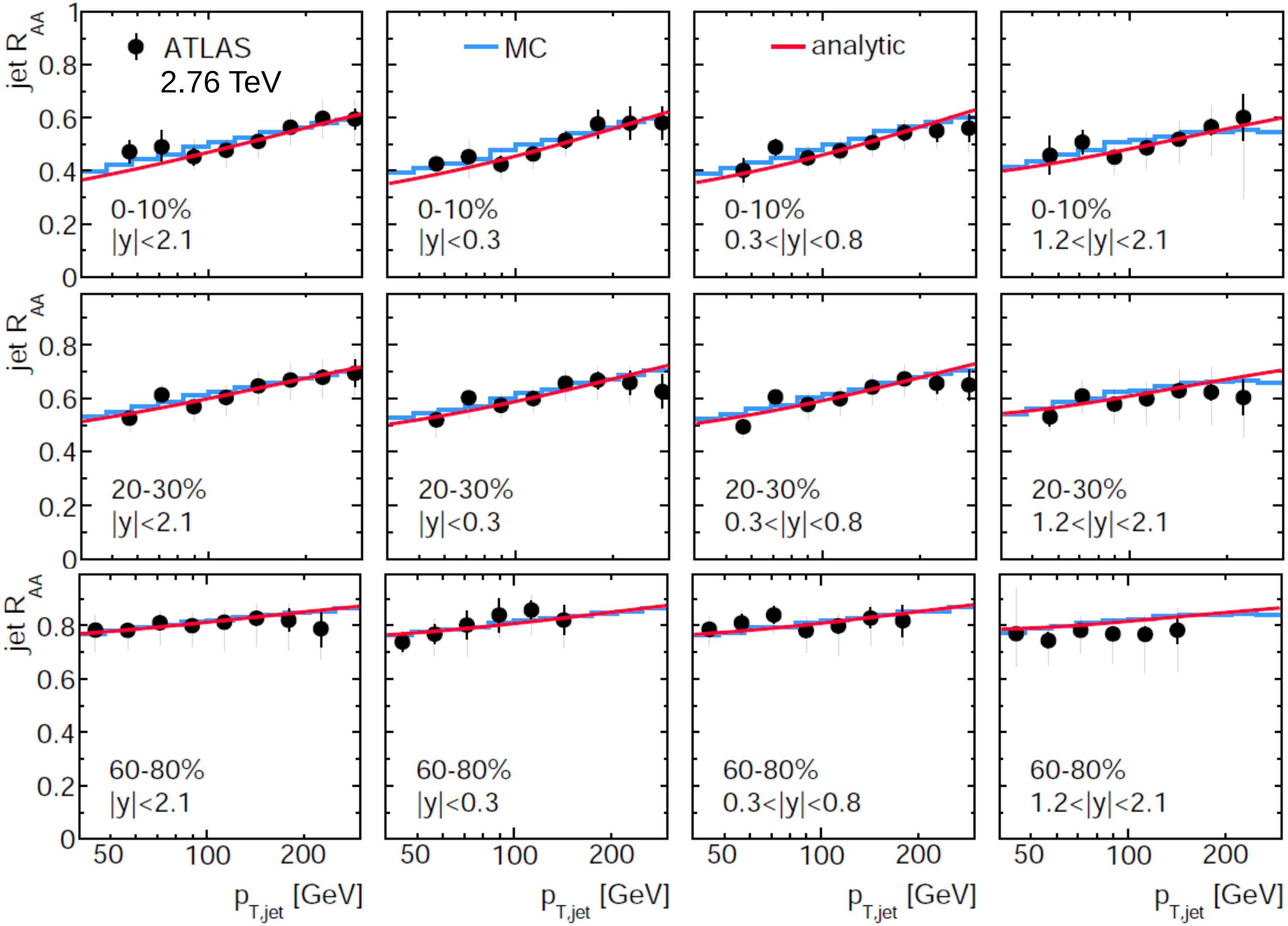
$$\frac{dn}{dp_{\mathrm{T}}^{\mathrm{jet}}} = A\left(\frac{p_{T0}}{p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{n+\beta\log\left(p_T^{jet}/p_{T0}\right)}$$

Realistic parameterization of input jet spectra

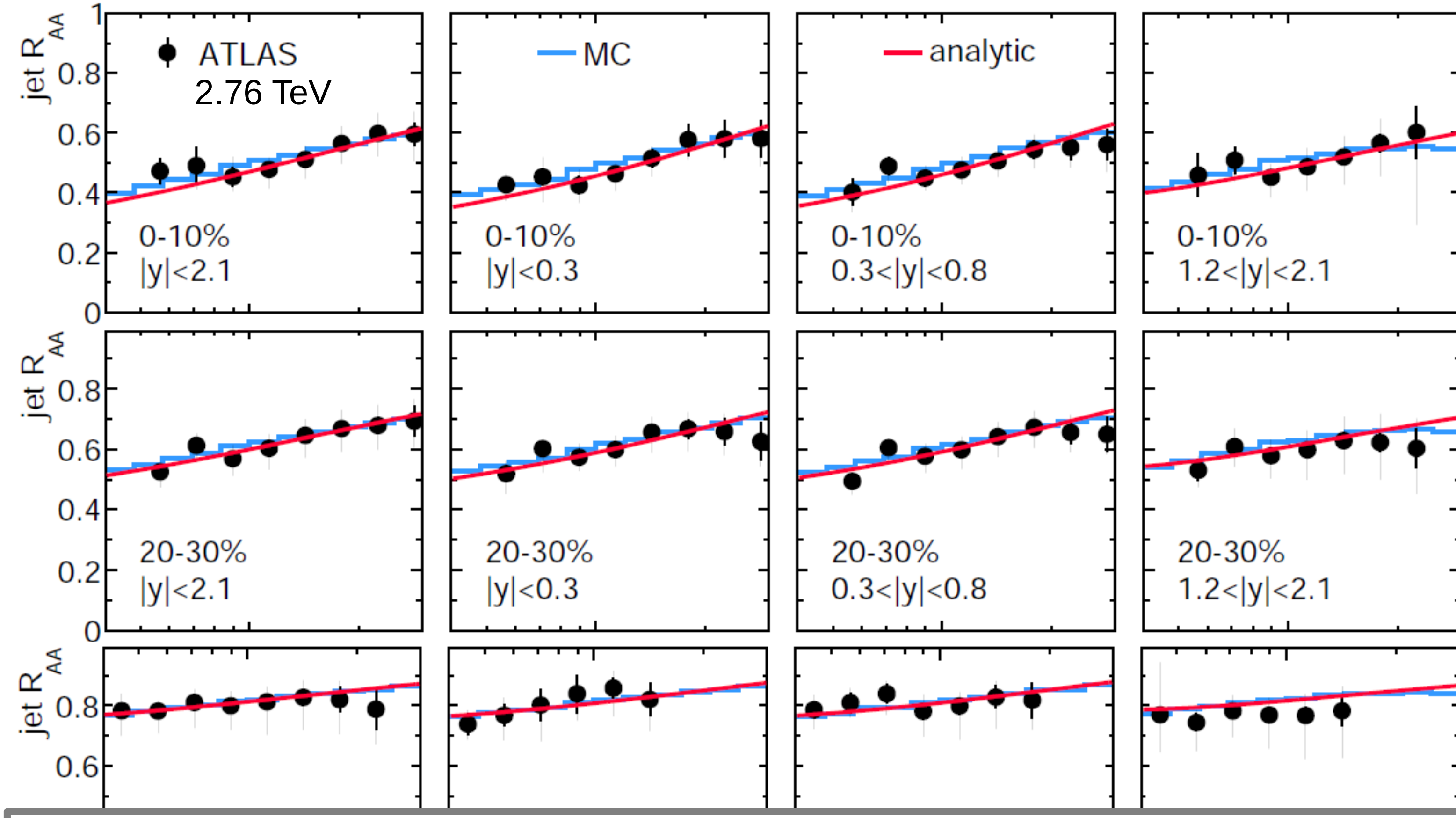
General modeling of jet energy loss

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

Jet R_{AA} in realistic model

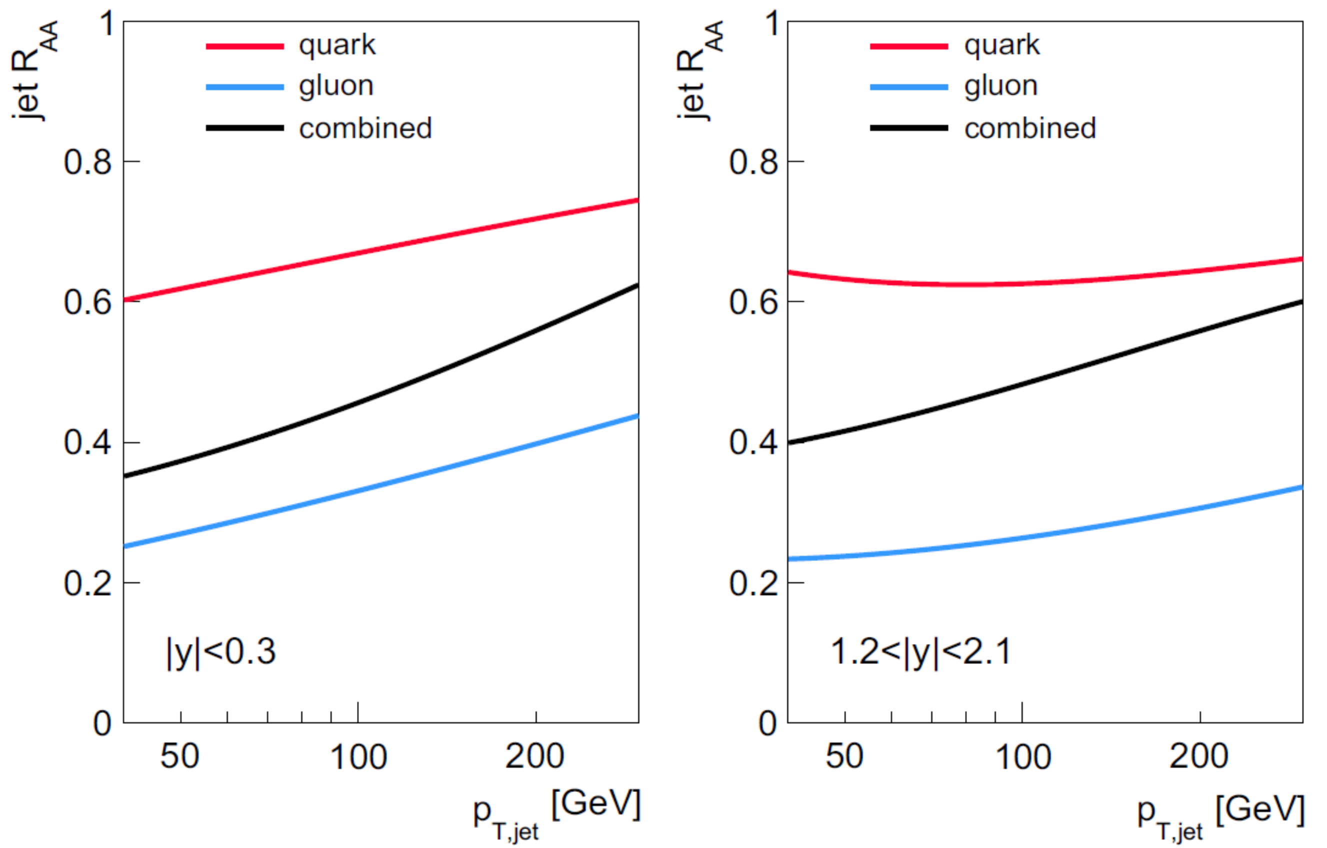


Jet R_{AA} in realistic model



–> Slow evolution with p_T and no rapidity dependence of jet R_{AA} can be interpreted as a result of different energy loss of quark and gluon initiated jets

Jet R_{AA} in realistic model

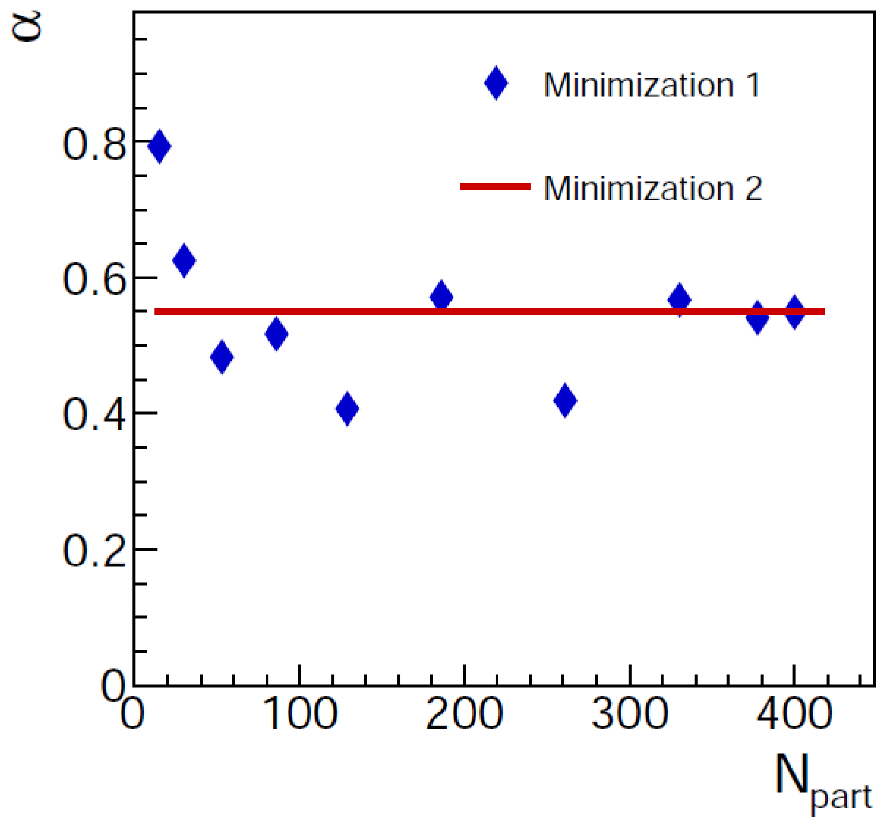


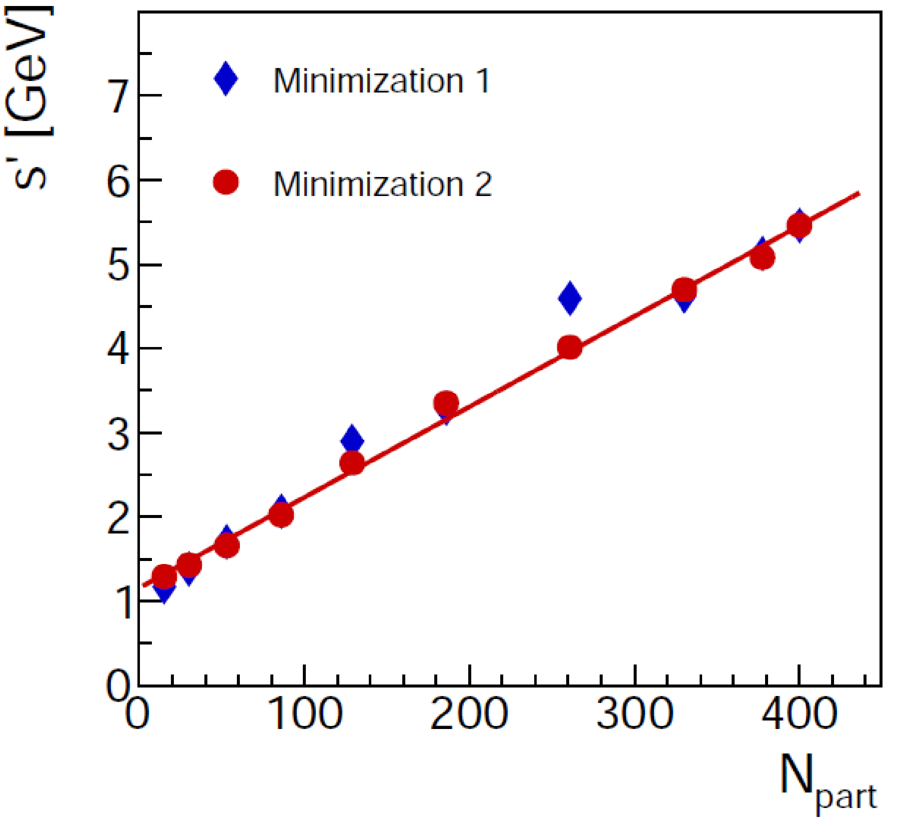
–> Flatness and no rapidity dependence of jet R_{AA} can be interpreted to be a result of different energy loss of quark and gluon initiated jets

Quantifying the parton energy loss, fixed c_F

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

Fixed to 9/4





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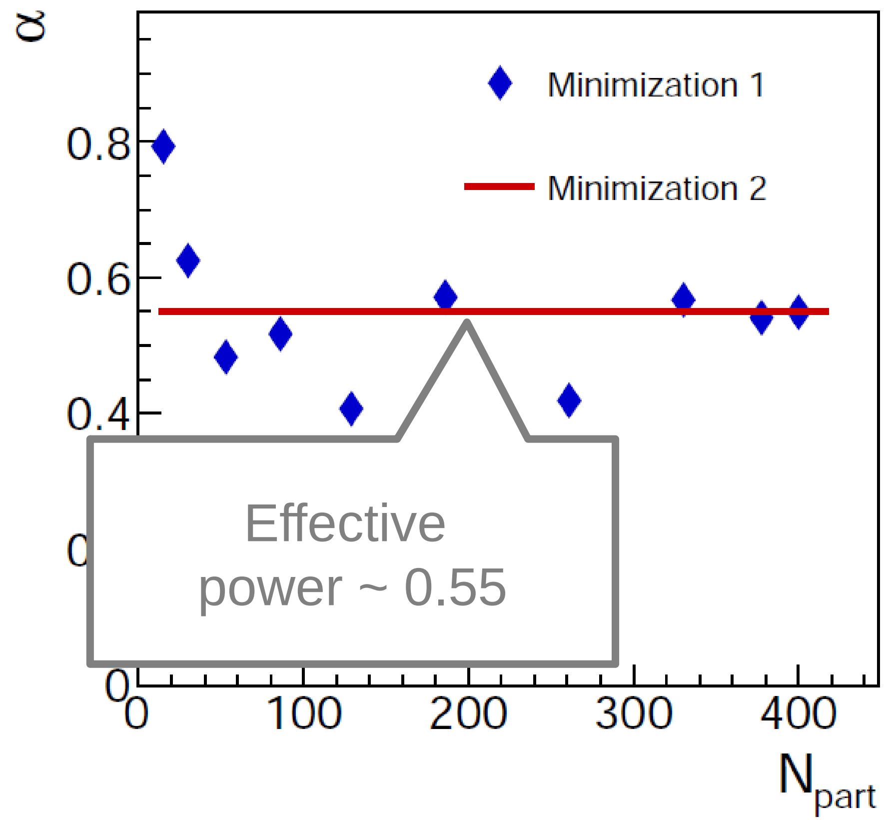

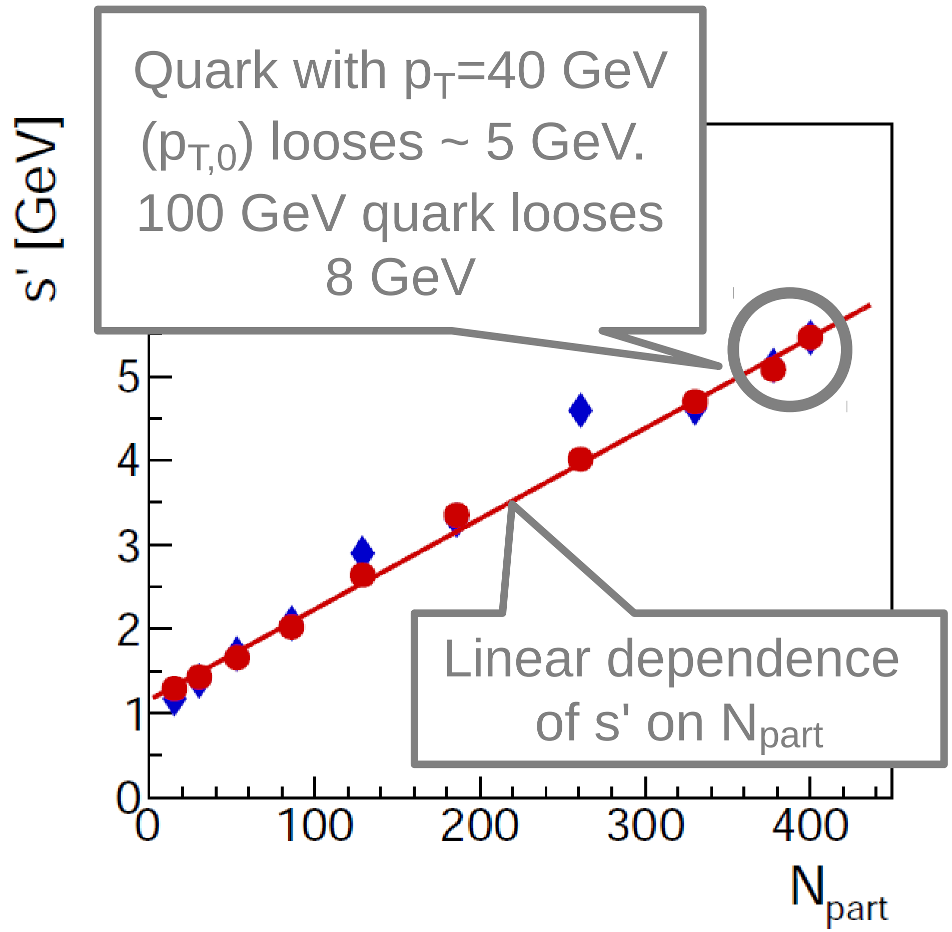

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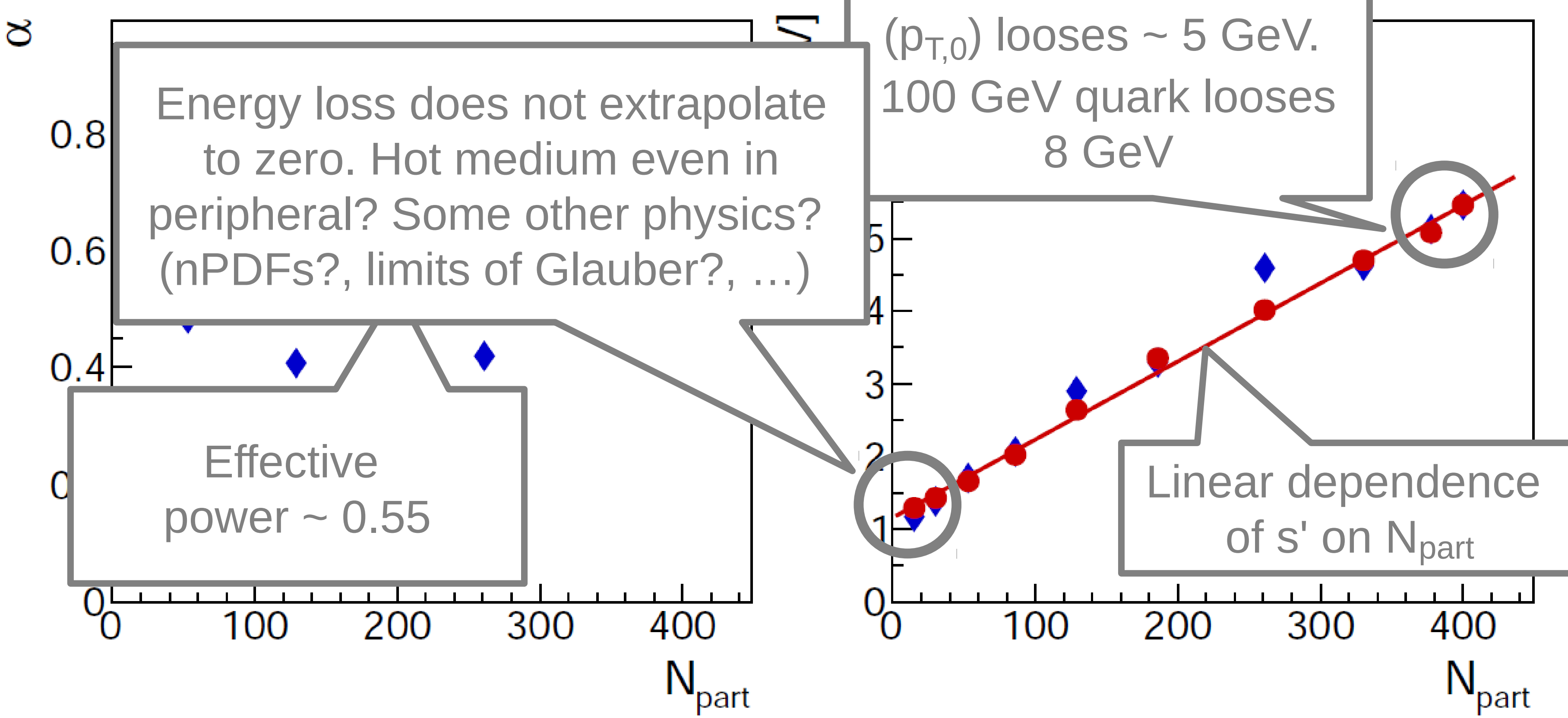
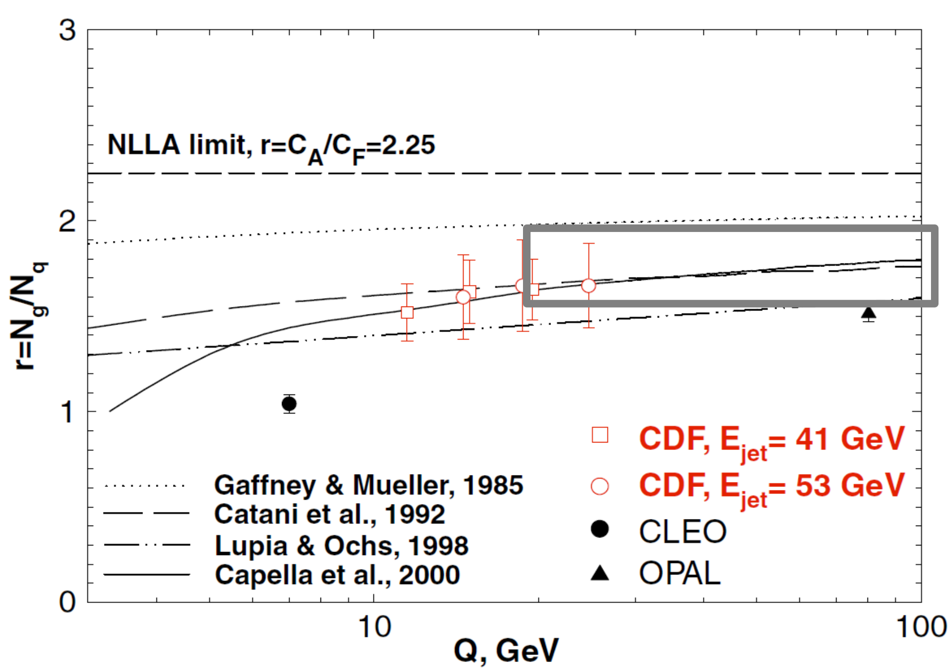


Quantifying the parton energy loss, free c_F

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

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



- Vacuum value of c_F measured and evaluated in pQCD (MLLA calculations)
- In vacuum, c_F = 1.7-1.8 for Q=20-100 GeV
- In-medium: **c_F = 1.78±0.12** – consistent with the value **in the vacuum** (Useful discussion on c_F also in arXiv:1812.06019)

Quantifying the parton energy loss

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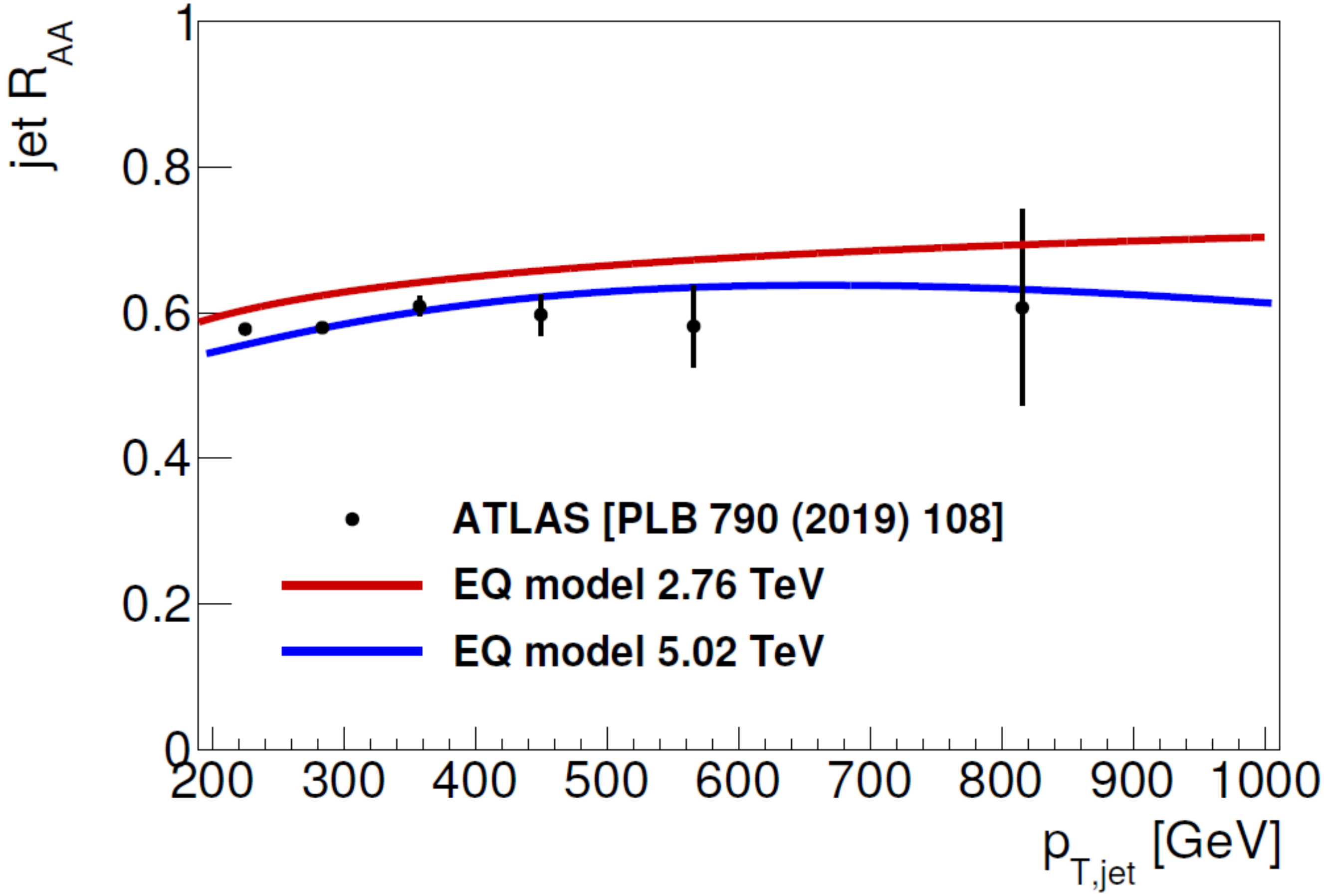
- Use rapidity differential jet R_{AA} measurement to perform a **multidimensional fit** and extract α, s' and c_F simultaneously (Input: **NLO** spectra – POWHEG+PYTHIA8 + 3 variations of PDFs)
- Full result:

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

- Average jet quenching encapsulated **in 4 parameters**.

5.02 TeV versus 2.76 TeV

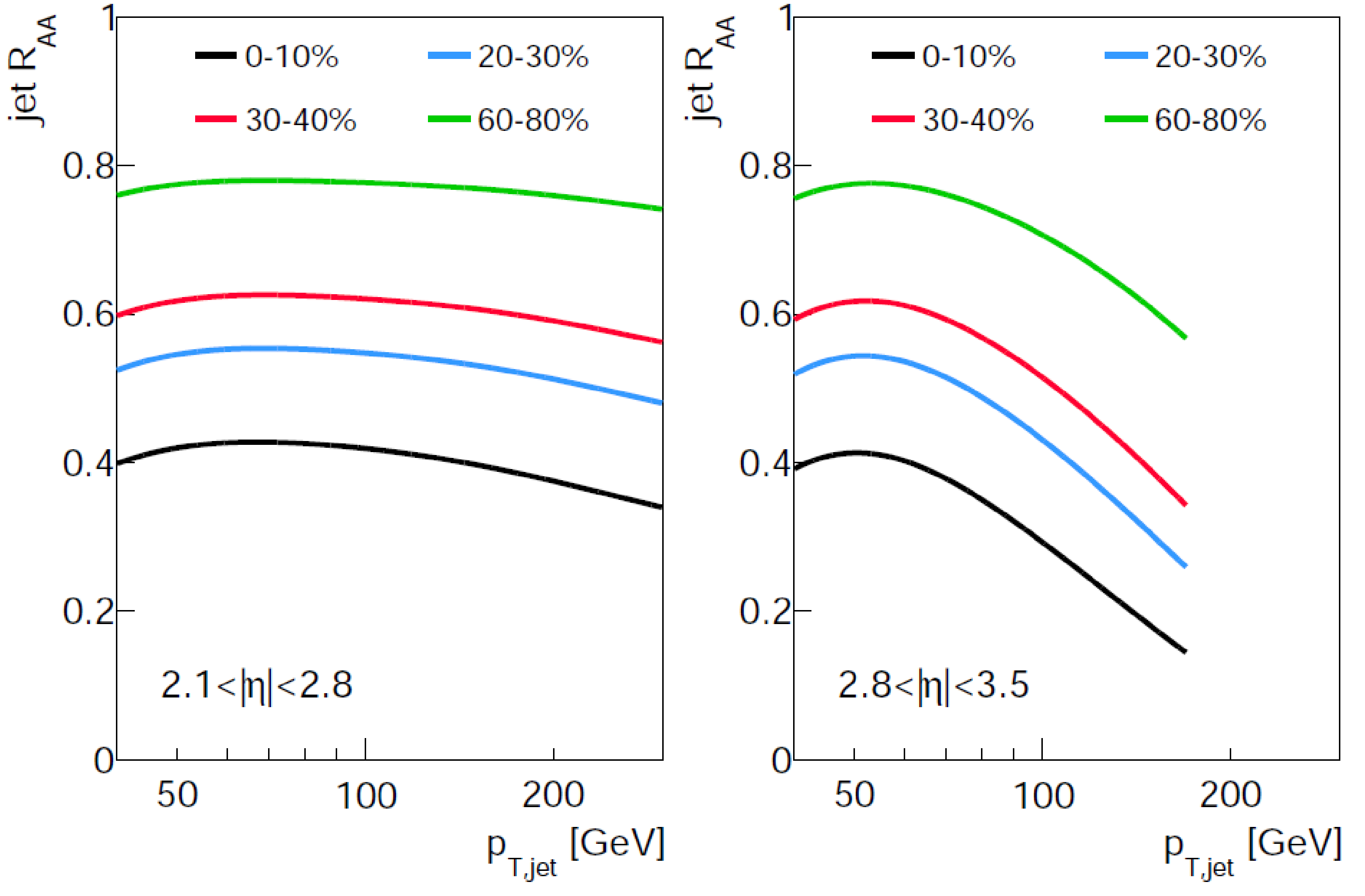


- Same jet R_{AA} … but that does not imply same energy loss.
- Spectra shape and flavor admixture are different
  => energy loss must be different.
- About 10% larger energy loss at 5.02 TeV compared to 2.76 TeV.

Note

- … jet R_{AA} … as a result of different energy loss of quark- and gluon-initiated jets
- Alternative: **shower shape** – wide jets lose more than narrow.
- How to **distinguish**?
- Do as **many comparisons** with data as possible (in the kinematic region insensitive to in-cone radiation / recoil effects). Here:
  - Rapidity dependence of the R_{AA},
  - Behavior of the R_{AA} in the forward region,
  - Jet fragmentation,
  - Jet shapes.
- More info in the **backup**: charged particle R_{AA}, b-jet R_{AA}, z_g, high-p_T charmonia, … and more to come
- Do as many comparisons as possible … and **look for a failure** (by seeing a failure of the model one can learn new stuff)

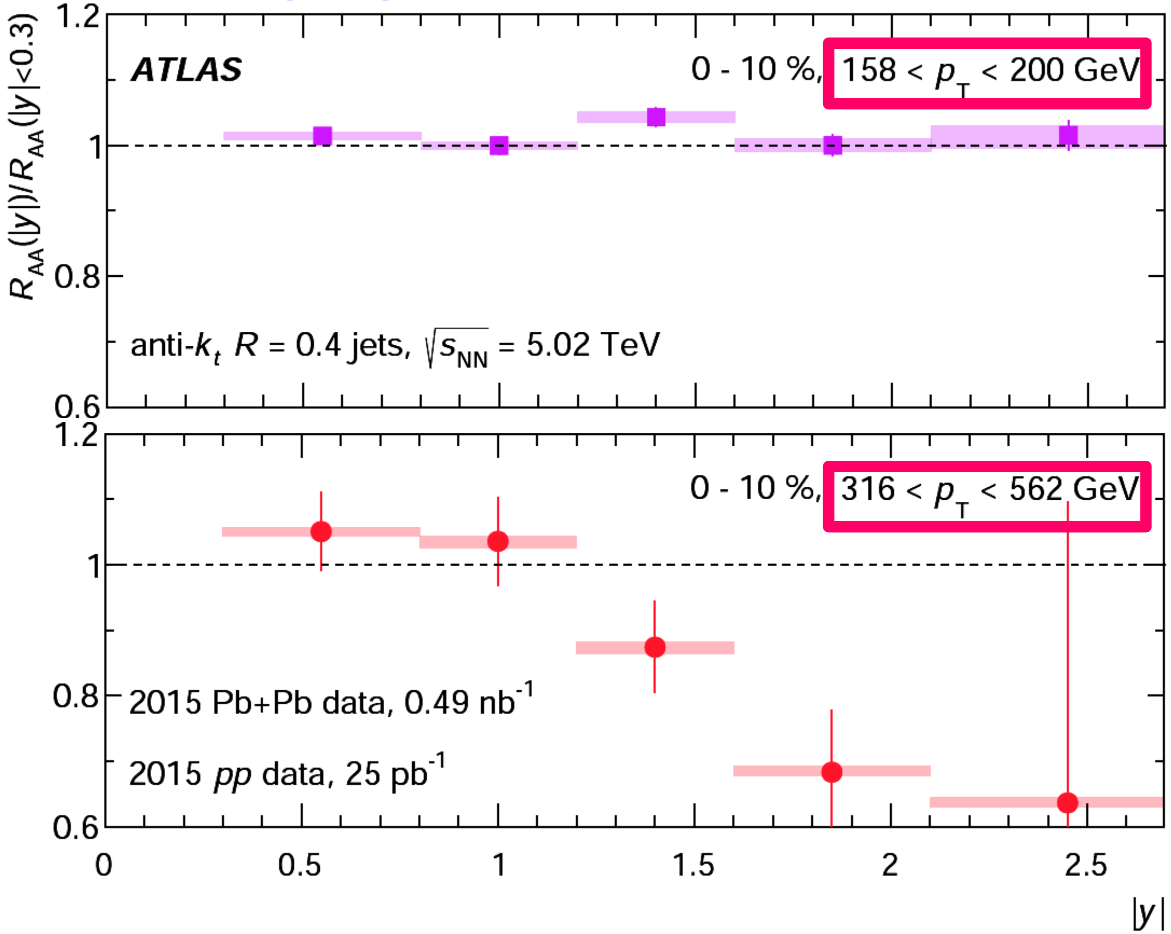
Predictions for the forward region



–> The jet R_{AA} **should decrease** in the forward region

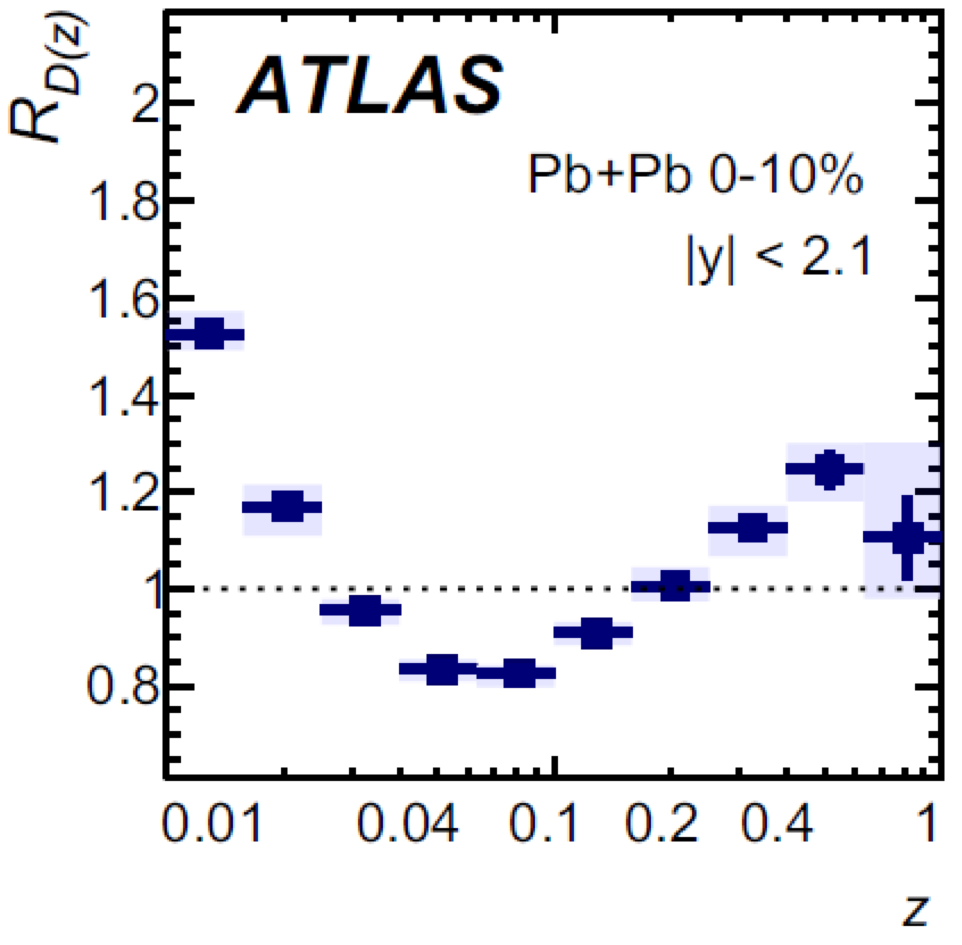
Measurement in the forward region

PLB 790 (2019) 108



–> The jet R_{AA} **does decrease** in the forward region

Modification of longitudinal structure of jet (fragmentation function)



PRC 98 (2018) 024908
EPJC 77 (2017) 379
PRC 90 (2014) 024908
...

Modifications of fragmentation functions

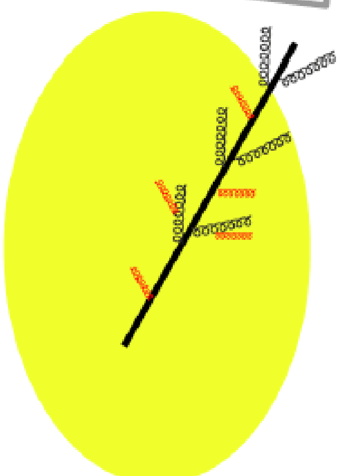
- How is the parton shower modified by the QCD medium?
- Basic picture …

Black = vacuum component of PS
Red = medium induced radiation

c) = a && b

For some configurations medium resolves parton shower

a)



Medium resolves parton shower

e.g.: Phys. Lett. B345 (1995), 277
Nucl. Phys. B582 (2000), 409
Phys. Rev. Lett. 85 (2000), 5535
Phys. Rev. D50 (1994), 1951
JHEP 12 (2001), 009

b)

Emission is coherent

e.g.: Phys. Rev. Lett. 106 (2011)
Phys. Lett. B725 (2013), 357
Phys. Rev. Lett. 111 (2013), 052001

! d) = a || b || c + more

in-cone radiation + jet excites medium => “recoiling” particles from the medium

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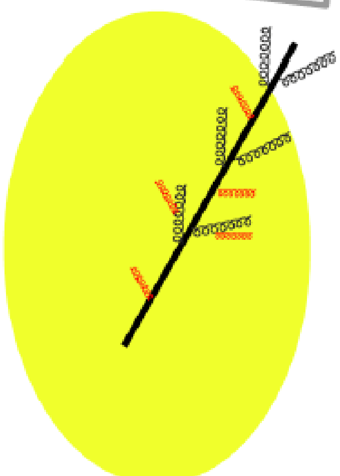

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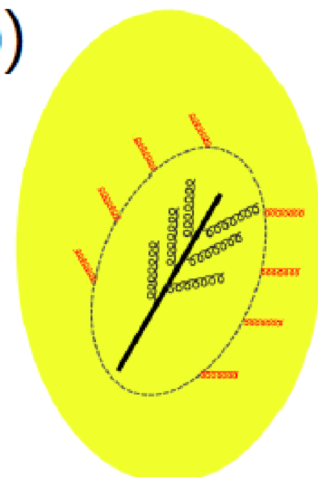

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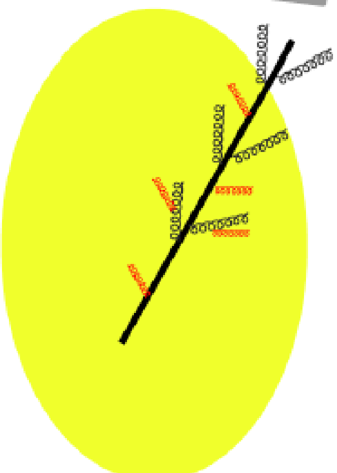

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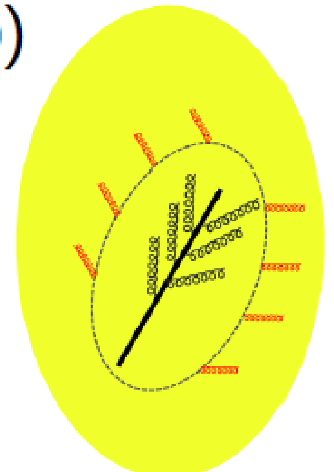

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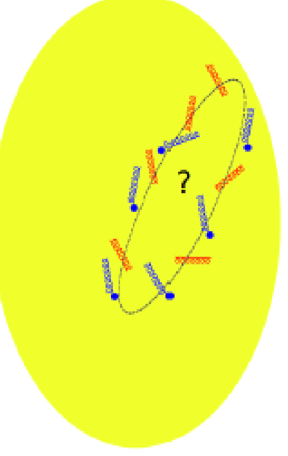

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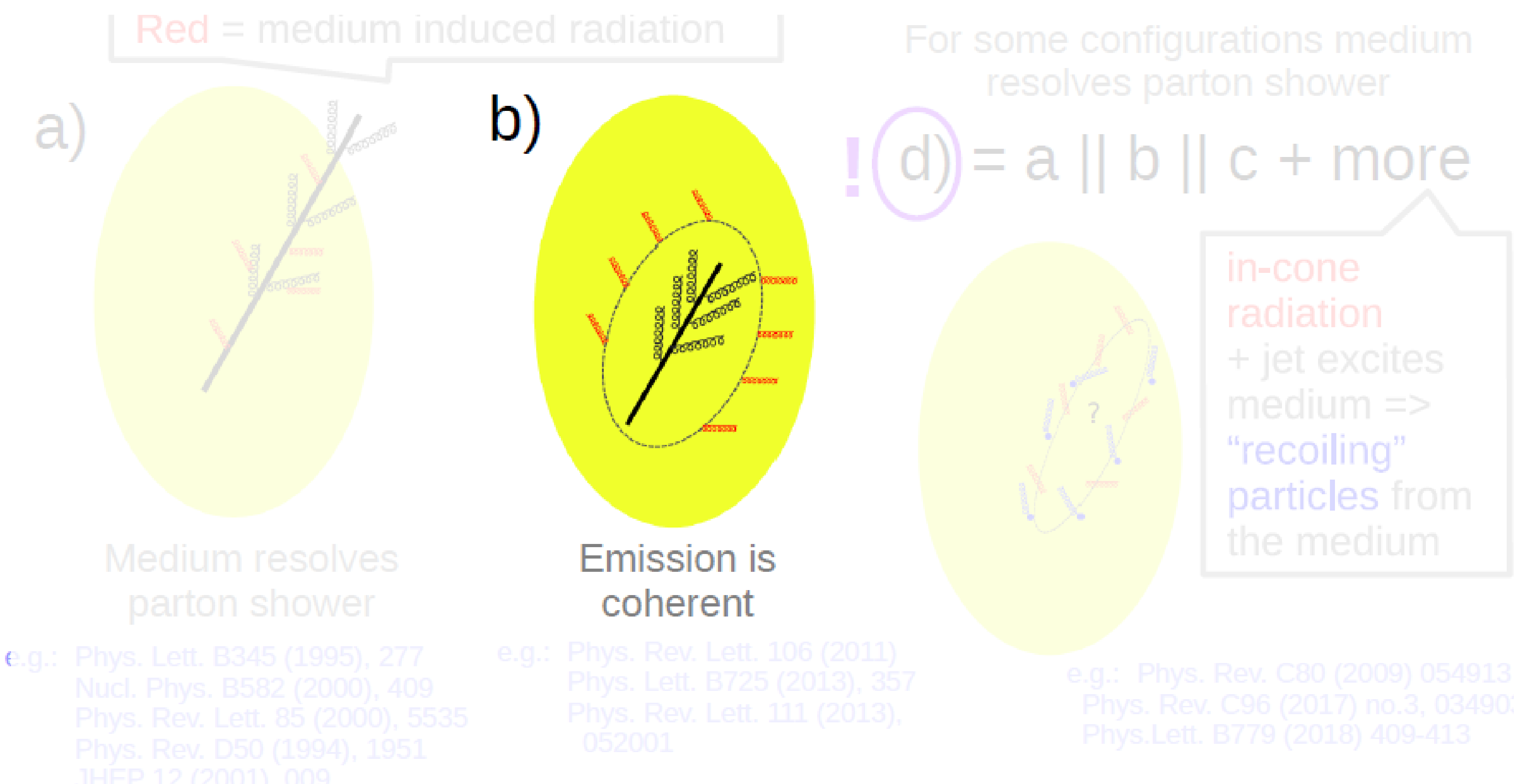
Modifications of fragmentation functions

–> Subtract the energy from the jet / initial parton and then let it fragment as in the vacuum



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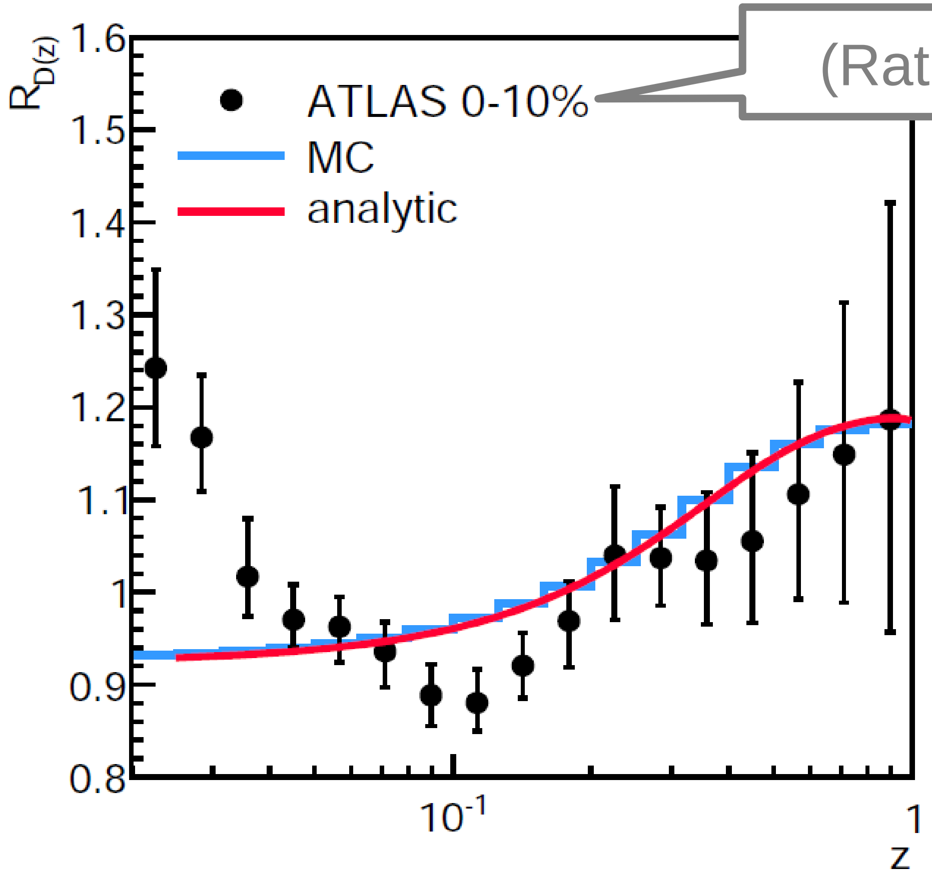
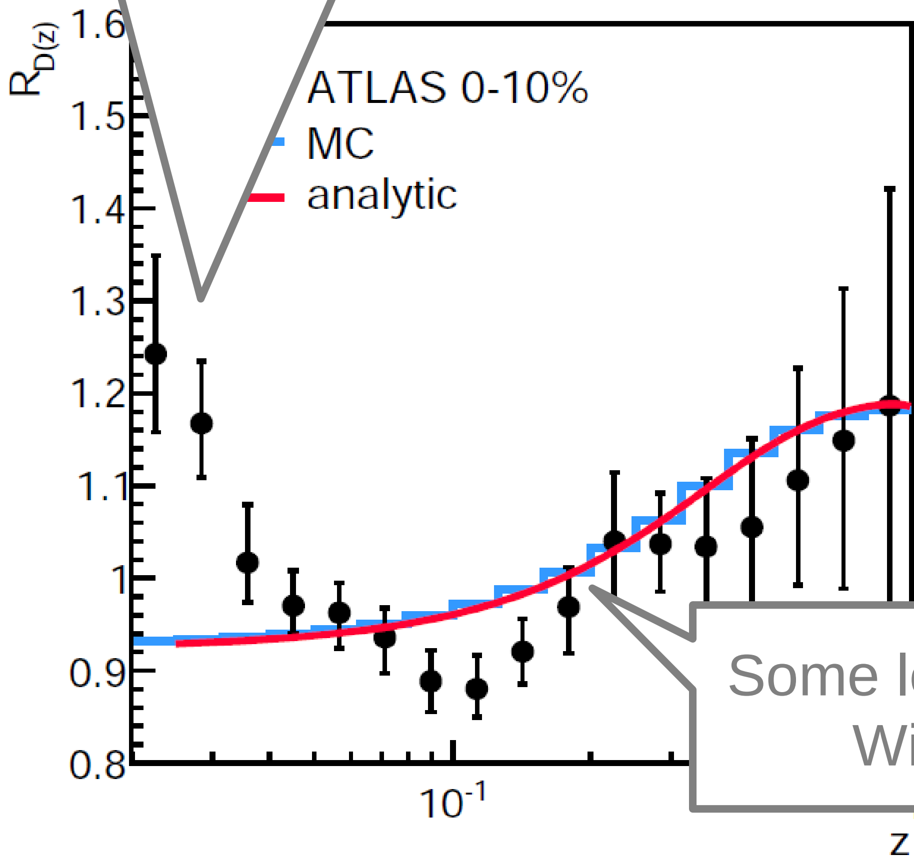


(Ratio of fragmentation functions)

Modifications of fragmentation functions

Excess of low-*z* not due to flavor effects (due to in-cone radiation or recoil effects)

...he jet / initial parton and ...e vacuum



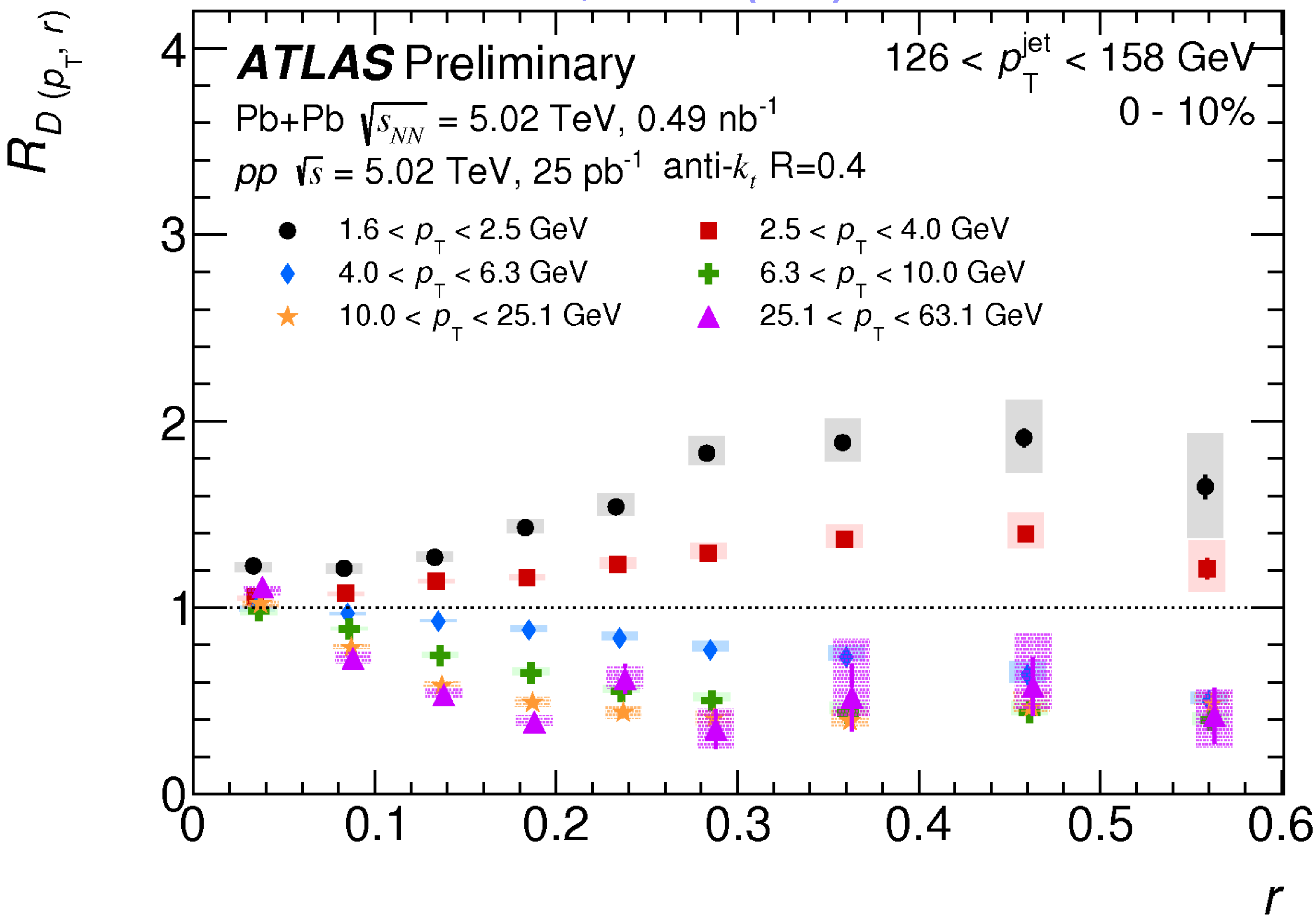
Some level of disagreement? Will get back to it ...

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

–> Speaks in favor of presence of color coherence effects in the data

Transverse structure of jet (jet shape)

ATLAS-CONF-2018-010, JHEP 05 (2018) 006



Modification of the jet shape

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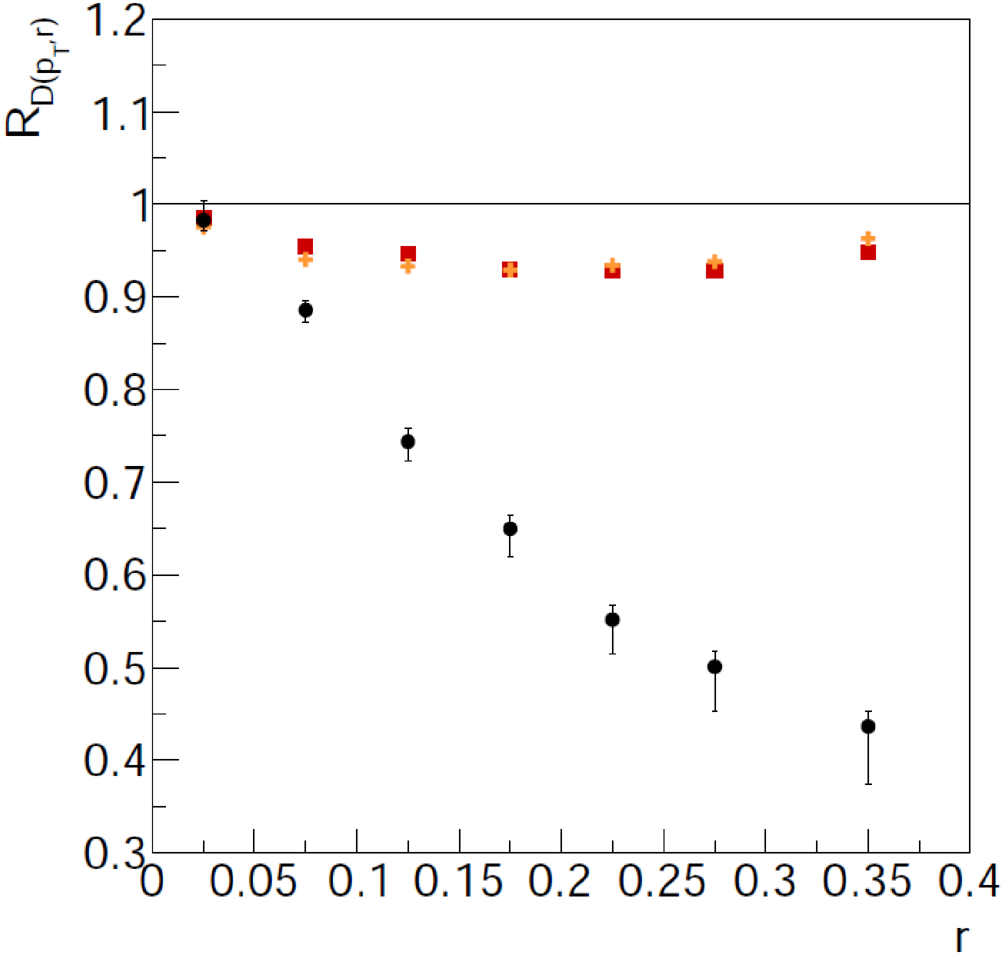
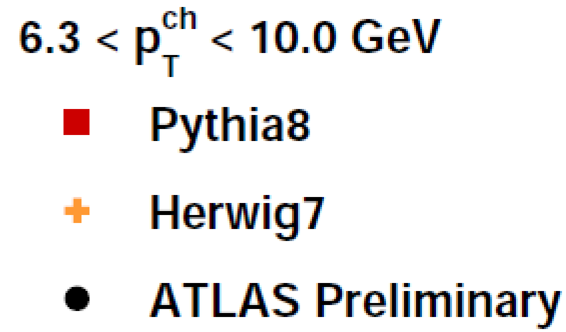
Modification of the jet shape

$126 < p_{T,jet} < 158$ GeV





- **r<0.05**: values well reproduced (for all p_T^{ch} bins)
- **r>0.05**: trends similar but magnitude very different … ... two particular possibilities:

  1) **Input spectra** are not well modeled (sub-dominant contributions to jet p_T)

  2) **Coherent picture** breaks for ~100 GeV jets at r~0.05

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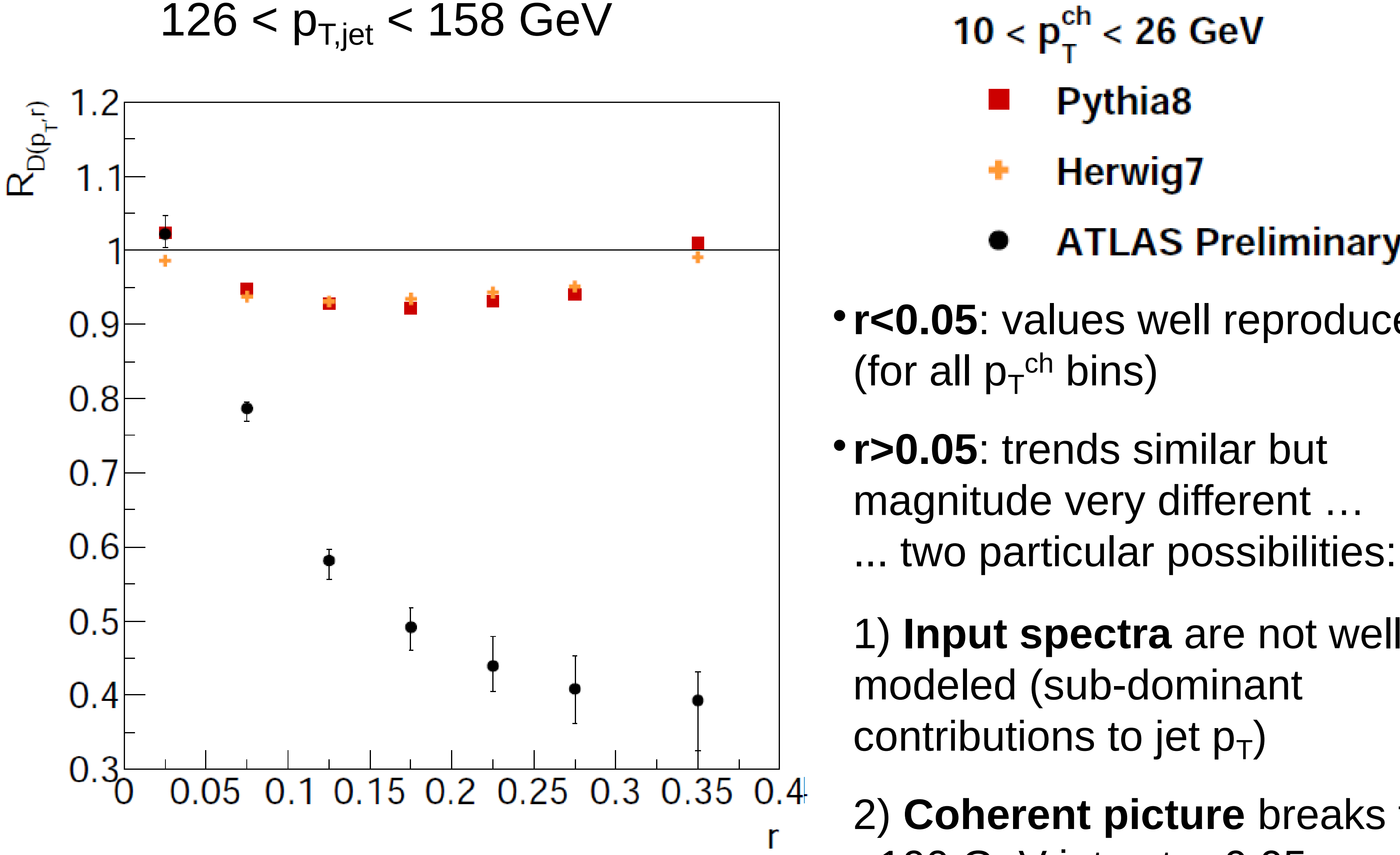

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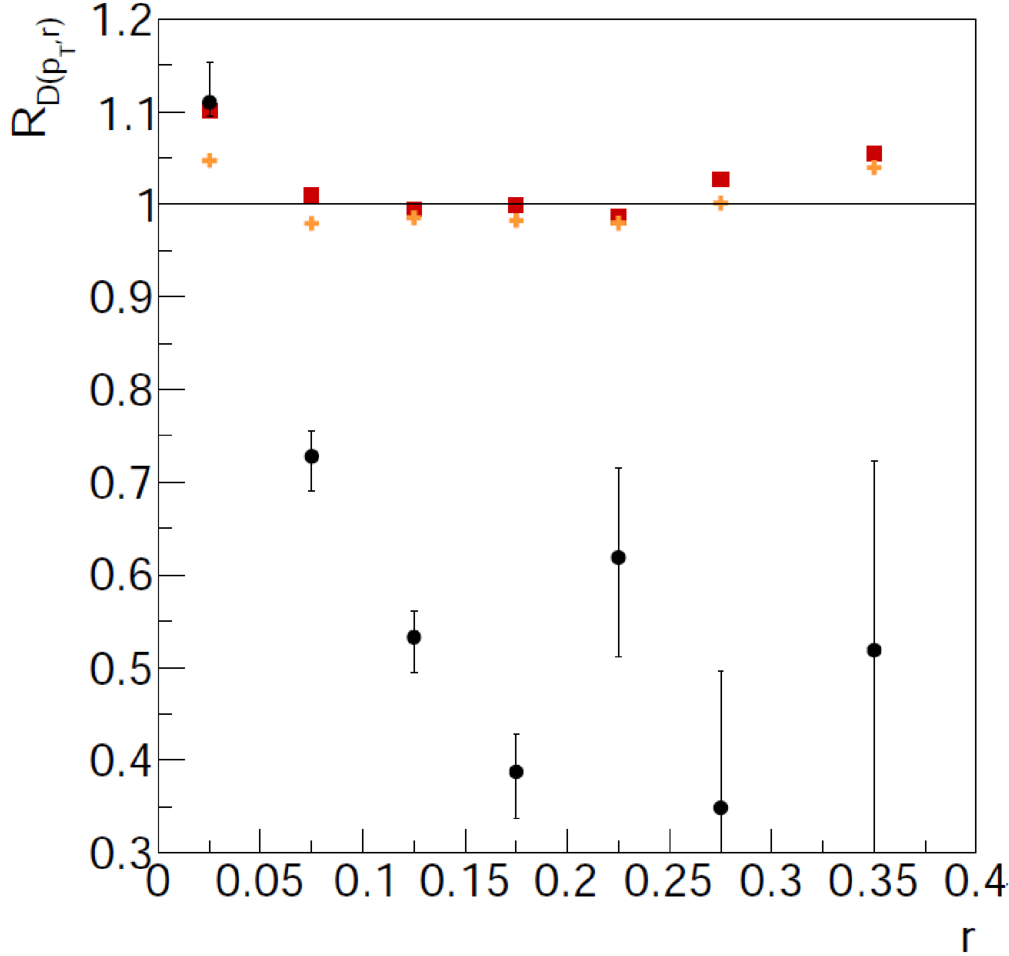

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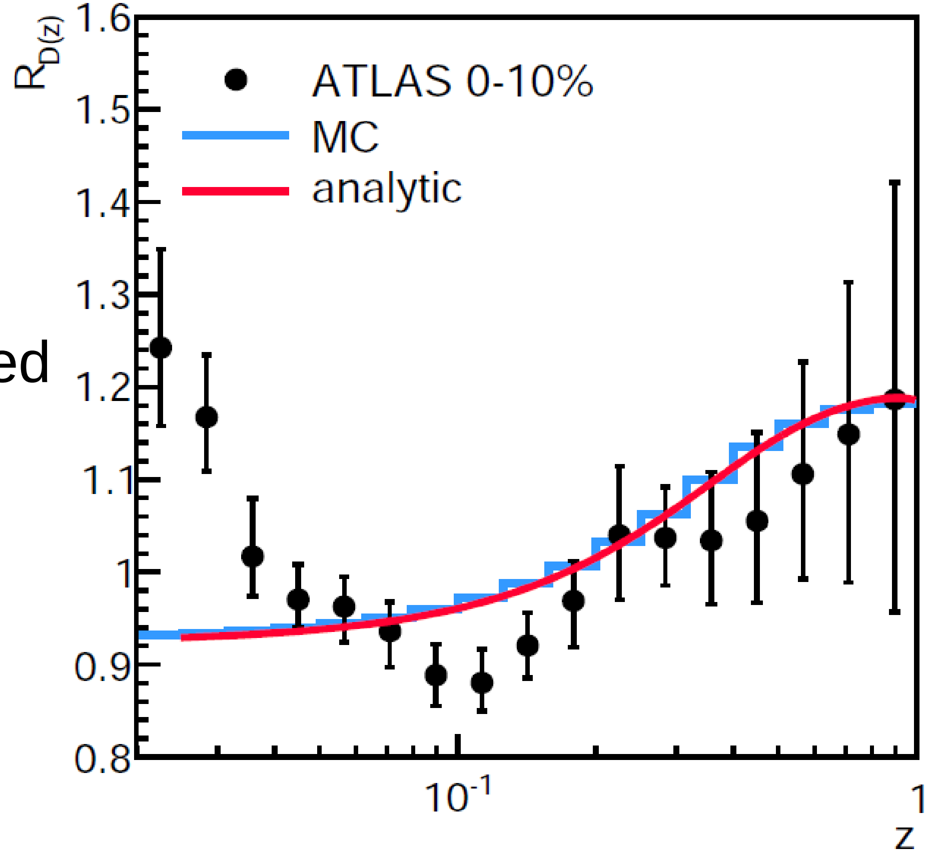
Modifications of fragmentation functions – a detail

Excess of low-*z* not due to flavor effects (due to in-cone radiation or recoil effects)

$$p_{\mathrm{T,jet}}^{\mathrm{measured}} = p_{\mathrm{T,jet}}^{\mathrm{quenched}} + p_{\mathrm{T}}^{\mathrm{soft}}$$

- These low-*z* hadrons contribute to the measured jet energy. Parameter *s*' contains this soft part.
- Soft part contributes to the measured fragmentation via denominator of *z*.



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$$p_{\mathrm{T,jet}}^{\mathrm{measured}} = p_{\mathrm{T,jet}}^{\mathrm{quenched}} + p_{\mathrm{T}}^{\mathrm{soft}}$$

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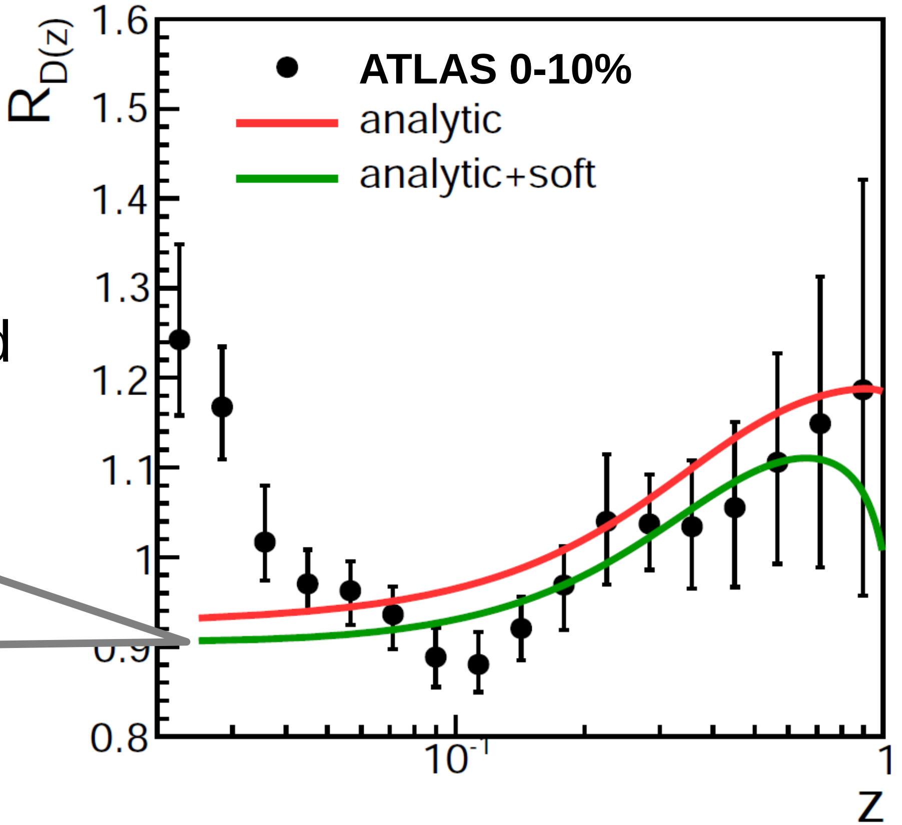

Contribution of soft hadrons to the jet energy can be estimated from the measurement at low-z => fragmentation distributions w/ correct soft contribution

Modifications of fragmentation functions – a detail

–> Prediction: detailed measurement of fragmentation at the highest-*z* (or lowest-ξ) should exhibit a depletion

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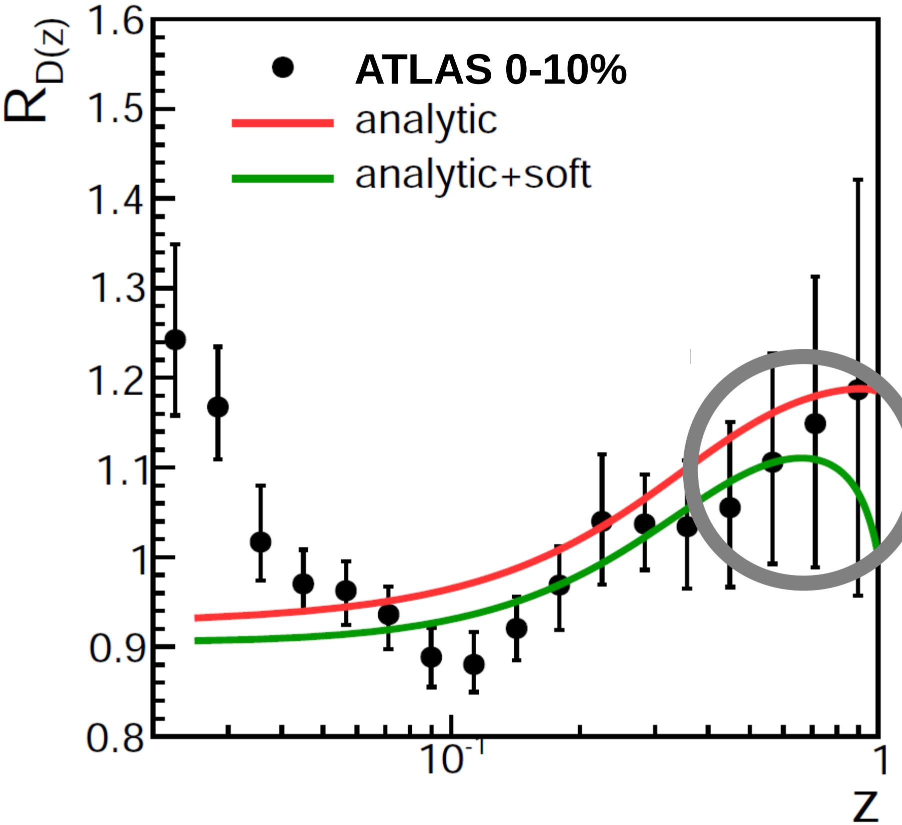

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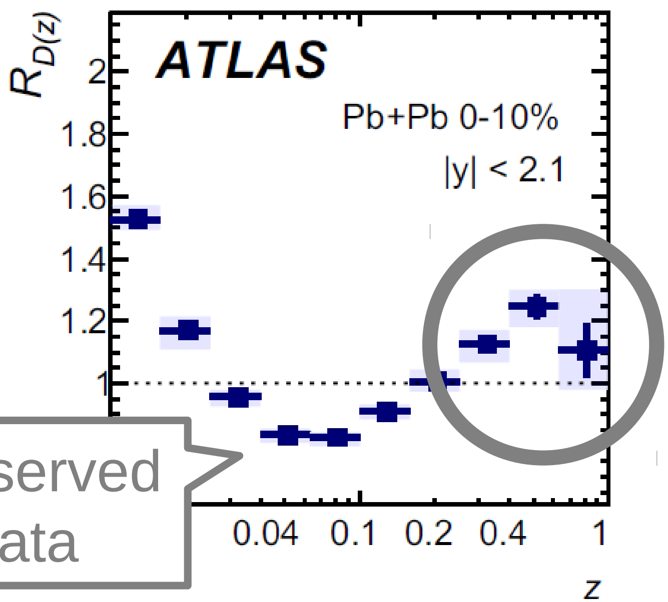
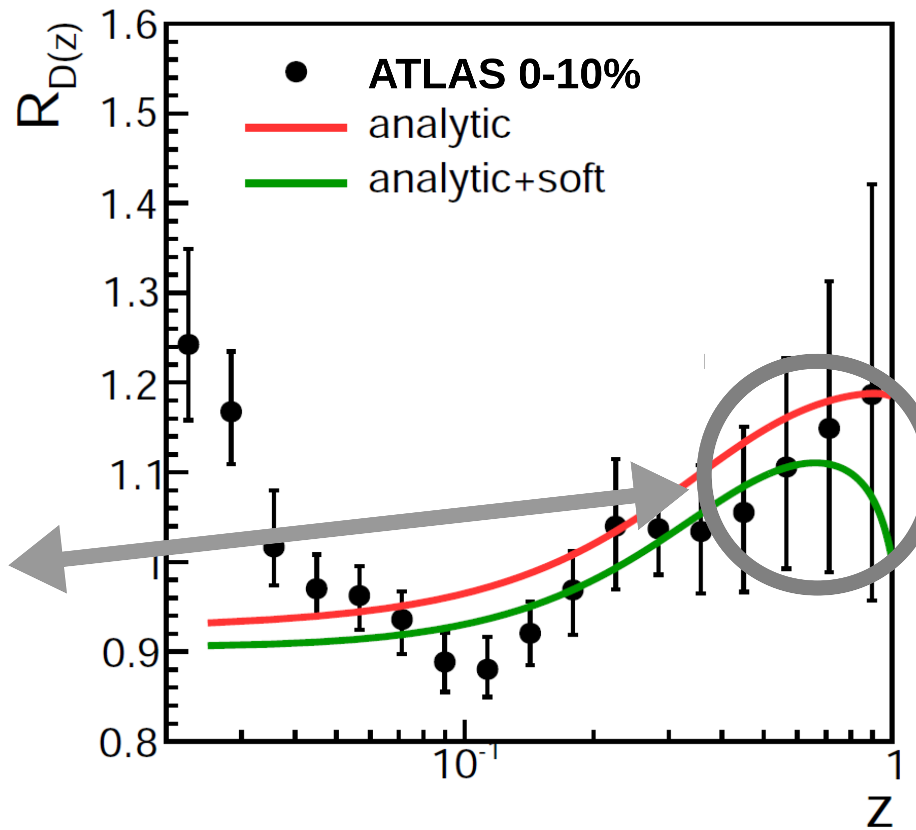
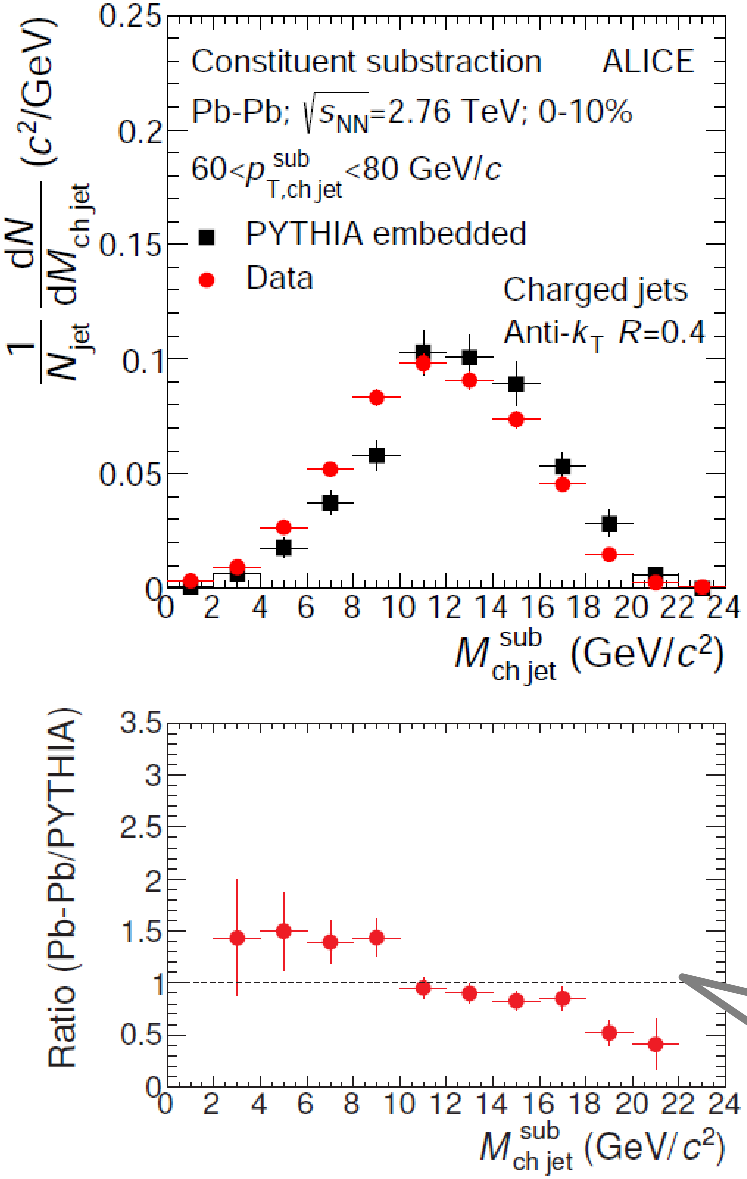


Seems observed in the data

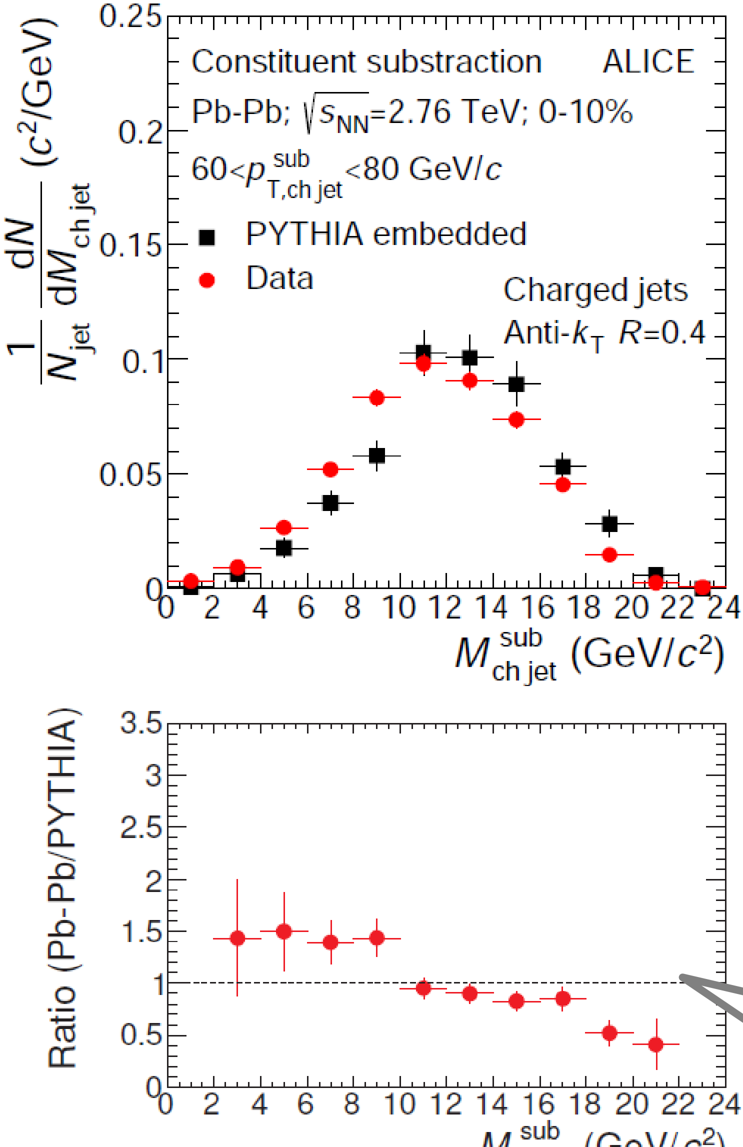


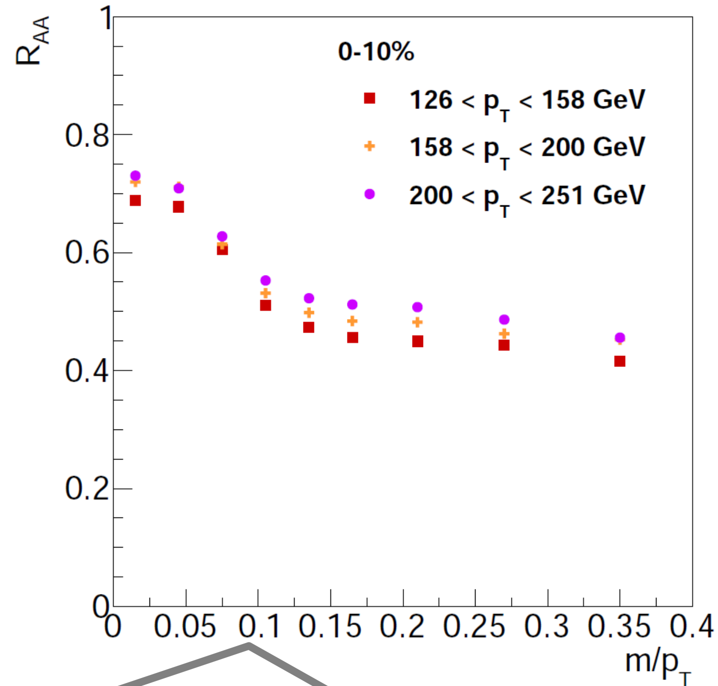
Example of other observables: non-groomed jet mass



A hint of possible shift to lower jet mass values seen in the data

Example of other observables: non-groomed jet mass



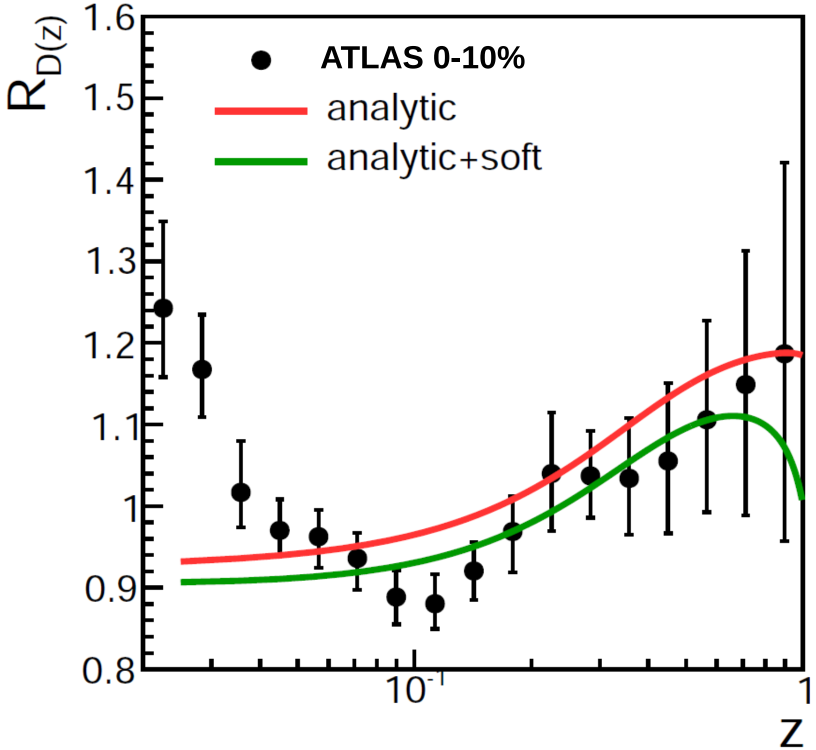


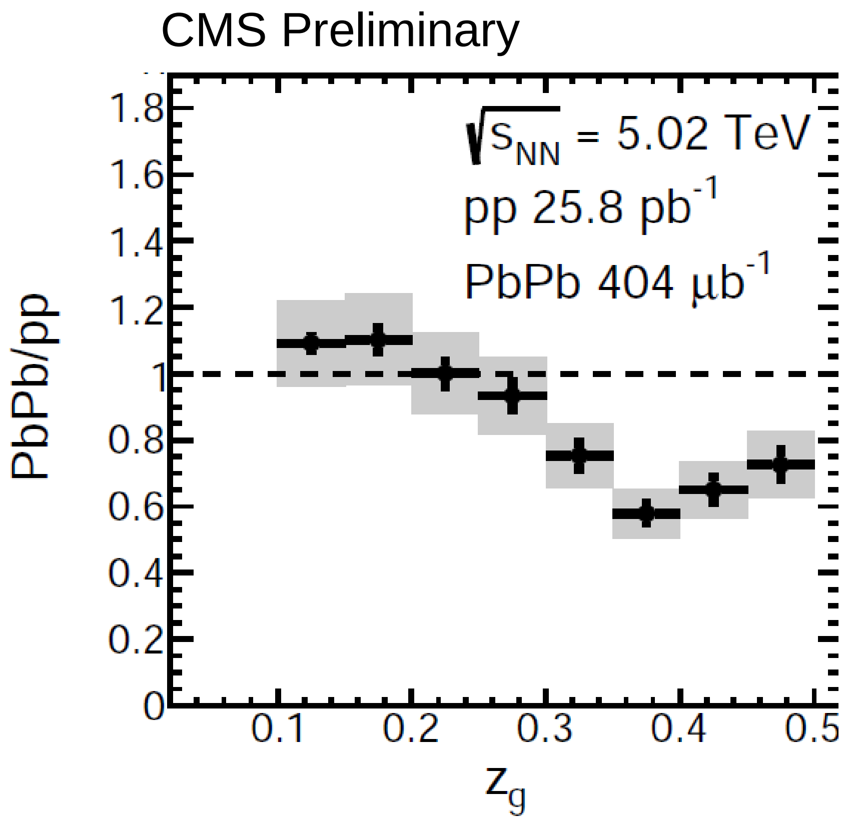
… but rather complicated observable: significant flavor dependence + dependence on recoil at low-p_T

A hint of possible shift to lower jet mass values seen in the data

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?





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J/Ψ & Ψ(2S)

What about other objects?

Data tell us that the medium largely sees a jet as one object
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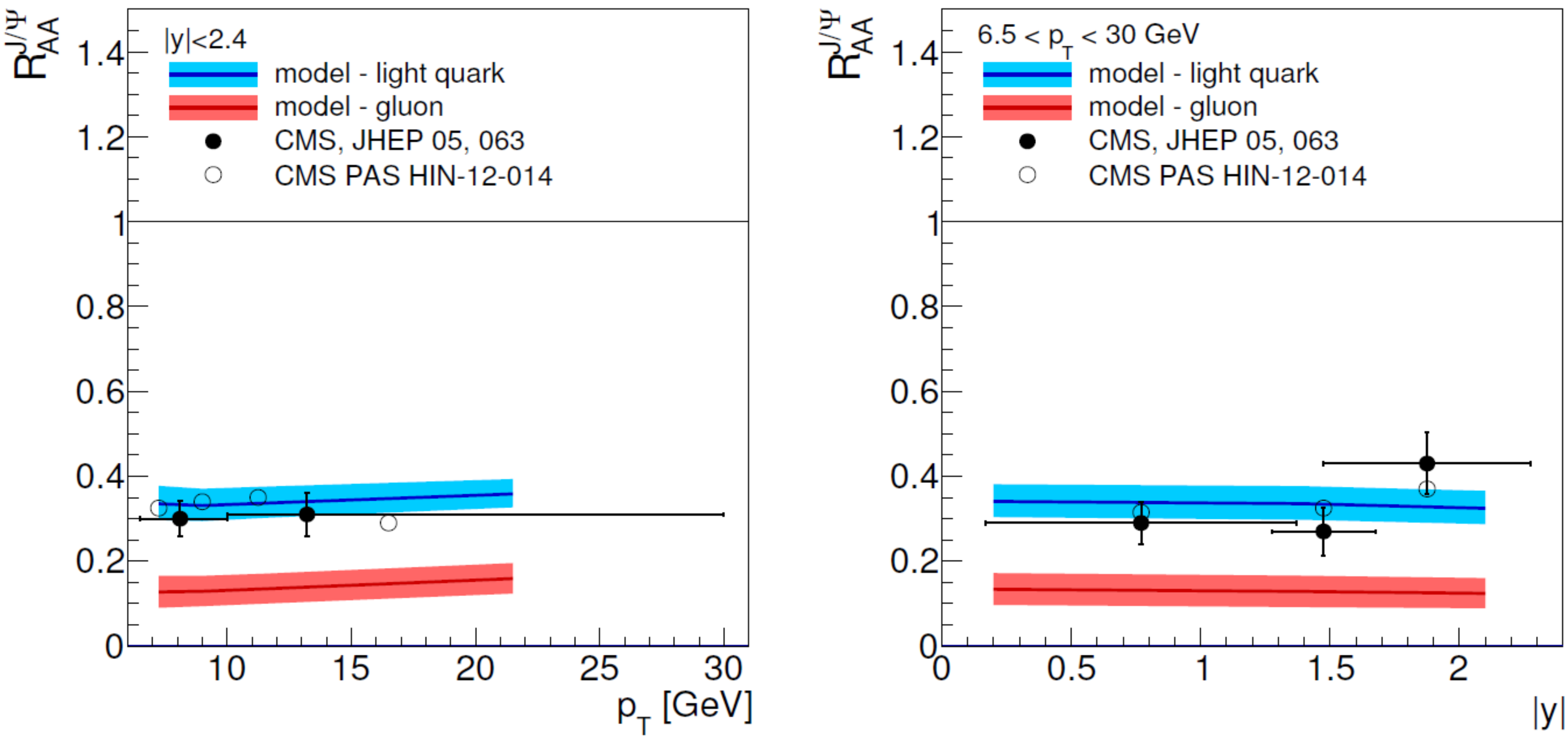
J/Ψ & $\Psi(2S)$

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

Input:

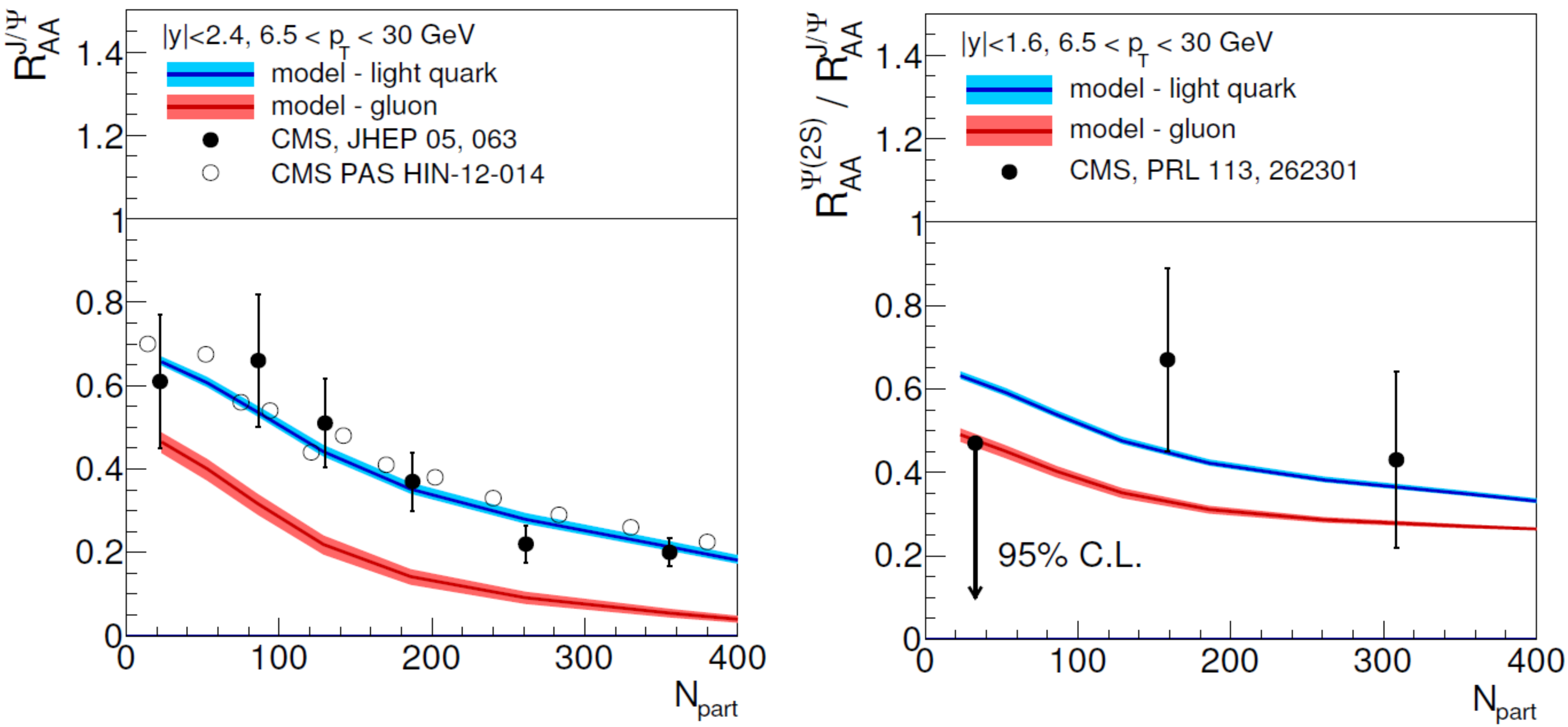
- Measured pp spectra of charmonia (cannot rely on out of the box PYTHIA or other generator)
- Energy loss extracted from jets

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]
6.5 < p_T < 30 GeV
|y|

Charmonia



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

Summary

- **Flavor** dependence of the jet quenching seems to drive quite a lot of what we see in the data.
- Average jet quenching can be **quantified** from the data as follows:

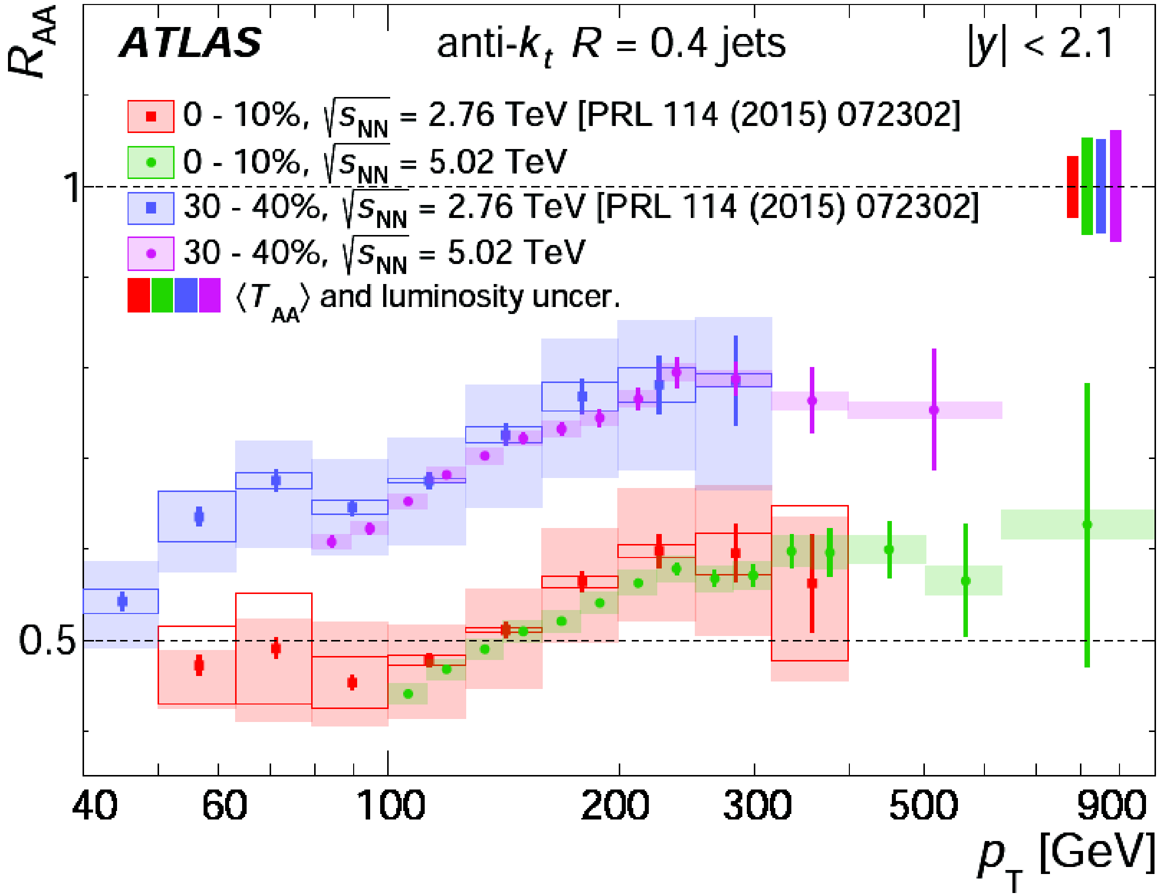
$s = x \cdot N_{\text{part}} + y$	$x = 12.3 \pm 1.4$ GeV, $y = 1.5 \pm 0.2$ GeV
α	0.52 ± 0.02
c_{F}	1.78 ± 0.12

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

- **Coherence** effects seem to be important, but for jets with pt~100 GeV they seem to **break at r~0.05**.
- **Recoil** (or in-cone radiation) can modify kinematic regions where one would not expect that (e.g. high-z fragmentation).
- **Precision** is really needed:
  – precision **data** are needed **to understand details** (recoil via high-z fragmentation, jet shapes at low r; flavor via V-jets).
  – precision **MC** is needed to have the **reference under the control**.
- Suppression of **charmonia** at p_T>6.5 GeV at midrapidity behaves like the suppression of light quark **jets**.

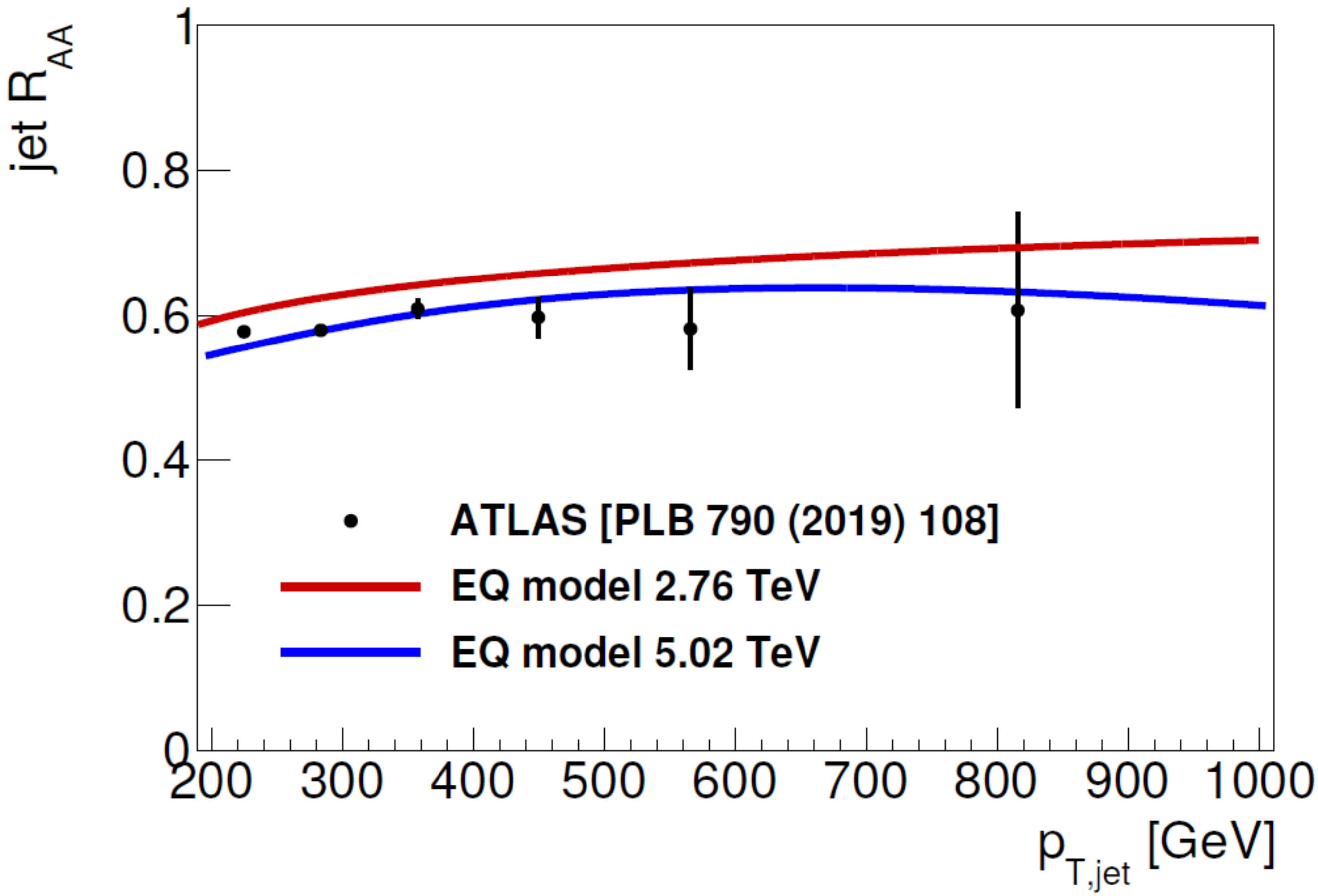
Slides with more information

5.02 TeV versus 2.76 TeV



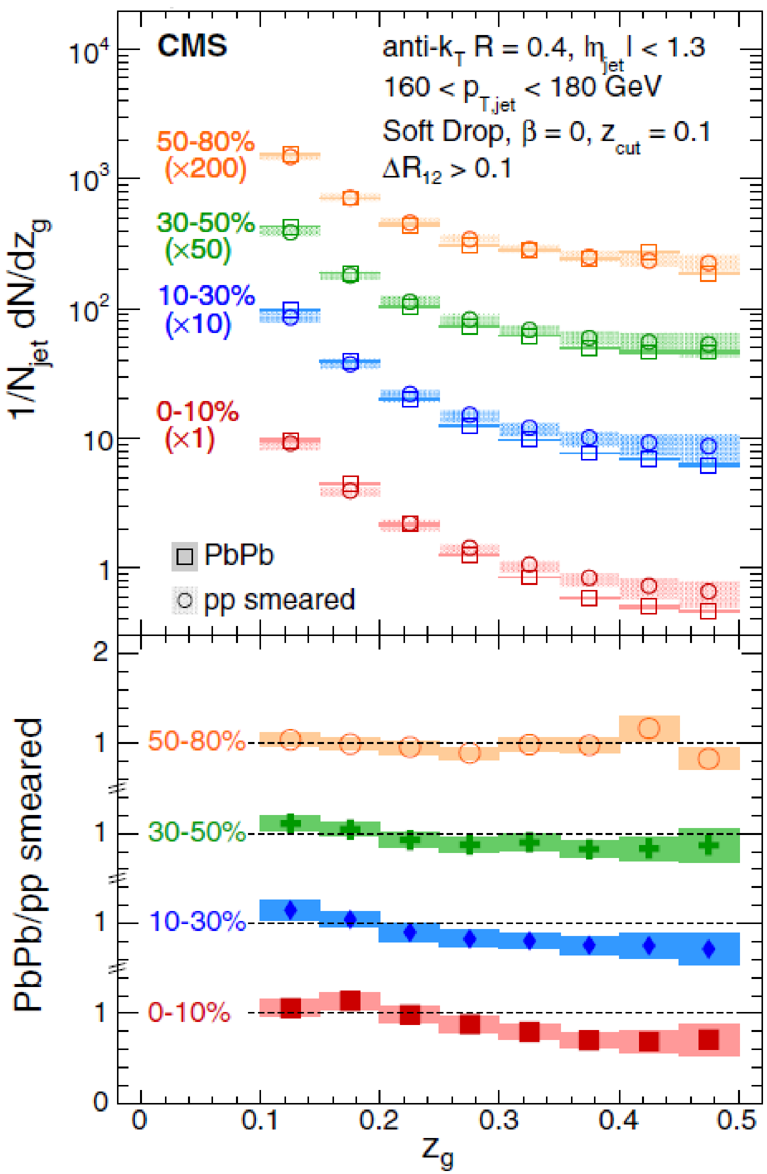
- Same jet R_{AA} … but that does not imply same energy loss.
- Spectra shape and flavor admixture are different
  => energy loss must be different.

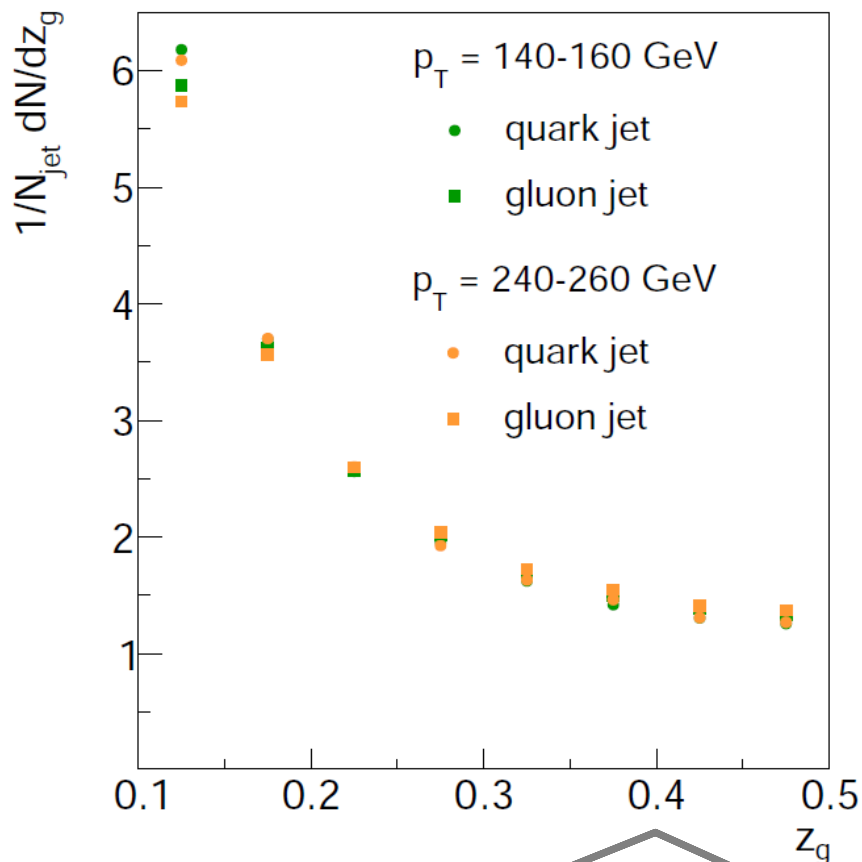
5.02 TeV versus 2.76 TeV



- Same jet R_{AA} … but that does not imply same energy loss.
- Spectra shape and flavor admixture are different
  => energy loss must be different.
- About 10% larger energy loss at 5.02 TeV compared to 2.76 TeV.

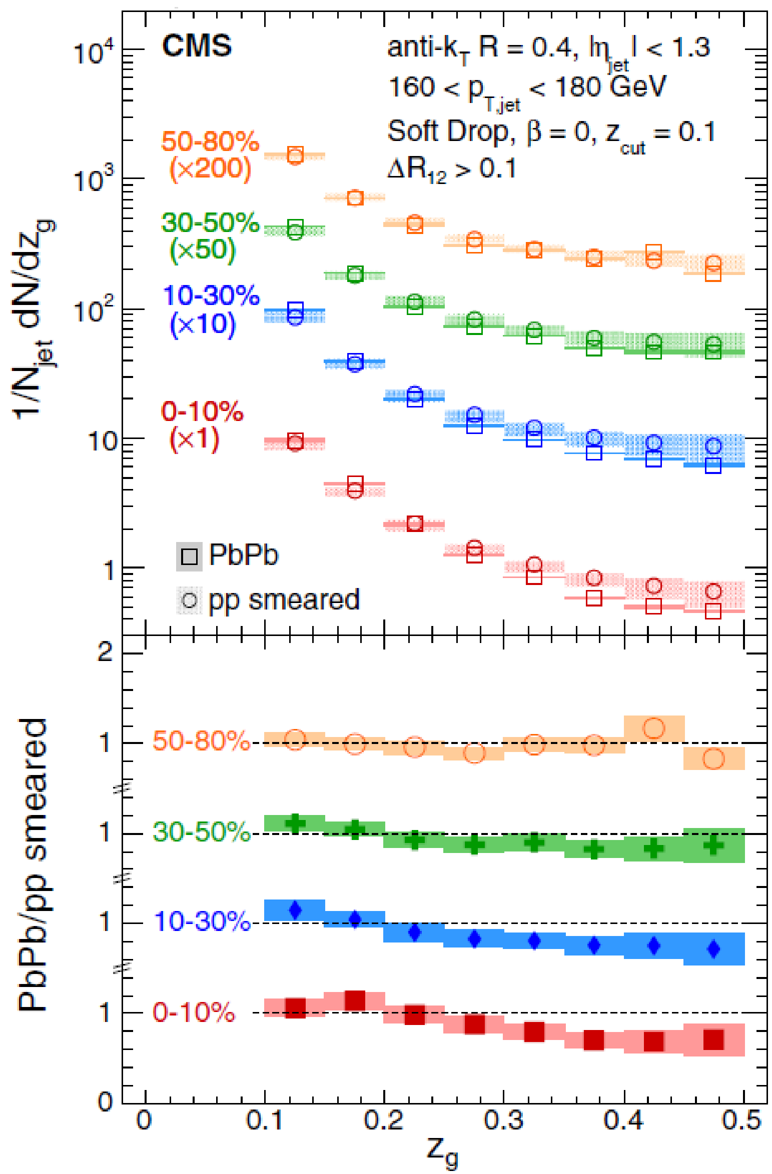
Groomed z_g … checking the impact of jet flavor

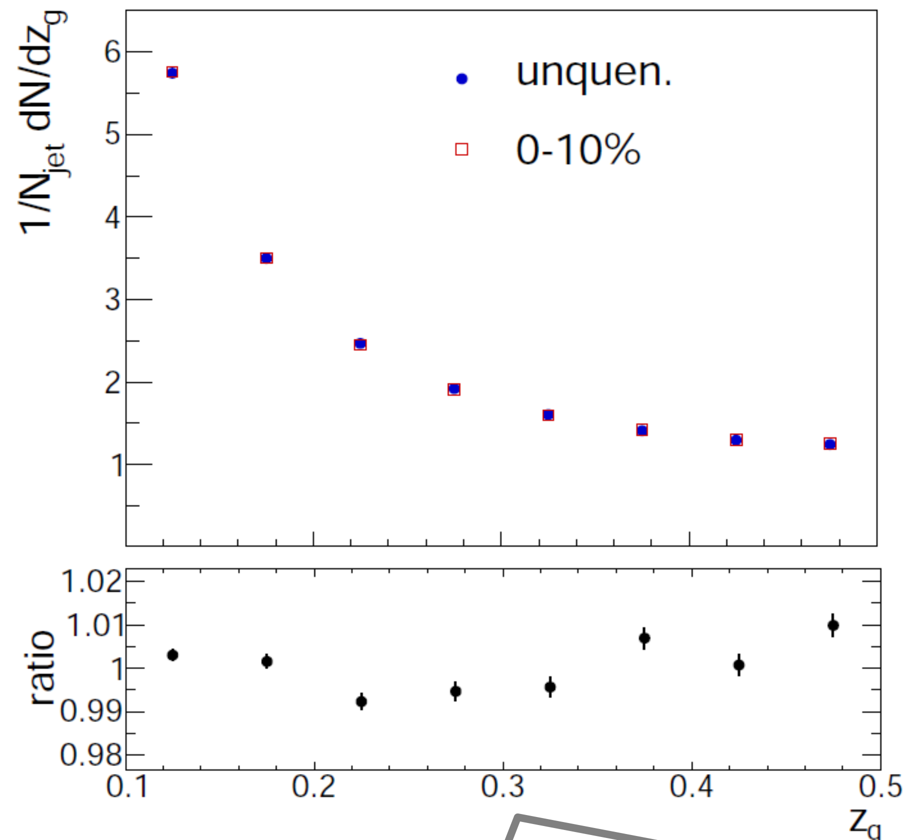




Using PYTHIA:
z_g does not depend much on the flavor or jet p_T

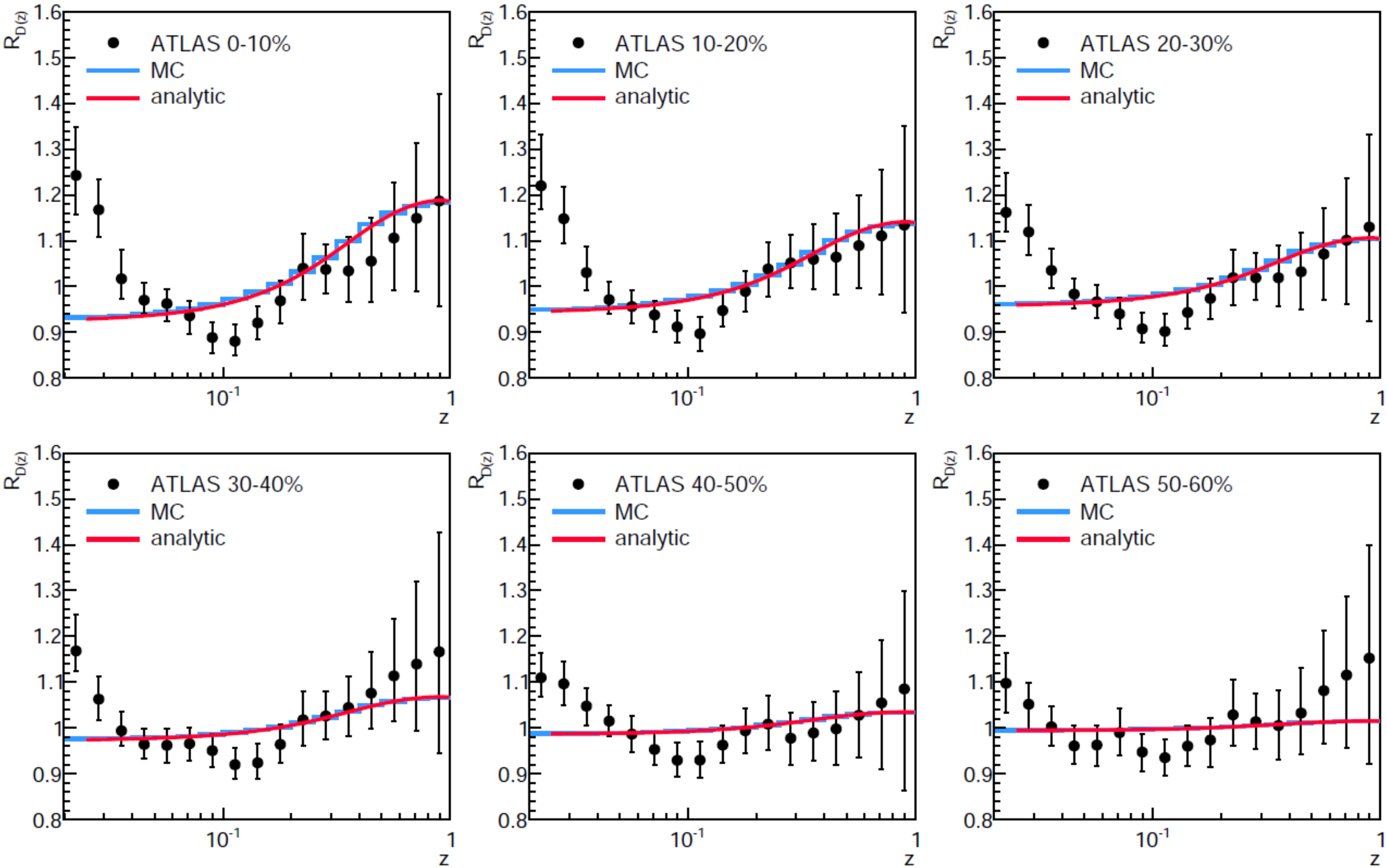
Groomed z_g … checking the impact of jet flavor





Same procedure as for modeling fragmentation functions => no modification seen => measured modification not due to a flavor

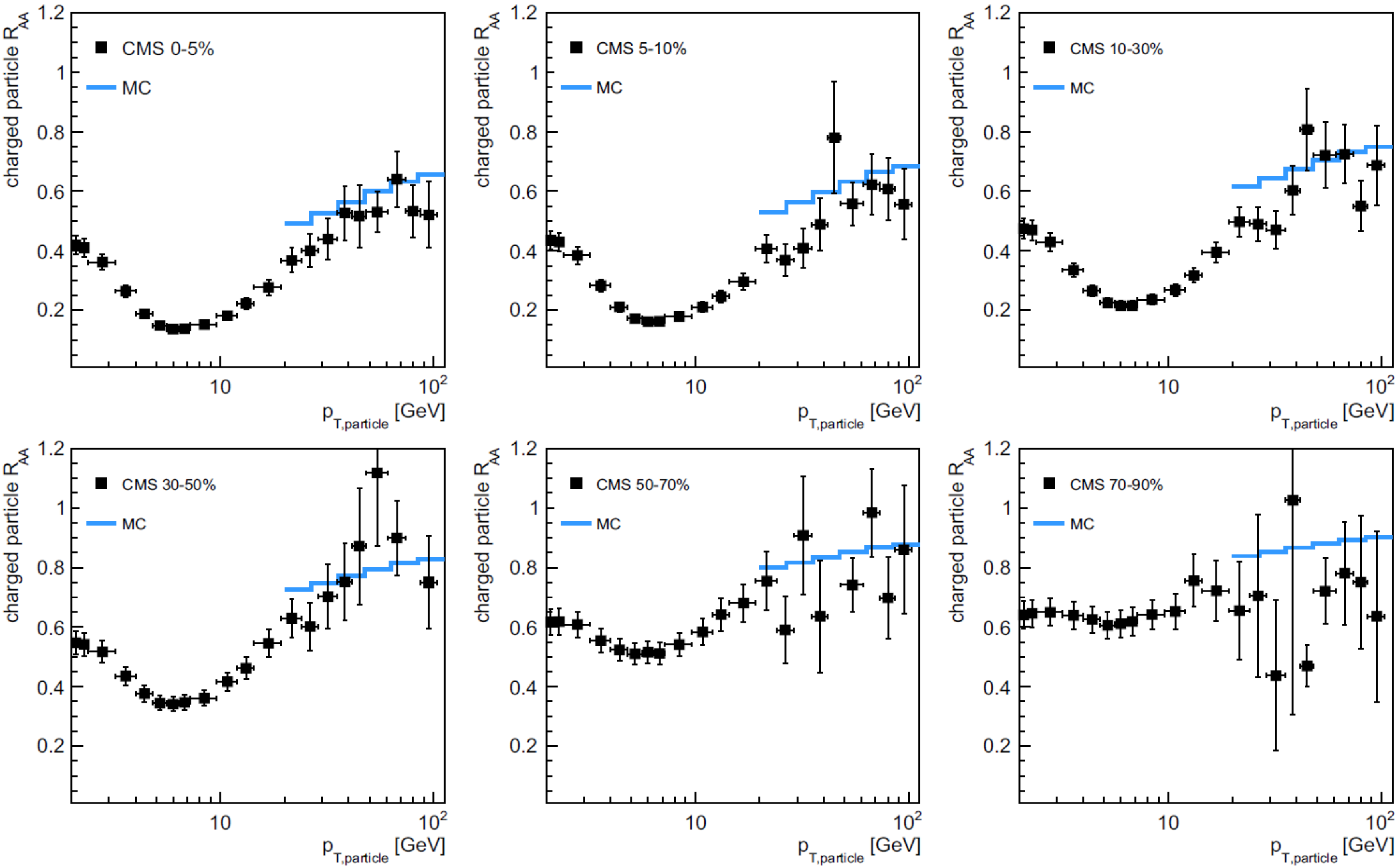
Modifications of fragmentation functions



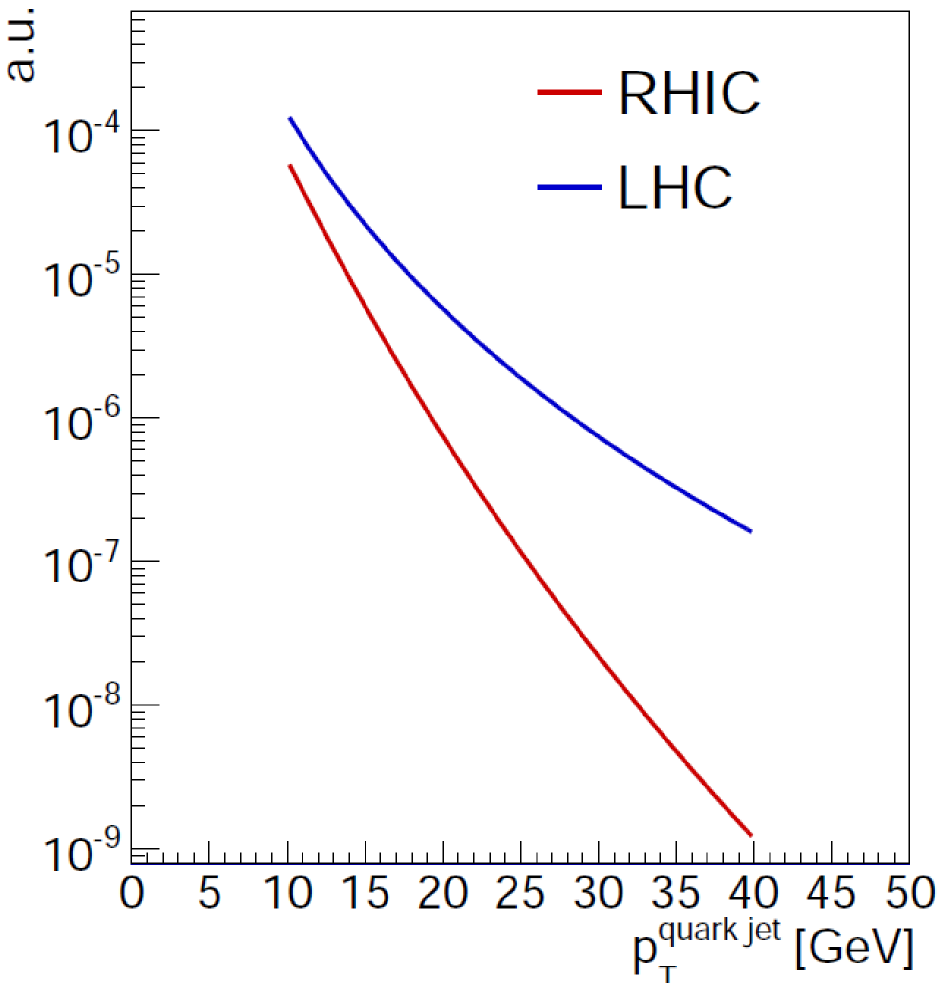
From jet internal structure to charged particle R_{AA}

Each particle of a given p_T must be in a jet of the same or higher p_T
=> Charged particle R_{AA} (at high-p_T) = convolution of flavor dependent jet suppression and fragmentation functions

From jet internal structure to charged particle R_{AA}



Jets at RHIC versus LHC

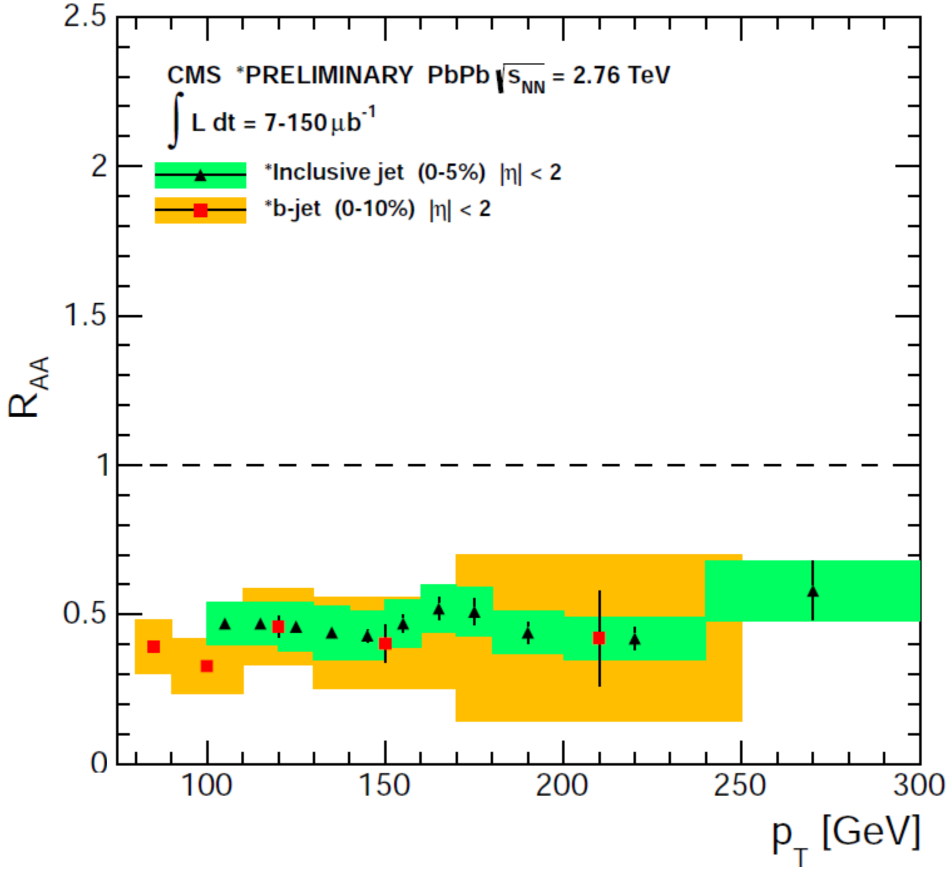


- Jets very different between LHC and RHIC
- Jet spectra for a given flavor more steep at RHIC
- Flavor composition also different

–> Will impact charged particle R_{AA}

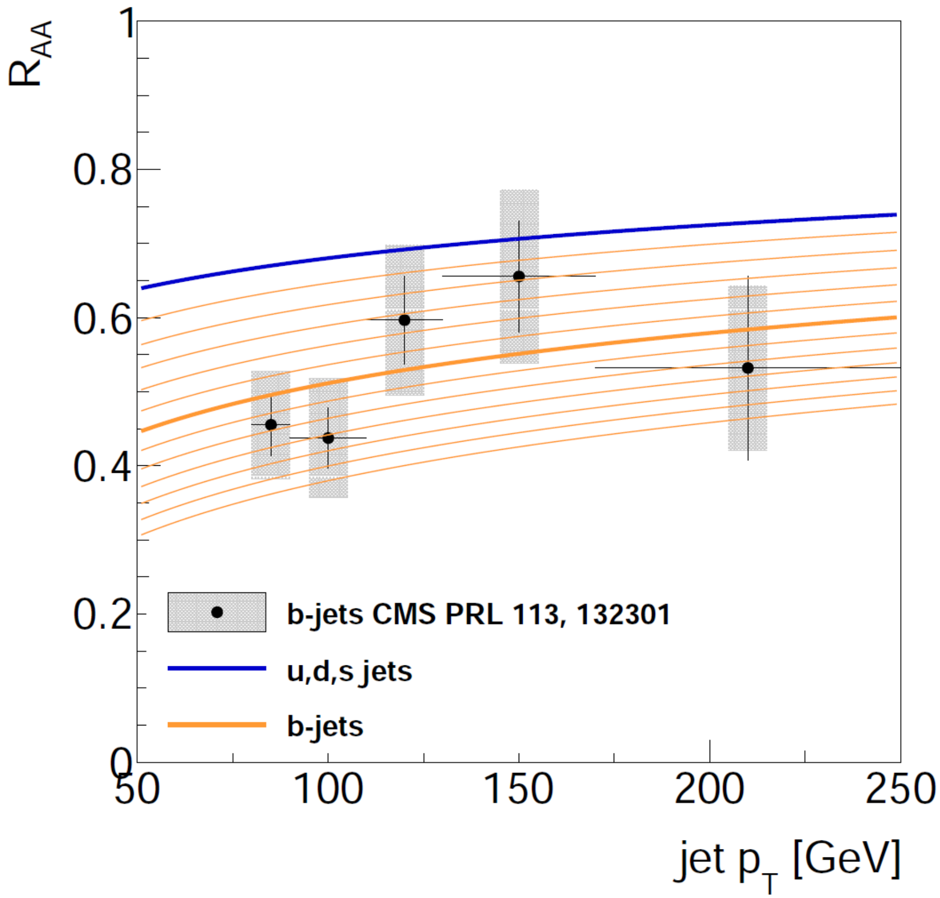
–> Apply the effective quenching factors extracted at the LHC to RHIC jets

b-jets suppression



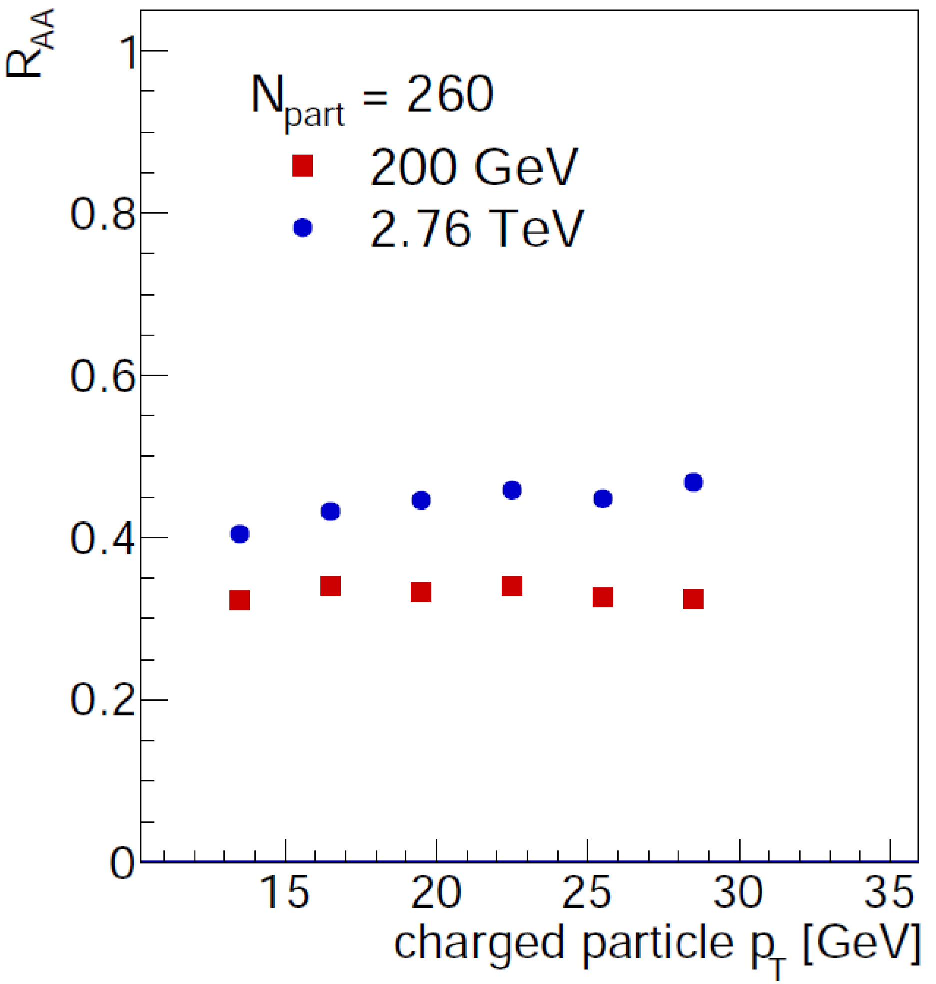
- b-jet R_{AA} … comparable with inclusive jet R_{AA} … but again, spectral shapes are different
- Moreover, just one flavor => direct comparison misleading

b-jets suppression



- b-jet R_{AA} … comparable with inclusive jet R_{AA} … but again, spectral shapes are different
- Moreover, just one flavor => direct comparison misleading
- Use the model + b-jet cross-section measurement to quantify the difference between inclusive jets and b-jets.
- Results of minimization wrt to (statistically limited) data + including role of gluon splitting: ***b*-jets are suppressed by 1.5±0.4 more** than light quark jets.

Charged particle R_{AA} RHIC vs LHC



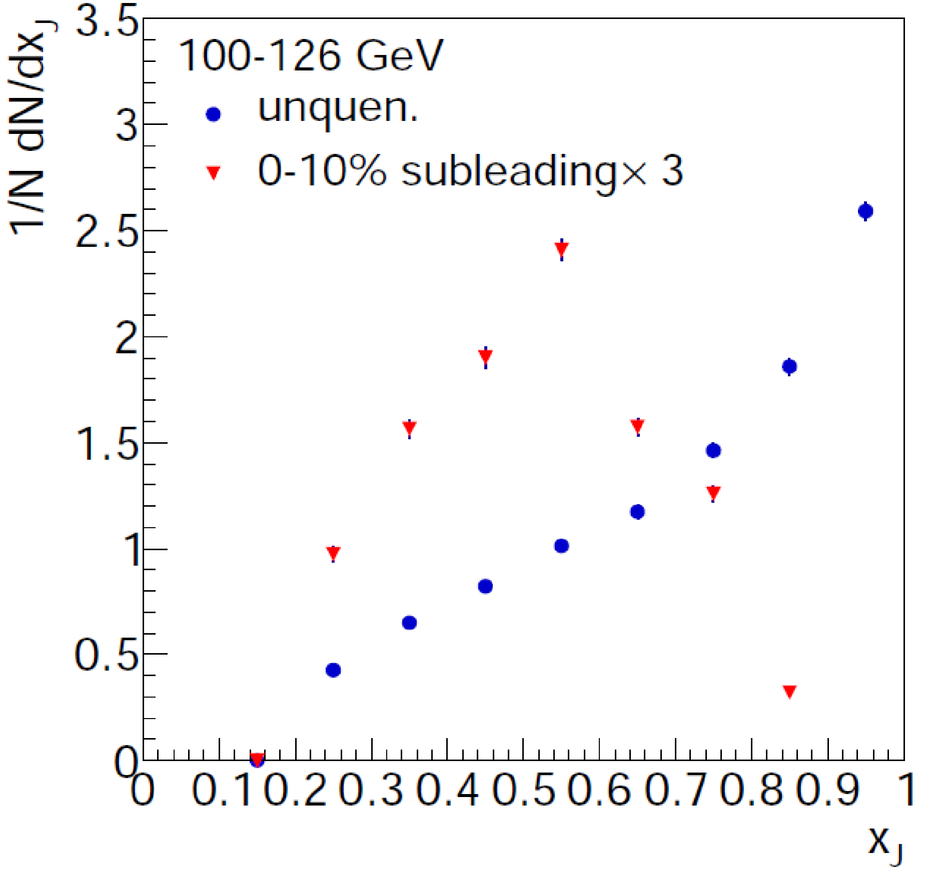
- Underlying jet spectra very different between RHIC and LHC
- Effective quenching factors from LHC applied to RHIC parton/jet spectra
- **Same quenching leads to smaller R_{AA} in the case of RHIC**

=> Initial parton spectra and flavor composition are very important for the extraction of the size of jet quenching

Dijet asymmetry

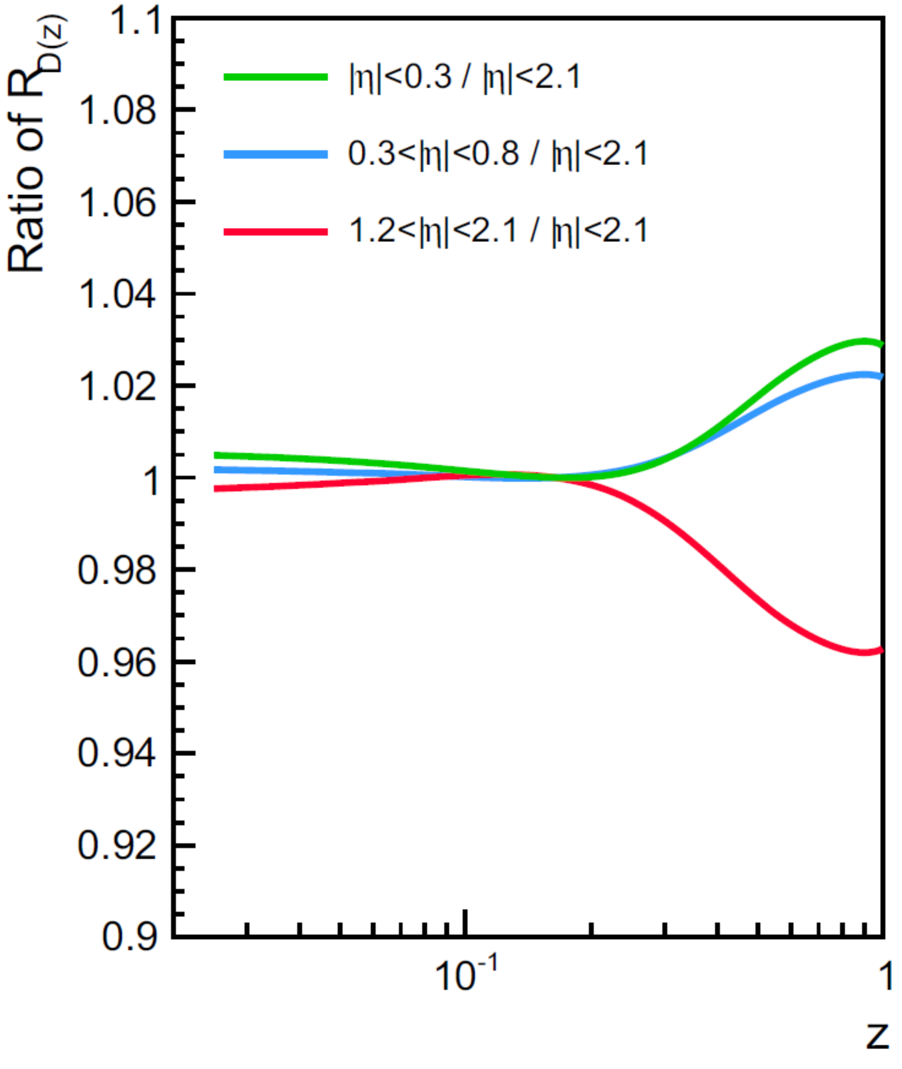
–> The subleading jet is quenched very differently then the leading jet –> quantify

–> The subleading jet in the maximum of the x_J is suppressed by a factor of ~3 larger than the leading jet



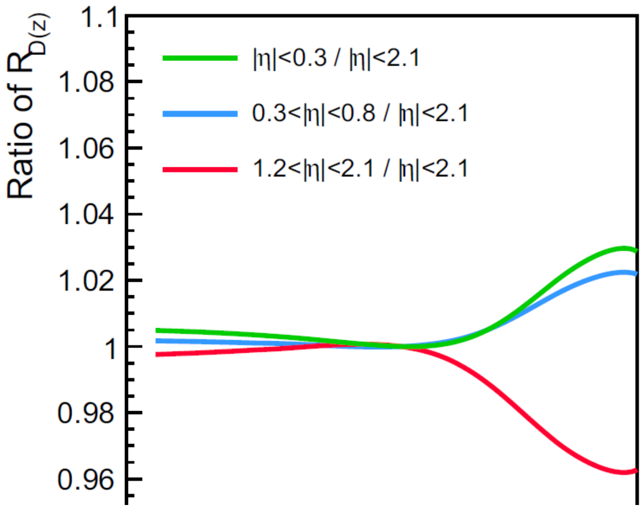
Unused slides, technical details

Modifications of fragmentation functions – prediction



… central rapidity – higher yields at high-z (but not by much)

Modifications of fragmentation functions – prediction



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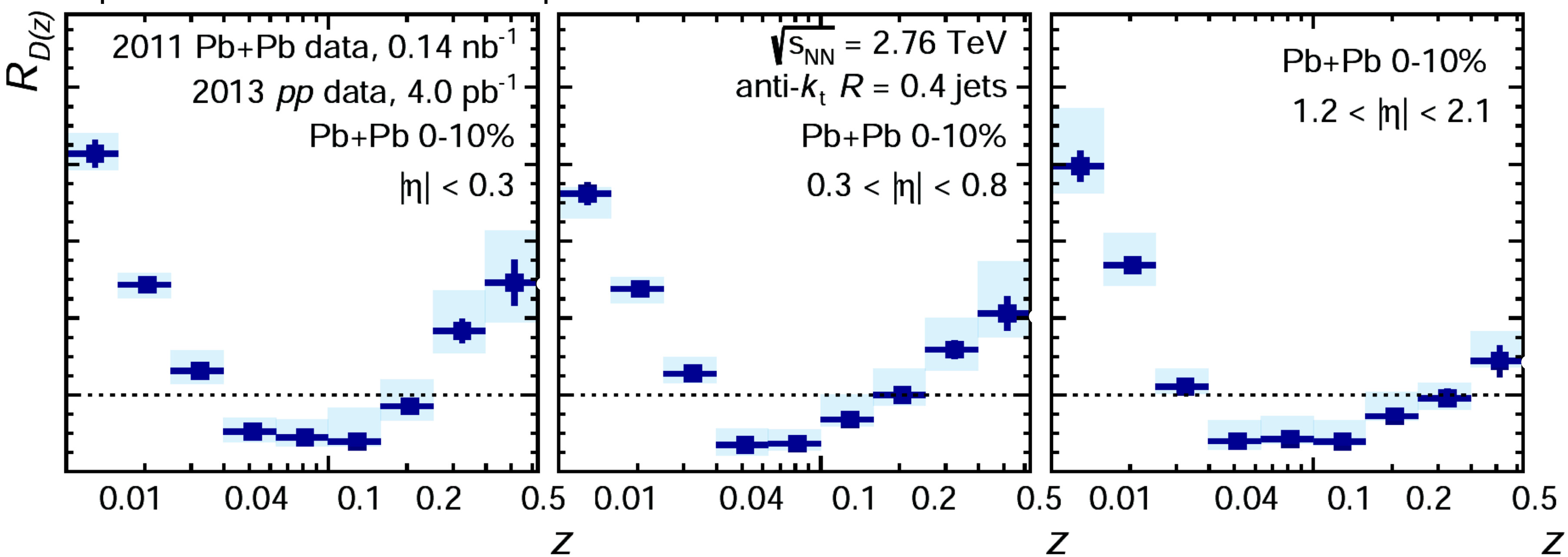
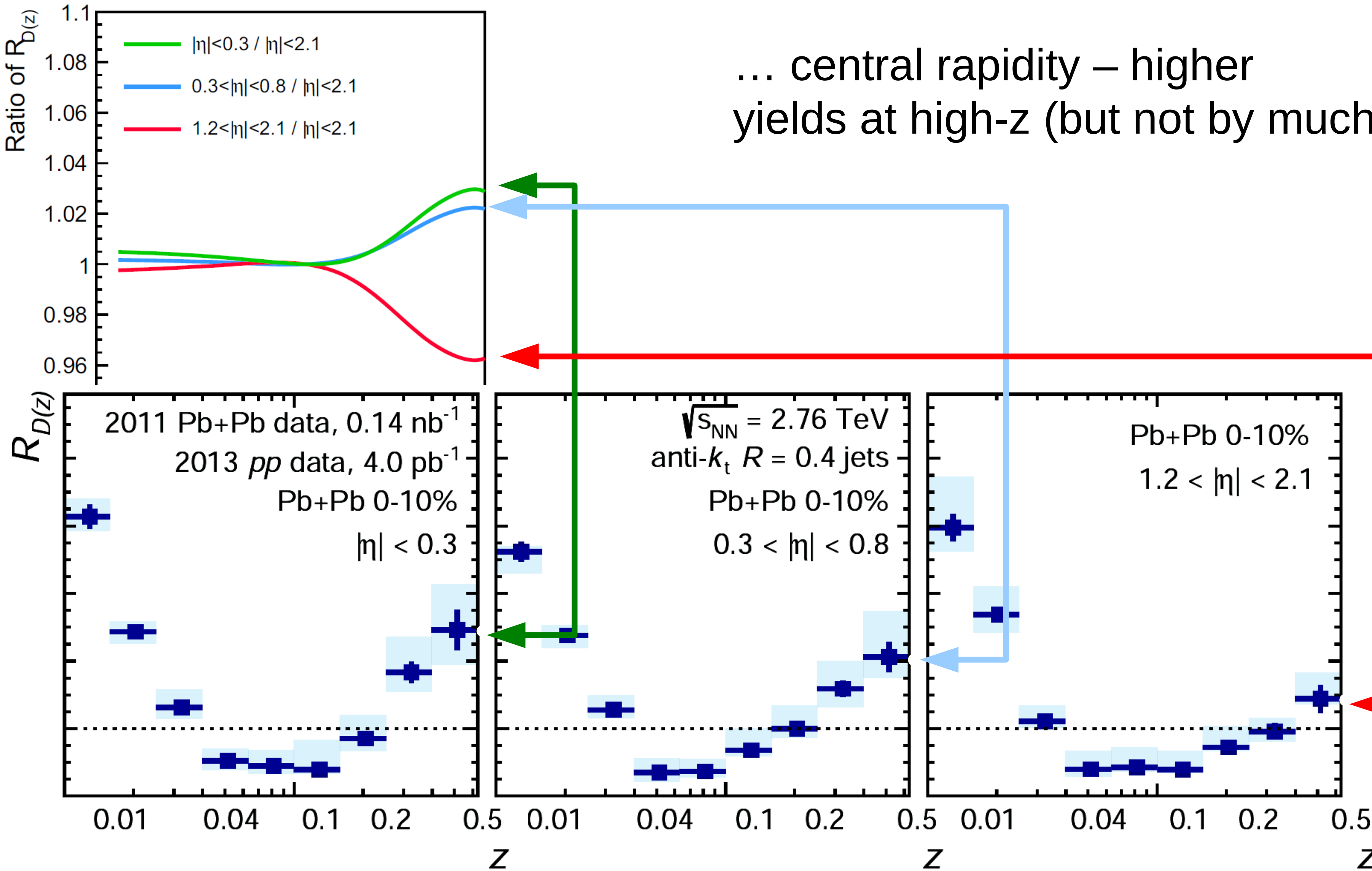


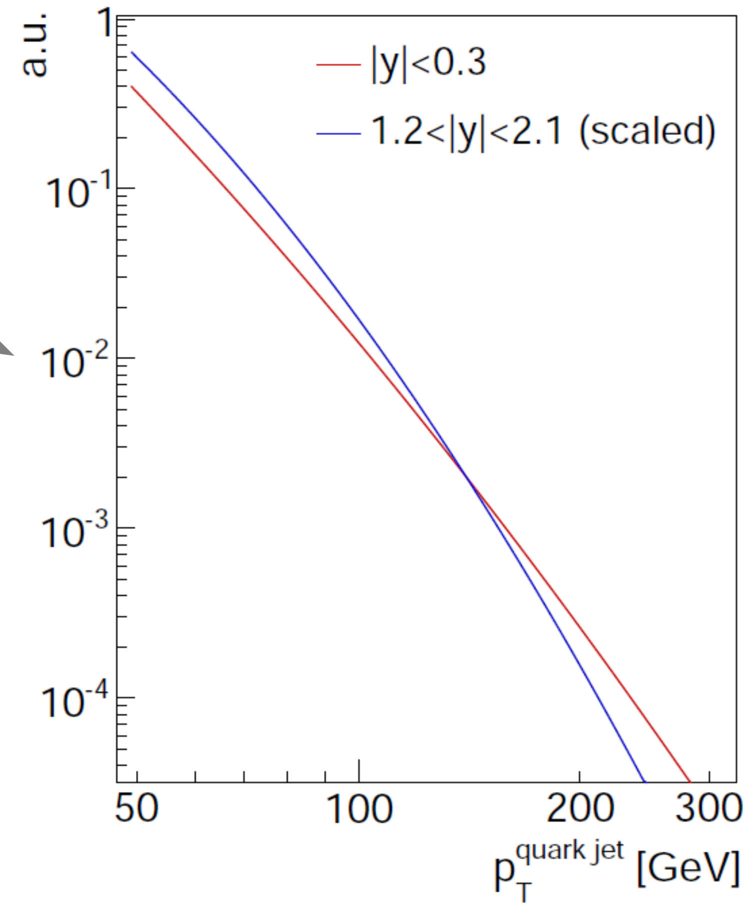
Modifications of fragmentation functions – prediction



… central rapidity – higher yields at high-z (but not by much)

Start: Two basic questions

- Why do have the jet and charge particle R_{AA} almost **no rapidity dependence** given quite different input parton spectra and flavor composition at different rapidities?
- What is responsible for the **enhancement** (= not suppression) at high *z* seen in the fragmentation?



Start: Two basic questions

- Why do have the jet and charge particle R_{AA} almost **no rapidity dependence** given quite different input parton spectra and flavor composition at different rapidities?
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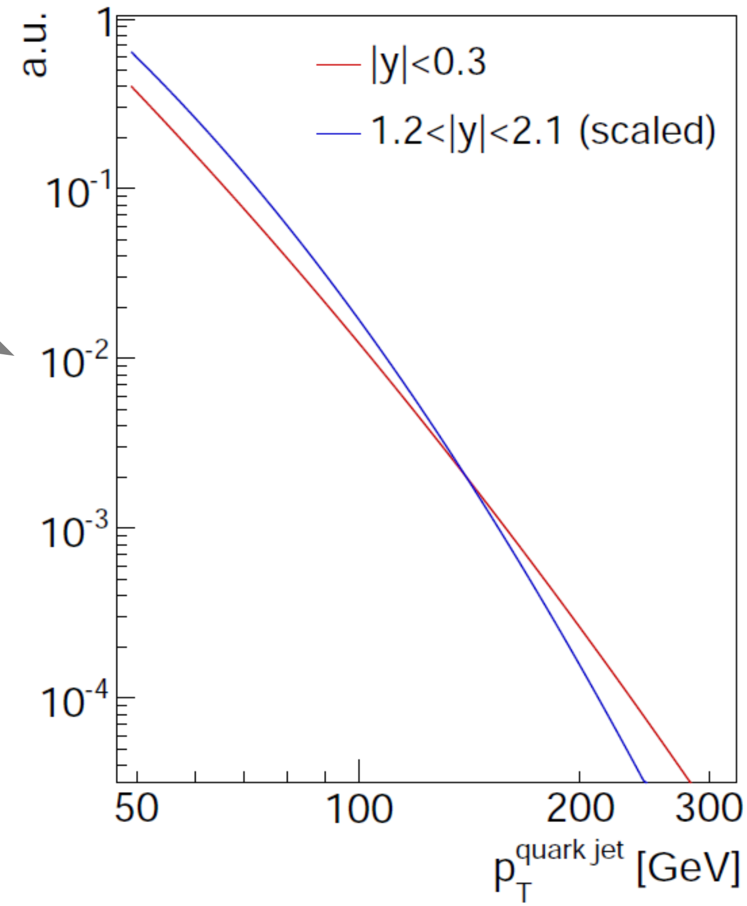
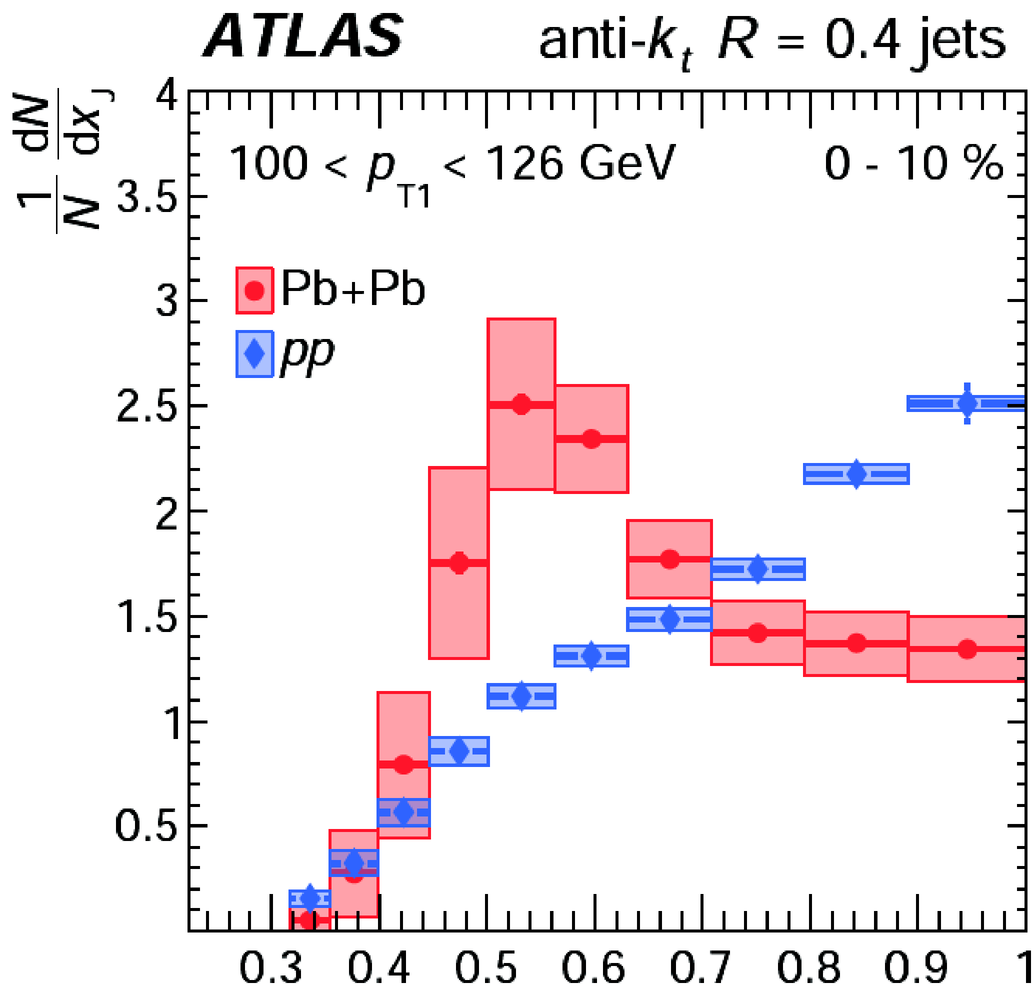


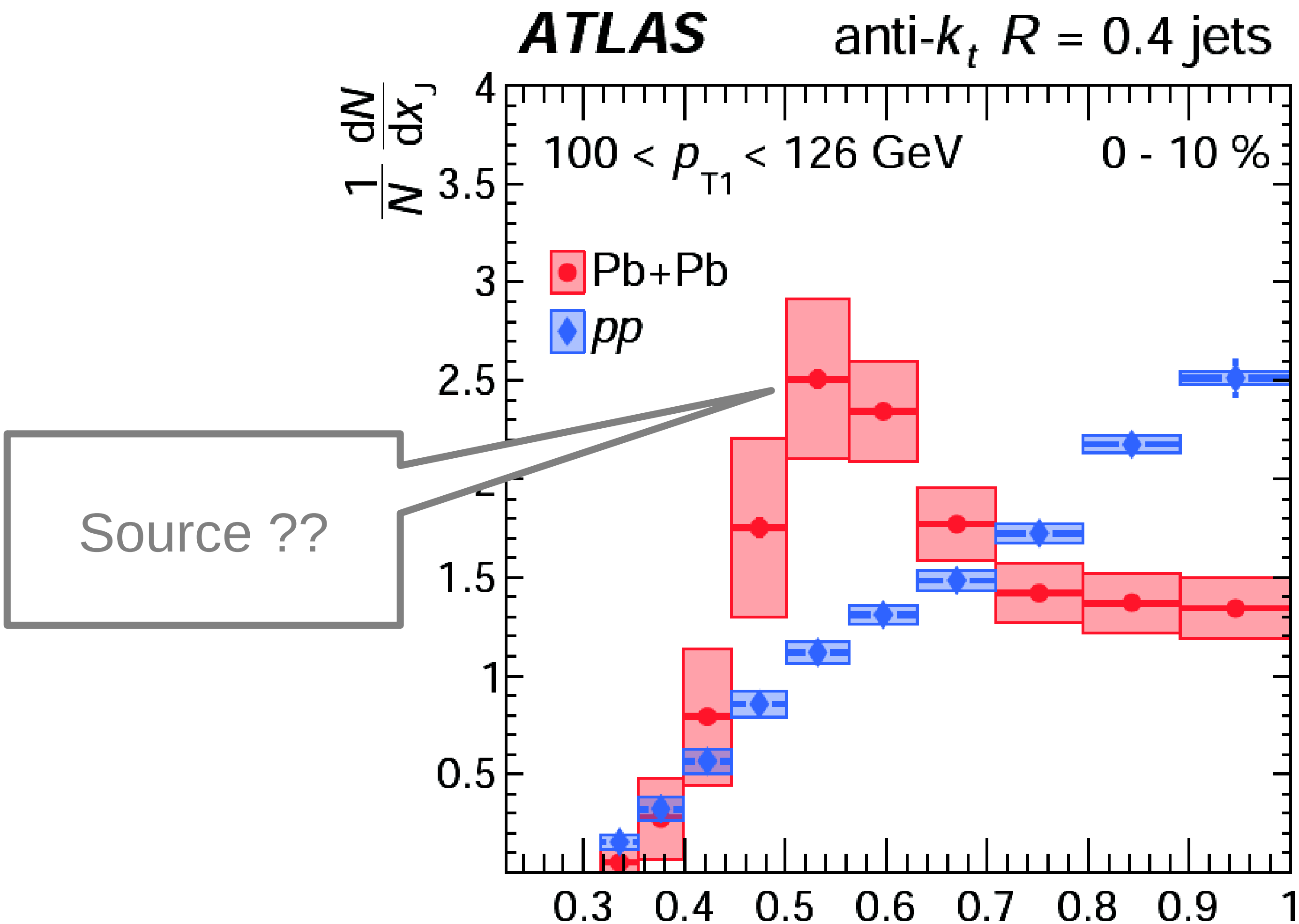
–> Use a simple model with minimal assumptions on the quenching physics to extract basic properties of the jet quenching

Dijet asymmetry



$$x_J = \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}}}$$

Dijet asymmetry



$$x_J = \frac{p_{T,\mathrm{subleading}}}{p_{T,\mathrm{leading}}}$$

Dijet asymmetry

- Test the role of path-length dependence

$$S(p_{T,\mathrm{ini}}, l) =$$
$$= \frac{c_{\mathrm{F}}\, s}{\langle l \rangle} \left(\frac{p_{T,\mathrm{ini}}}{p_{T,0}} \right)^{\alpha} f(l)$$

$$l^k$$
$$k = 0.5, 1, 2, 3$$

$$l = \int \mathrm{d}\tau\, \tau \rho(\vec{r})$$

Dijet asymmetry

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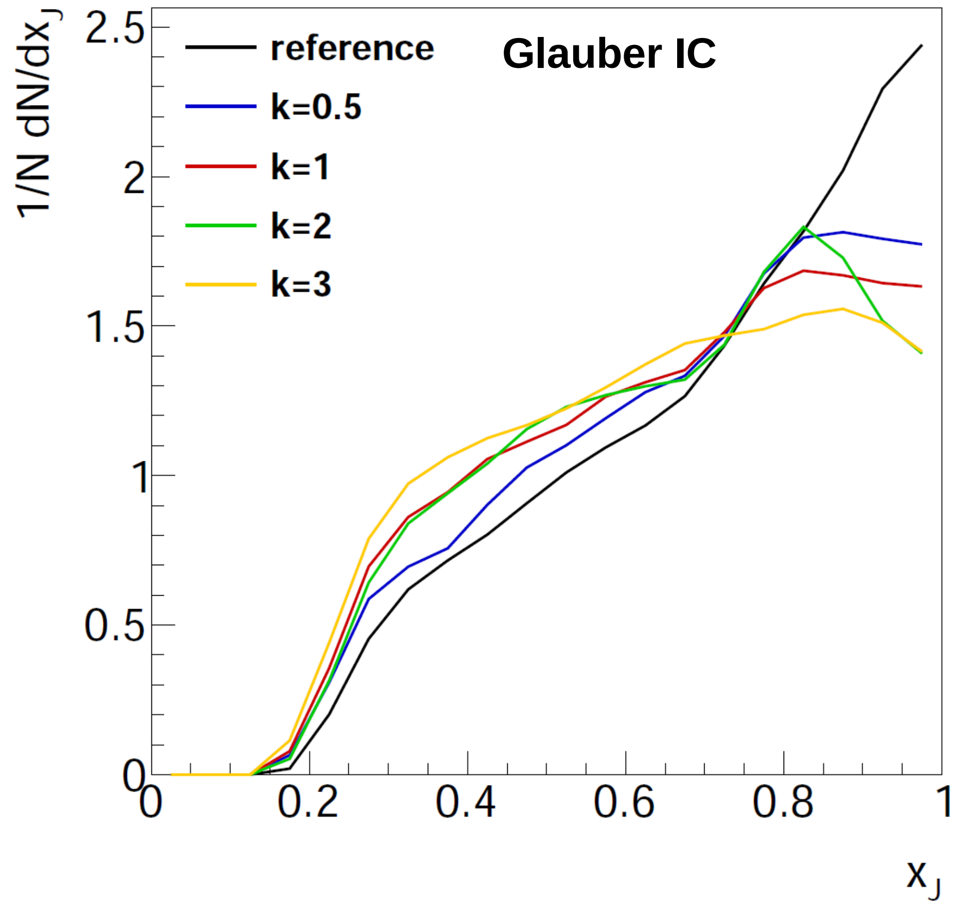

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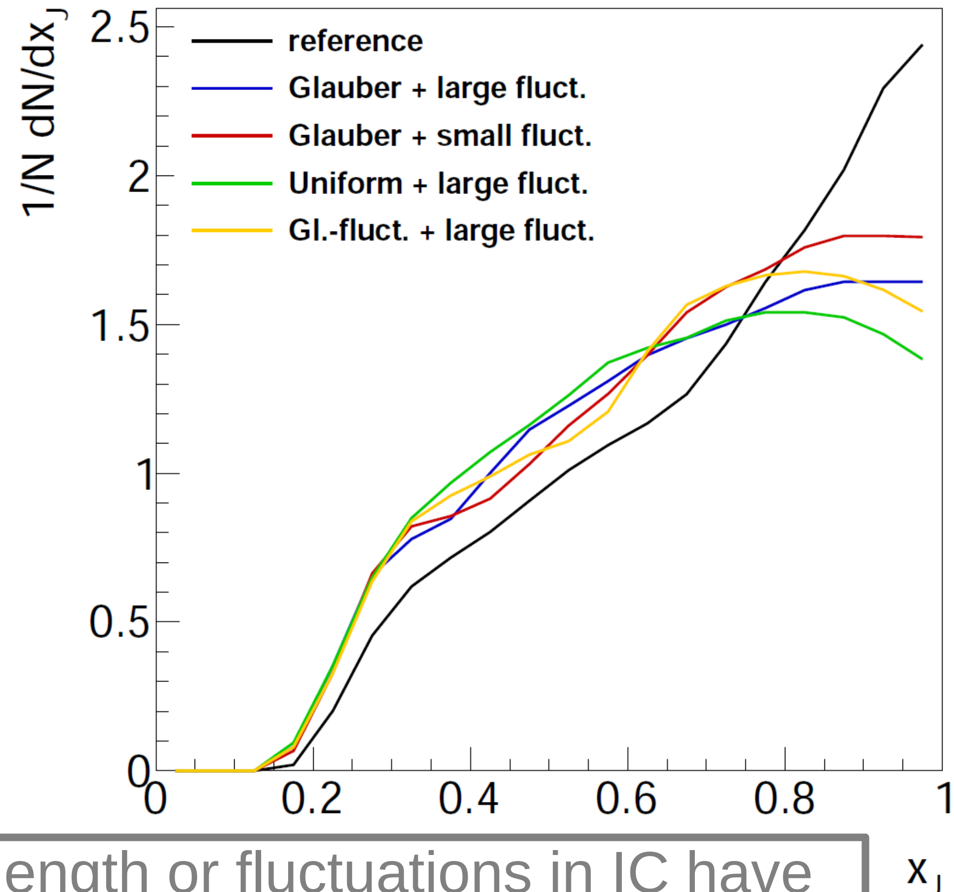
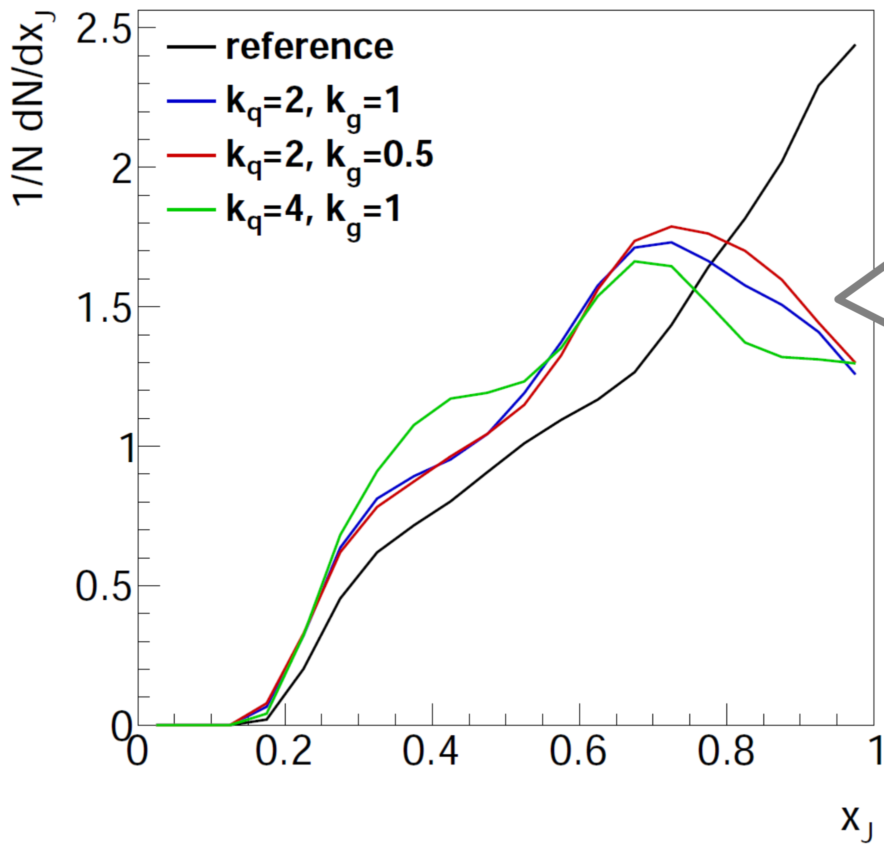


Path-length or fluctuations in IC have no major impact (similar conclusions in EPJC 76 (2016) no.5, 288)

Dijet asymmetry

- Test the role of flavor

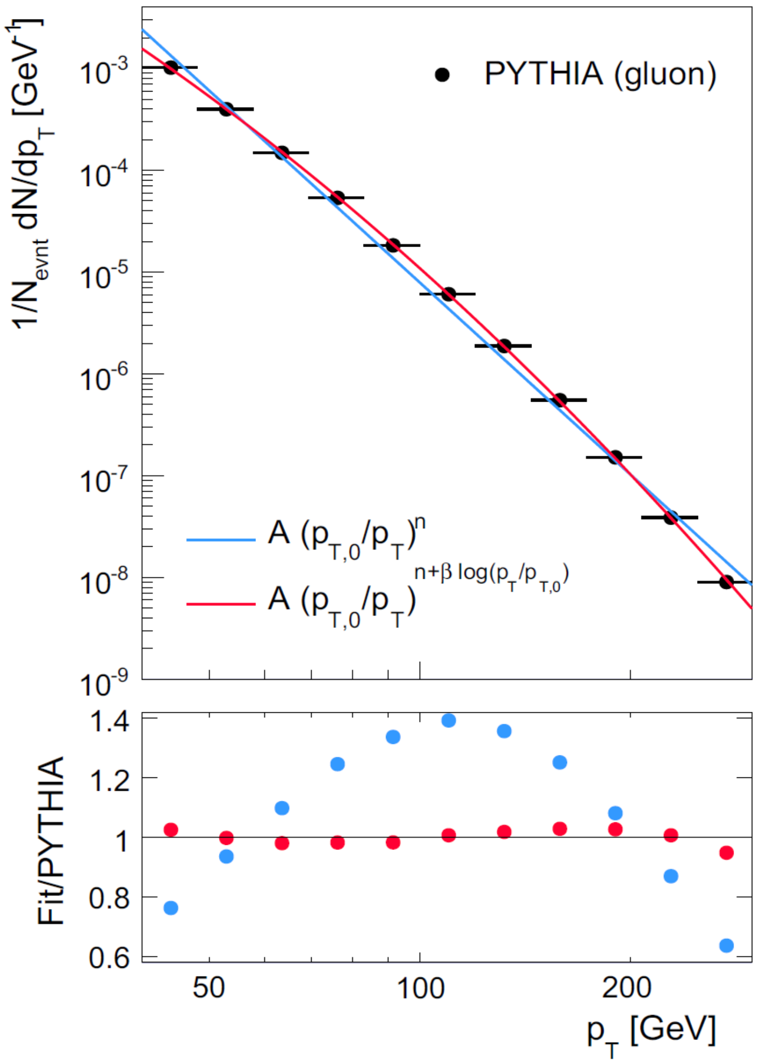
$$S(p_{T,\mathrm{ini}}, l) = \frac{c_\mathrm{F}\, s}{\langle l^{k(c_\mathrm{F})}\rangle}\left(\frac{p_{T,\mathrm{ini}}}{p_{T,0}}\right)^{\alpha} f(l^{k(c_\mathrm{F})})$$



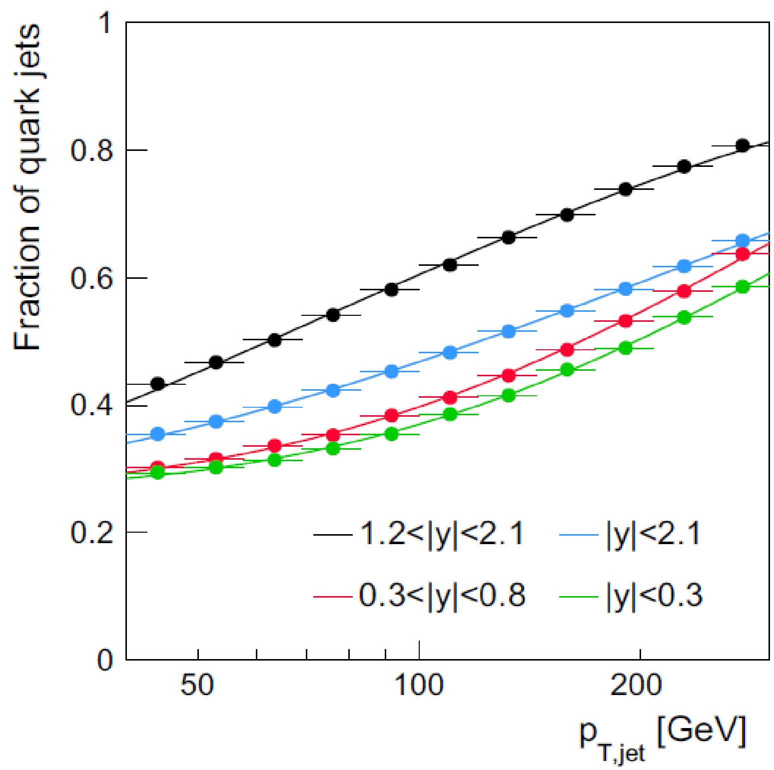
Peaking in the configurations when the loss of quark jets is more non-linear than the loss of gluon jets

… contra-intuitive

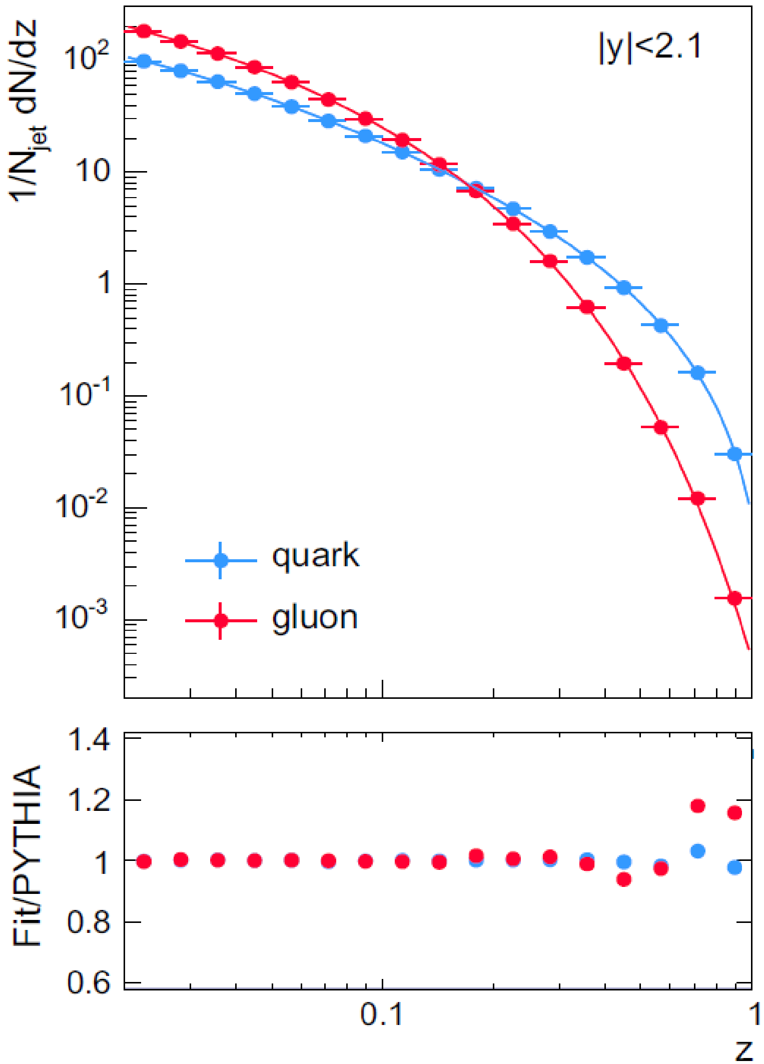
Flavor fractions and fit parameters



Fit type	Parameter	$\|y\| < 2.1$	$\|y\| < 0.3$	$0.3 < \|y\| < 0.8$	$1.2 < \|y\| < 2.1$
All	f_{q0}	0.34	0.28	0.29	0.40
Power law	n_q	5.66	5.37	5.40	6.15
	n_g	6.25	5.97	6.09	6.92
Extended power law	n_q	4.19	4.34	4.27	3.75
	β_q	0.71	0.49	0.54	1.2
	n_g	4.69	4.55	4.57	4.60
	β_g	0.80	0.71	0.76	1.2



D(z) parameterization



$$D(z) = a \cdot \frac{(1+dz)^b}{(1+ez)^c} \cdot \exp(-fz)$$

	a	b	c	d	e	f
Quark	318	2.51	1.44	−0.85	52.4	0
Gluon	574	1.87	2.32	9.09	32.0	10.3

R_{AA} – full analytic expression

$$R_{\mathrm{AA}} = f_q \left(\frac{1}{1+S_q/p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{n_q+\beta_q \log((p_{\mathrm{T}}^{\mathrm{jet}}+S_q)/p_{\mathrm{T}0})}$$

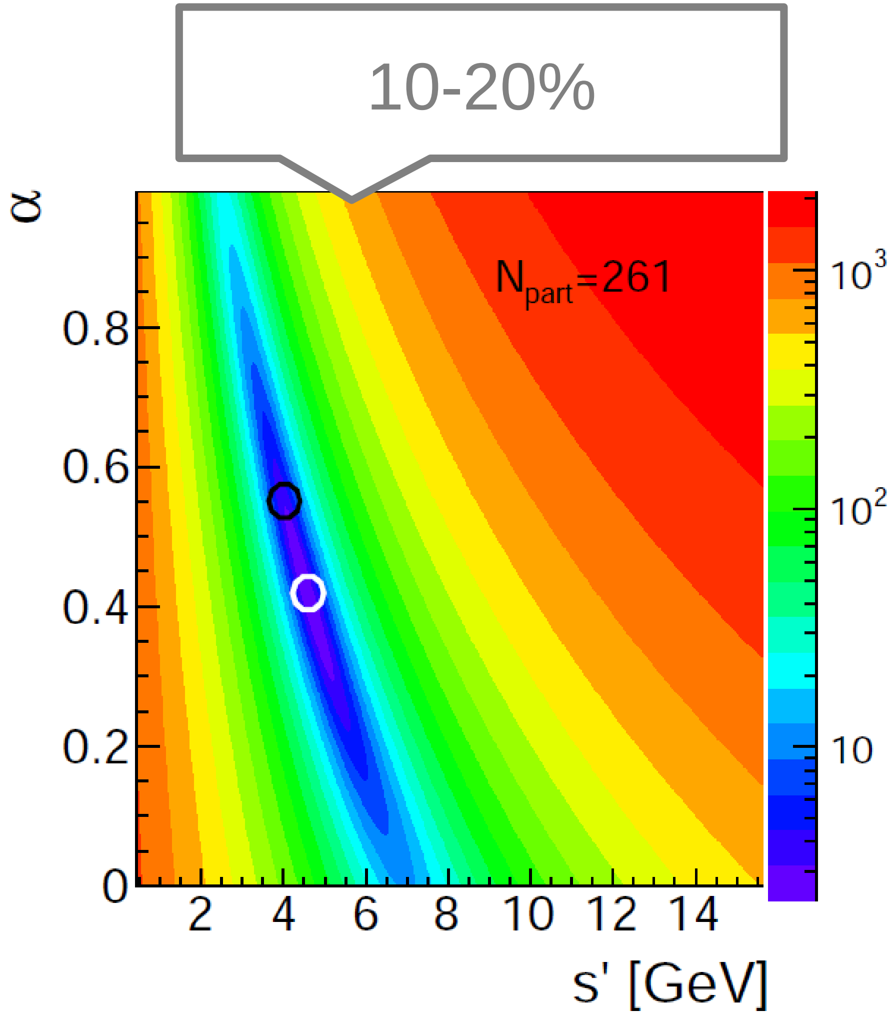
$$\times \left(\frac{p_{\mathrm{T}0}}{p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{\beta_q \log(1+S_q/p_{\mathrm{T}}^{\mathrm{jet}})} \left(1+\frac{dS_q}{dp_{\mathrm{T}}^{\mathrm{jet}}}\right)$$

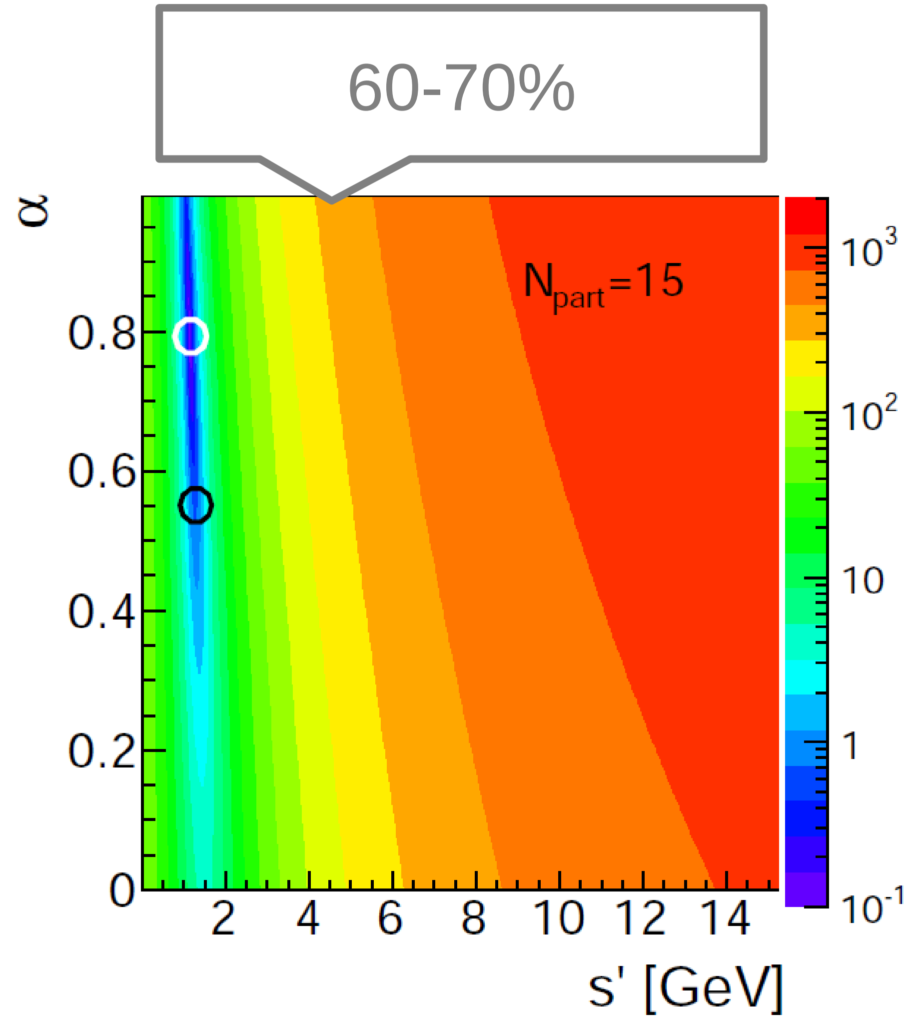
$$+ (1-f_q) \left(\frac{1}{1+S_g/p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{n_g \beta_g \log((p_{\mathrm{T}}^{\mathrm{jet}}+S_g)/p_{\mathrm{T}0})}$$

$$\times \left(\frac{p_{\mathrm{T}0}}{p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{\beta_g \log(1+S_g/p_{\mathrm{T}}^{\mathrm{jet}})} \left(1+\frac{dS_g}{dp_{\mathrm{T}}^{\mathrm{jet}}}\right),$$

$$f_q\left(p_{\mathrm{T}}^{\mathrm{jet}}\right) = \frac{1}{1+\left(\frac{1-f_{q0}}{f_{q0}}\right)\left(\frac{p_{\mathrm{T}0}}{p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{n_g-n_q+(\beta_g-\beta_q)\log\left(p_{\mathrm{T}}^{\mathrm{jet}}/p_{\mathrm{T}0}\right)}}.$$

Minimization in (I.)





Modifications of fragmentation functions – a detail

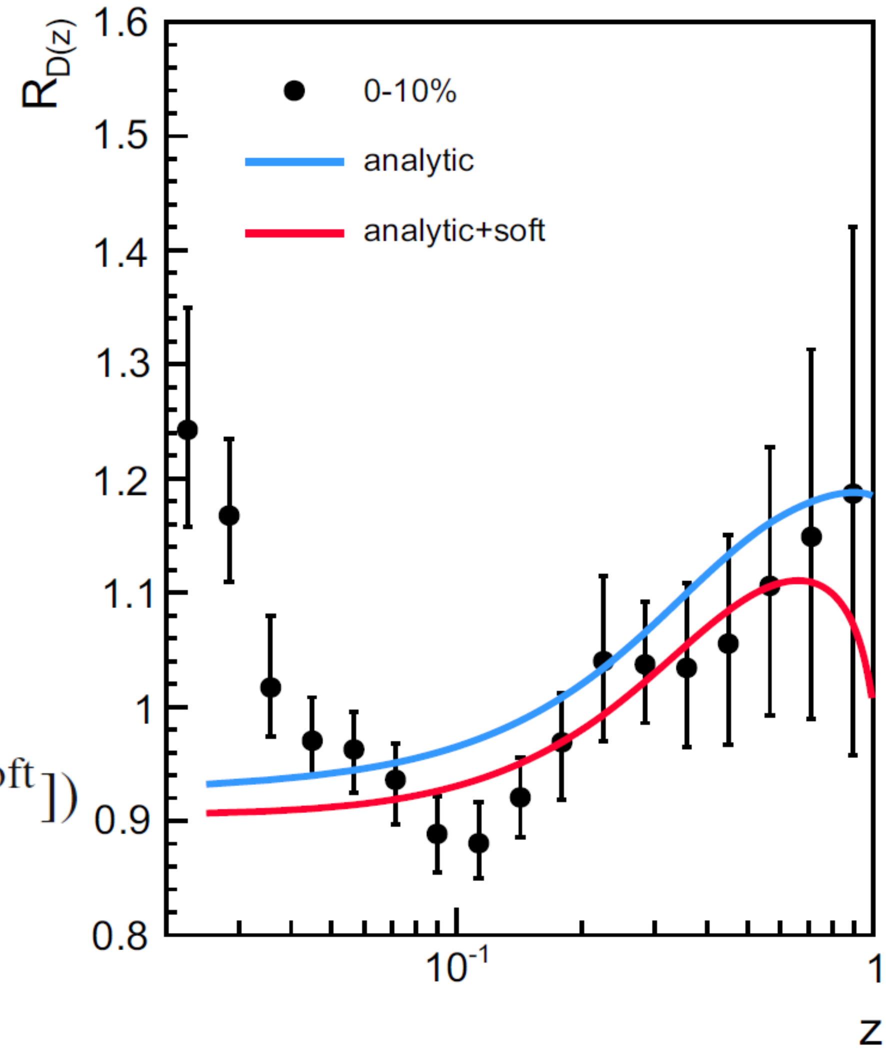
How is the soft excess estimated:

Measured
(at least partially)

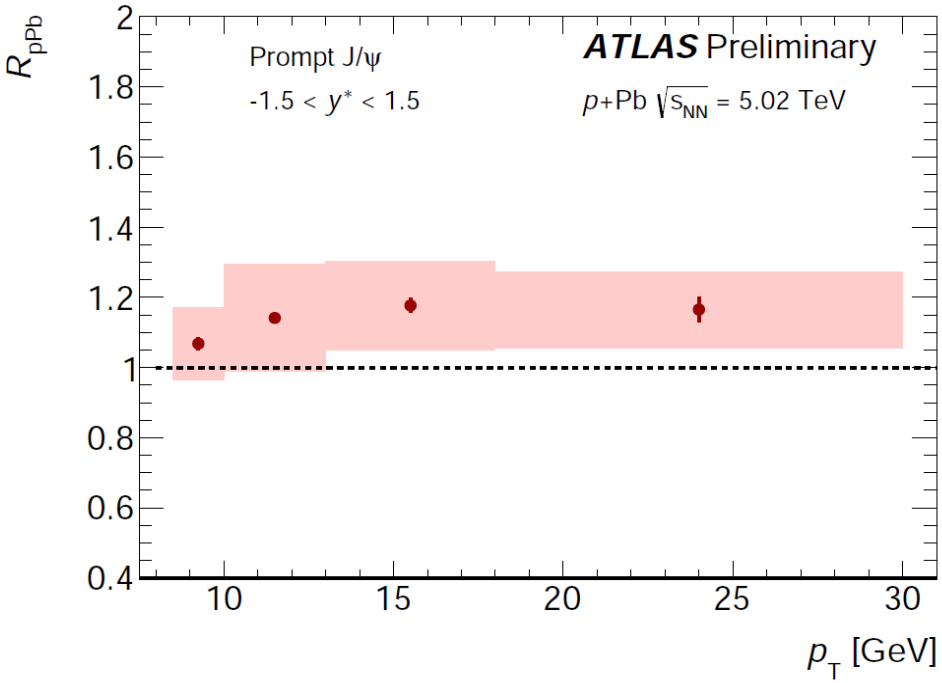
$$\Phi^{\text{soft}}_{\text{inc}} = f^{\text{int}}_q \Phi^{\text{soft}}_q + (1 - f^{\text{int}}_q)\Phi^{\text{soft}}_{\text{g}}$$

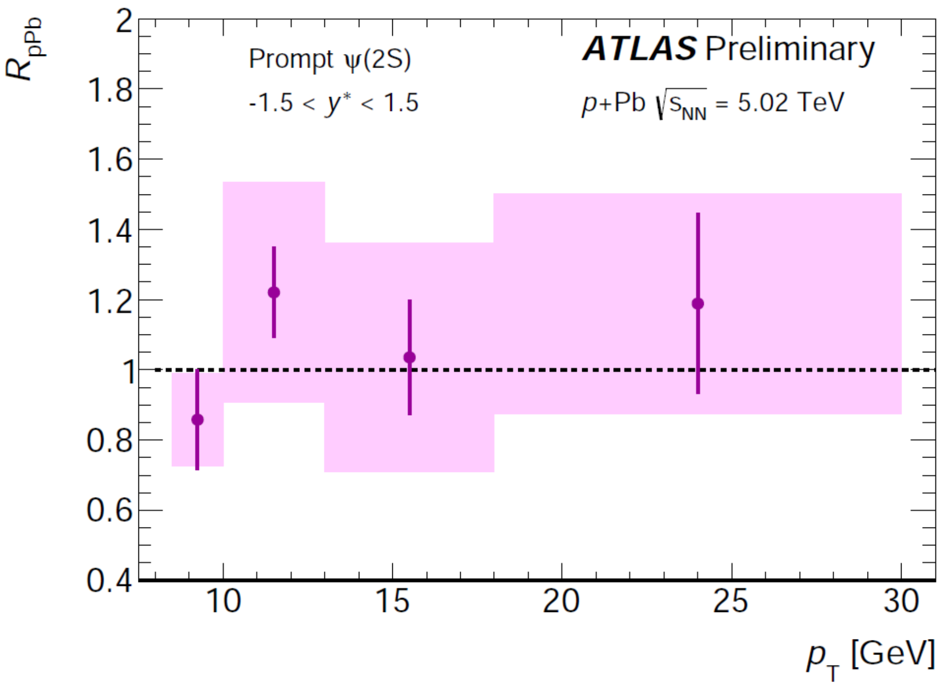
$$\Phi^{\text{soft}}_{\text{g}} = c_F \Phi^{\text{soft}}_q$$

$$D^{\text{meas}}(z) = f^{\text{int}}_q D_q(z[1+\Phi^{\text{soft}}_q]) + (1 - f^{\text{int}}_q) D_g(z[1+\Phi^{\text{soft}}_{\text{g}}])$$

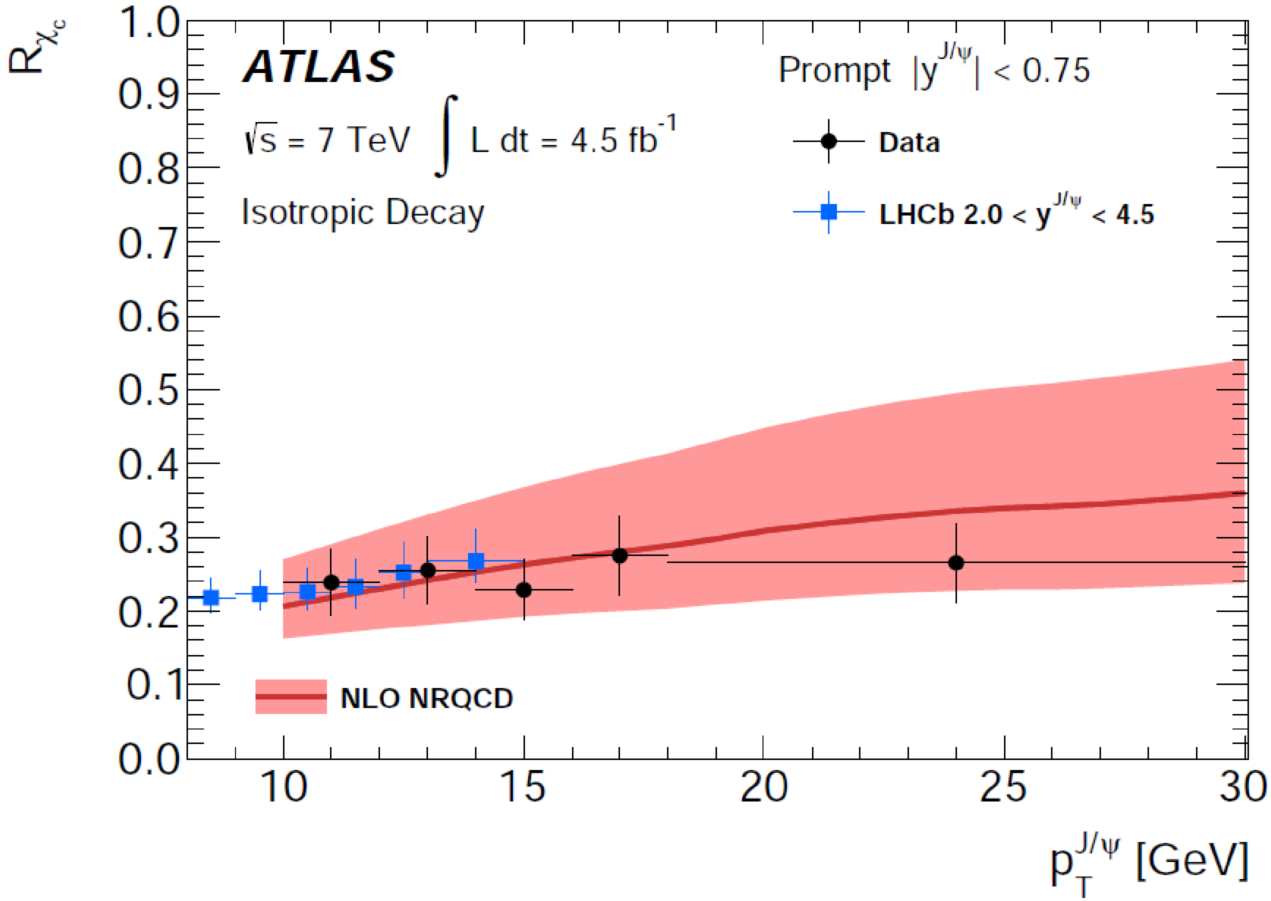


Charmonia in p+Pb



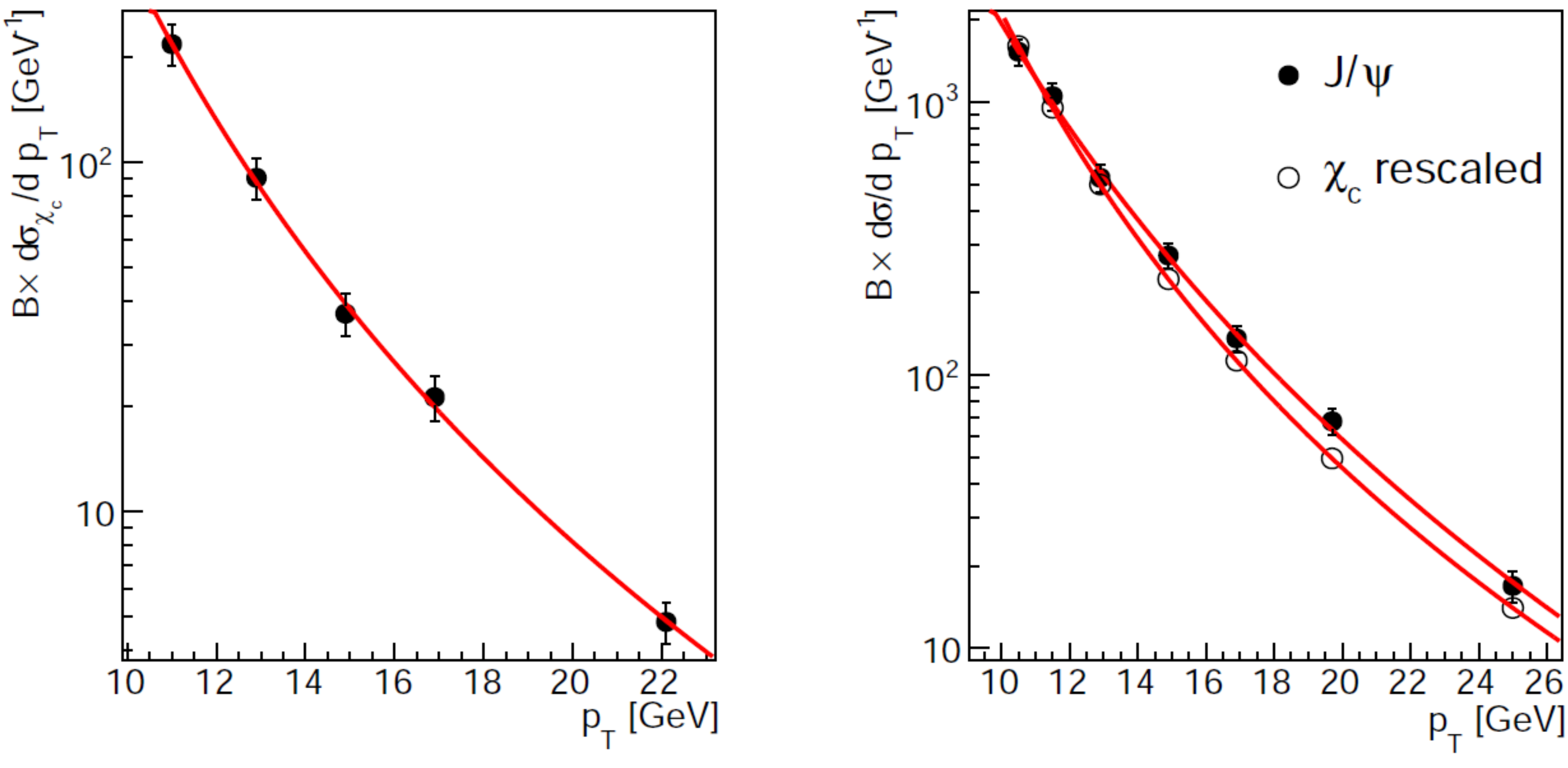


Feed down



ATLAS, JHEP 07 (2014) 154

Feed down



ATLAS, JHEP 07 (2014) 154

Introduction

Two paths:

- Be as realistic as one can:
  - MC generators → JEWEL (jewel.hepforge.org); QPythia (igfae.usc.es/qatmc); Martini (PRC 80 (2009) 054913)
  - JETSCAPE Collaboration
  - theory ...tions of parton enegy loss

The Jet Energy-loss Tomography with a Statistically and Computationally Advanced Program Envelope (goal provide modular software which includes: modeling of initial state + dynamical evolution of QGP + jet energy loss + advanced statistical tools; http://jetscape.wayne.edu/)

  - parametric modeling of parton energy loss

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arXiv:1702.01931

Eur.Phys.J. C76 (2016) no.2, 50