Flavor aspects of parton energy loss

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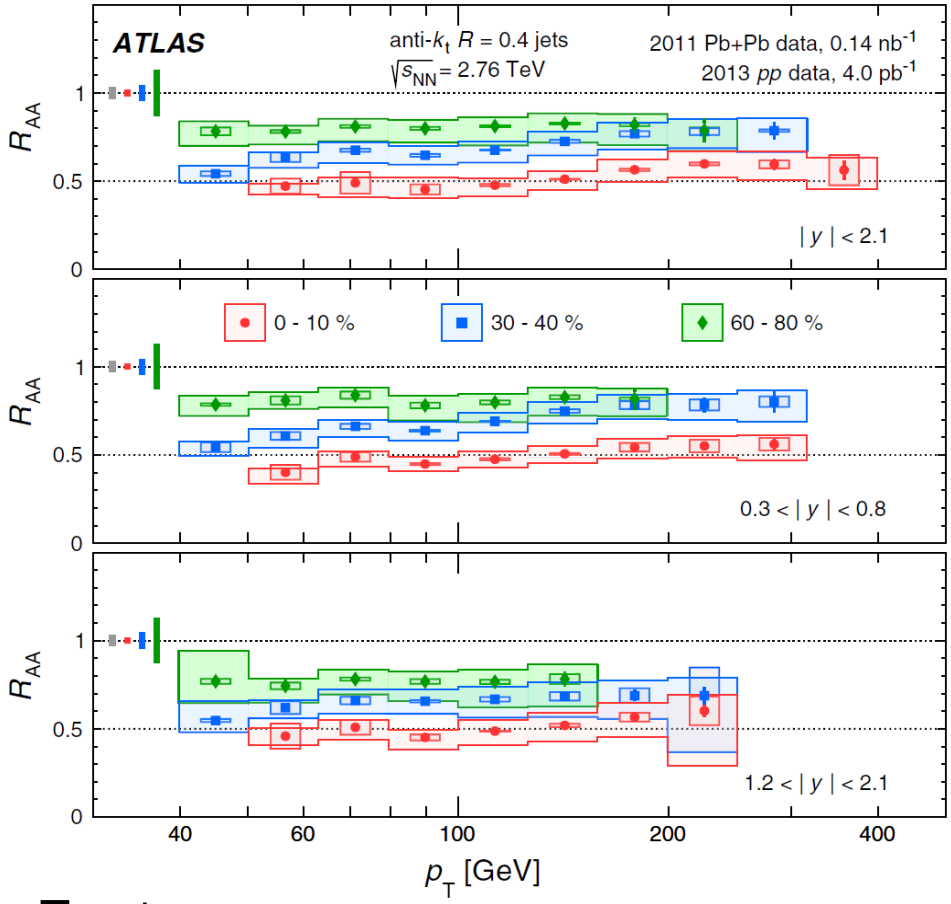
Charles University
in Prague

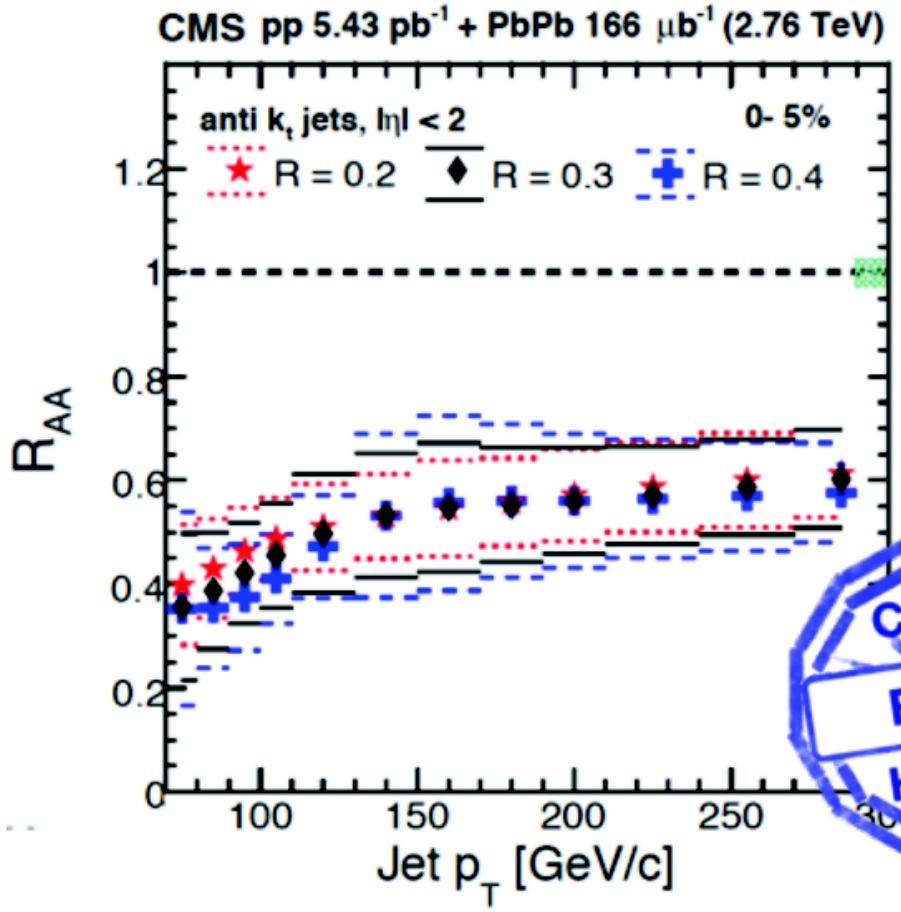
M.S., Brian Cole, EPJC 76 (2016) no.2 50
M.S., arXiv:1606.00903
+ new

Inclusive jet R_{AA}

PRL 114 (2015) 072302



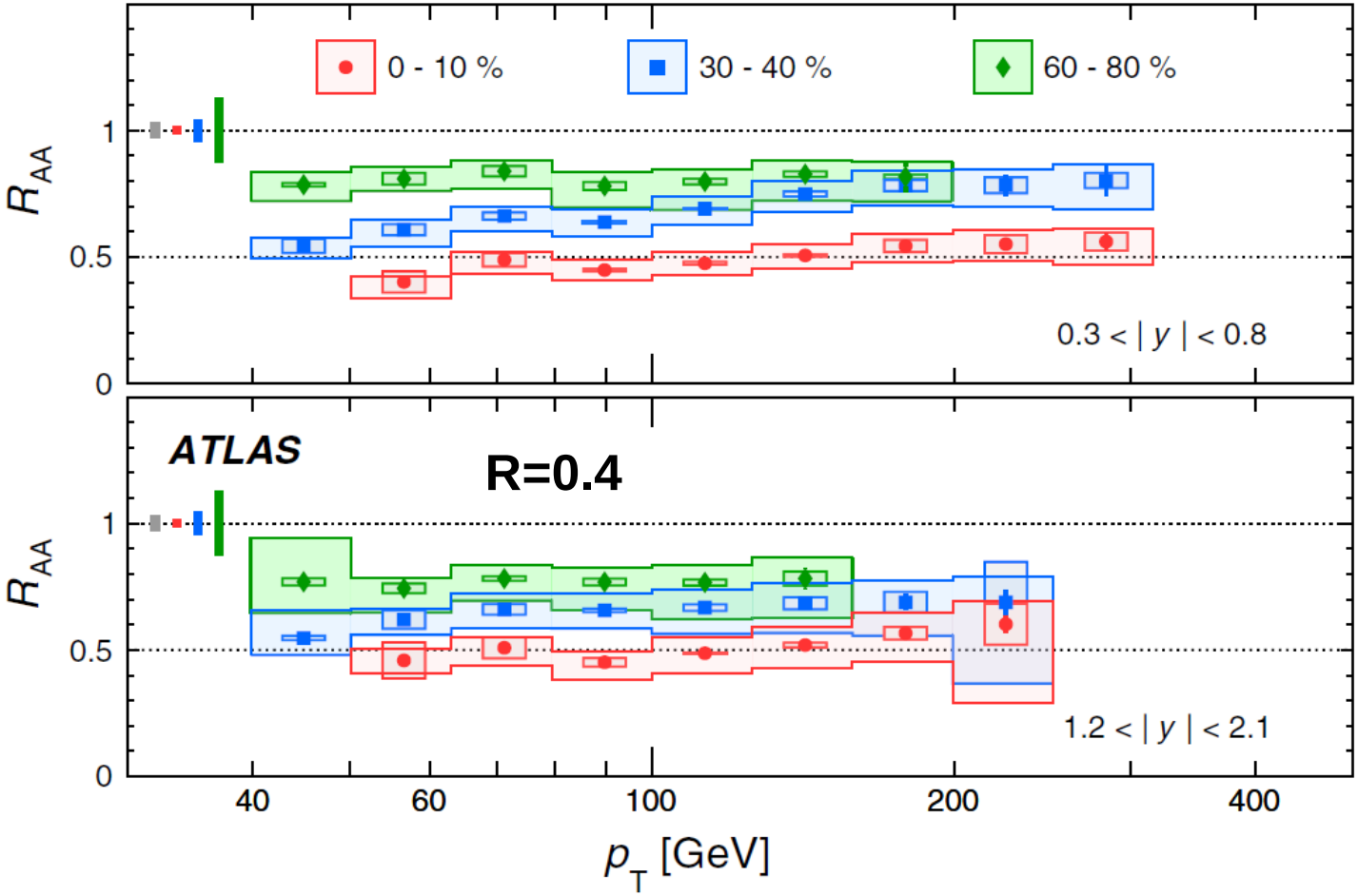
arXiv:1609.05383



Features:

1) only modest (if any) rise with increasing jet p_T,

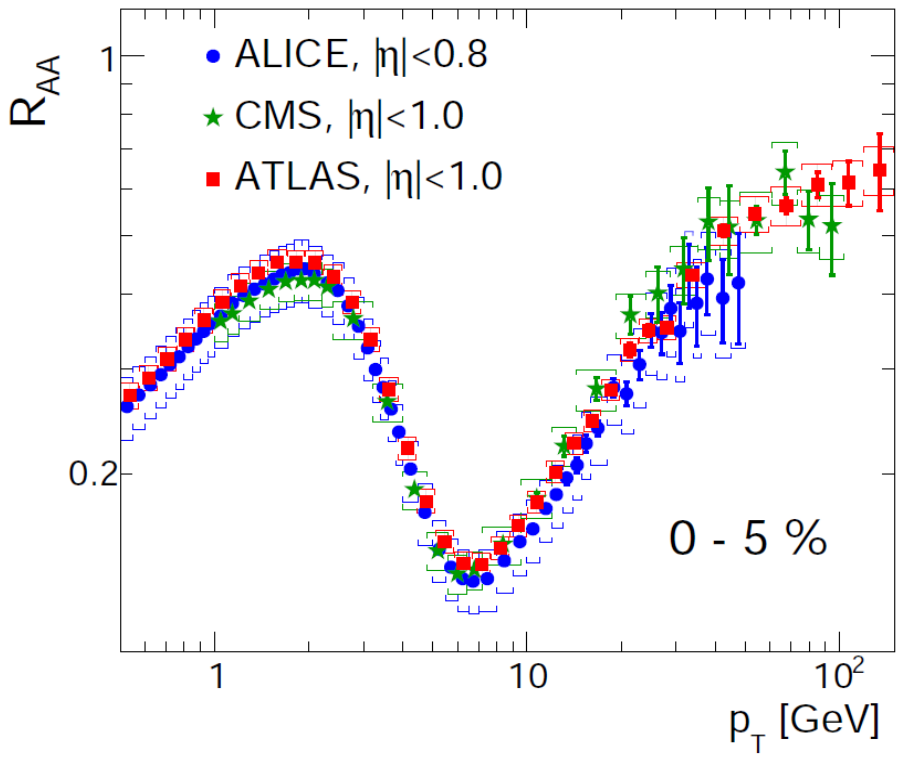
Inclusive jet R_{AA}

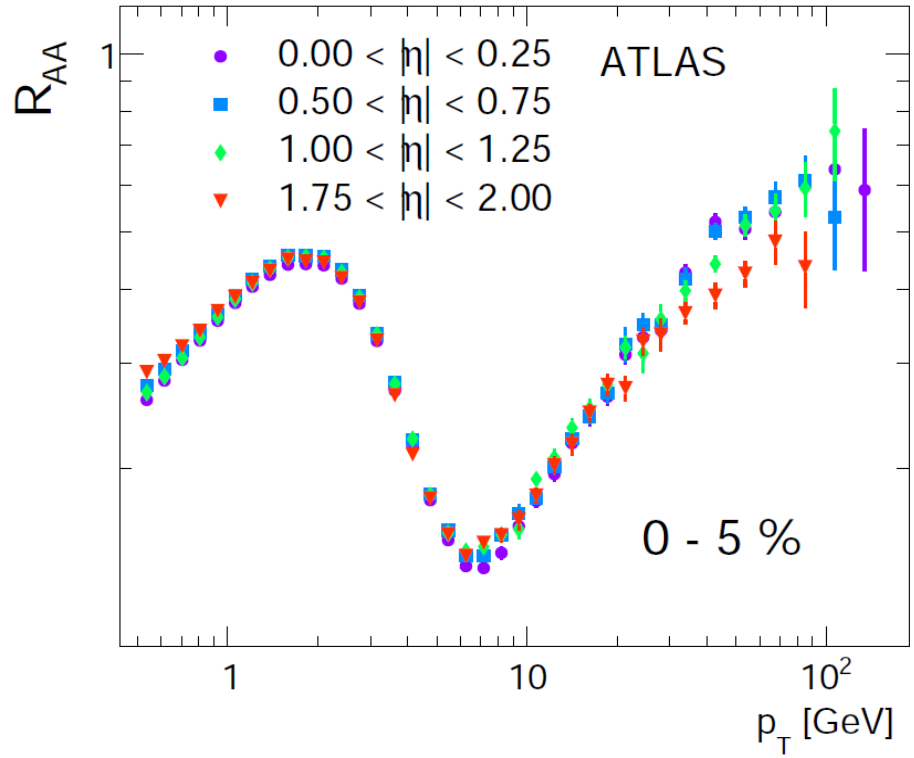


Features:

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

Charged particle R_{AA}





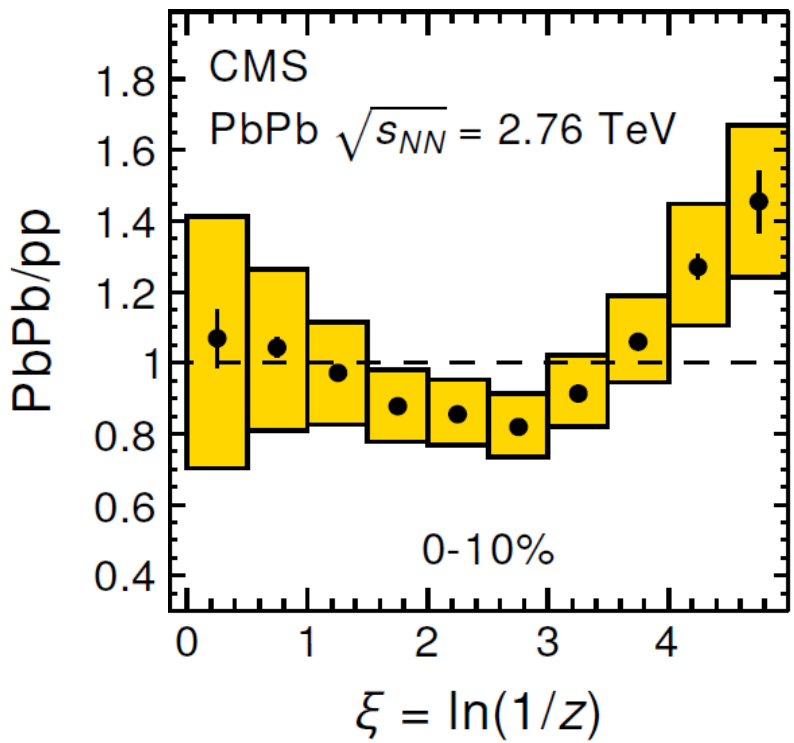
EPJC 72 (2012) 1945
PLB 720 (2013) 52
JHEP09 (2015) 050

Features:

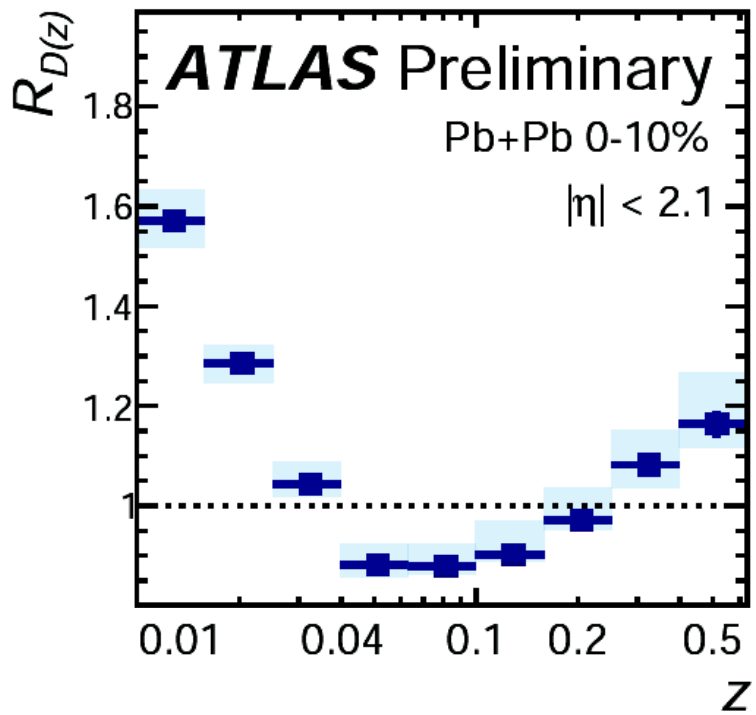
1) steep increase for p_T>10 GeV
2) almost no rapidity dependence

Charged particles in jets

PRC 90 (2014) 024908



PLB 739 (2014) 320
ATLAS-CONF-2015-055

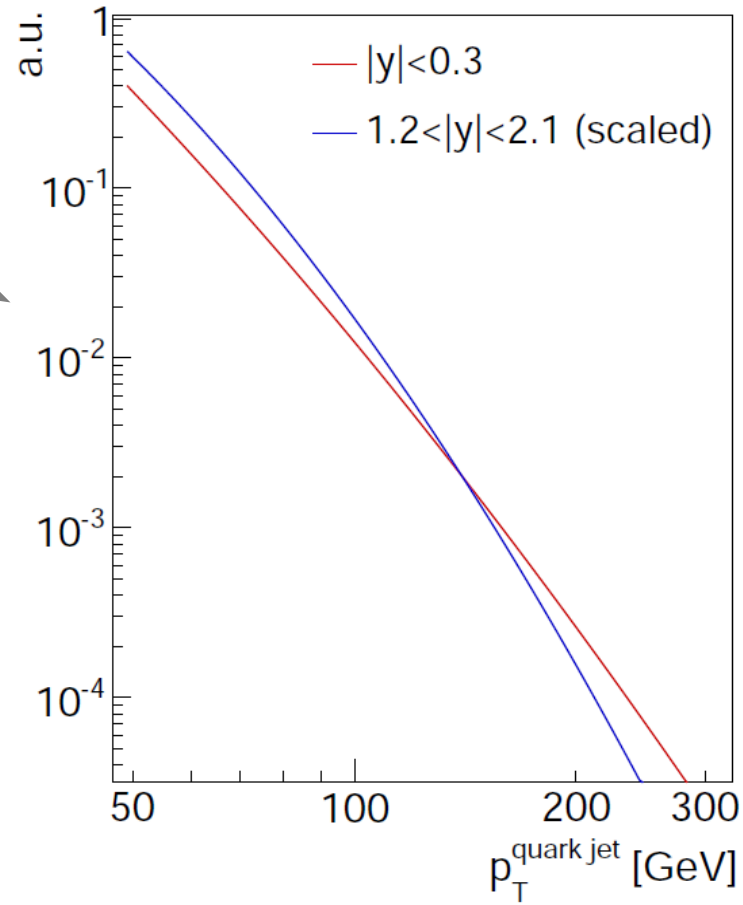


Features:

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 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 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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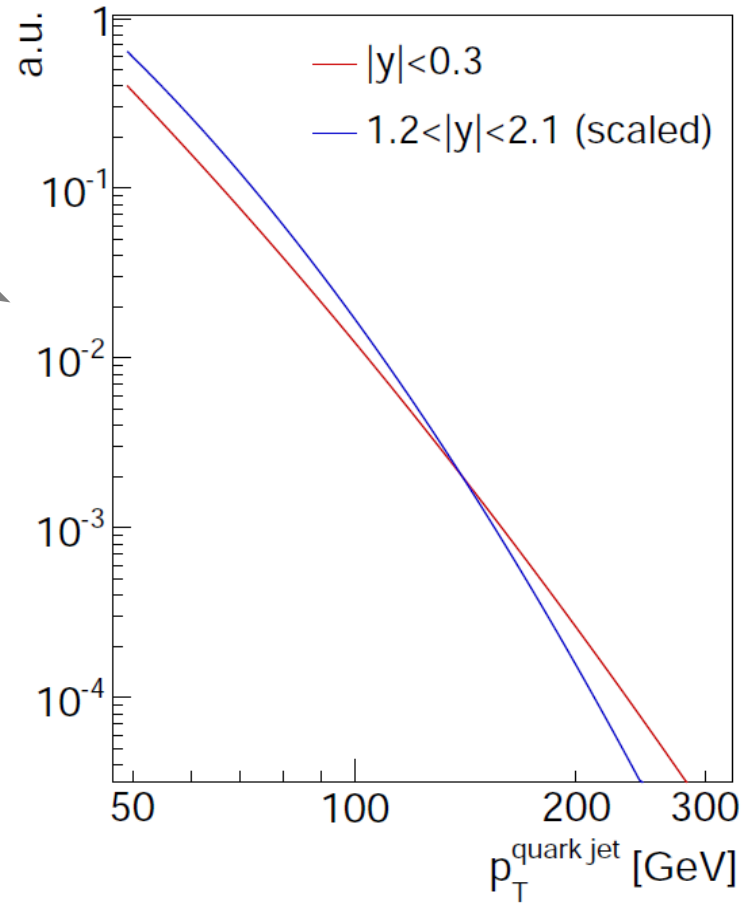


–> Use a simple model with minimal assumptions on the quenching physics to extract basic properties of the jet quenching

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 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

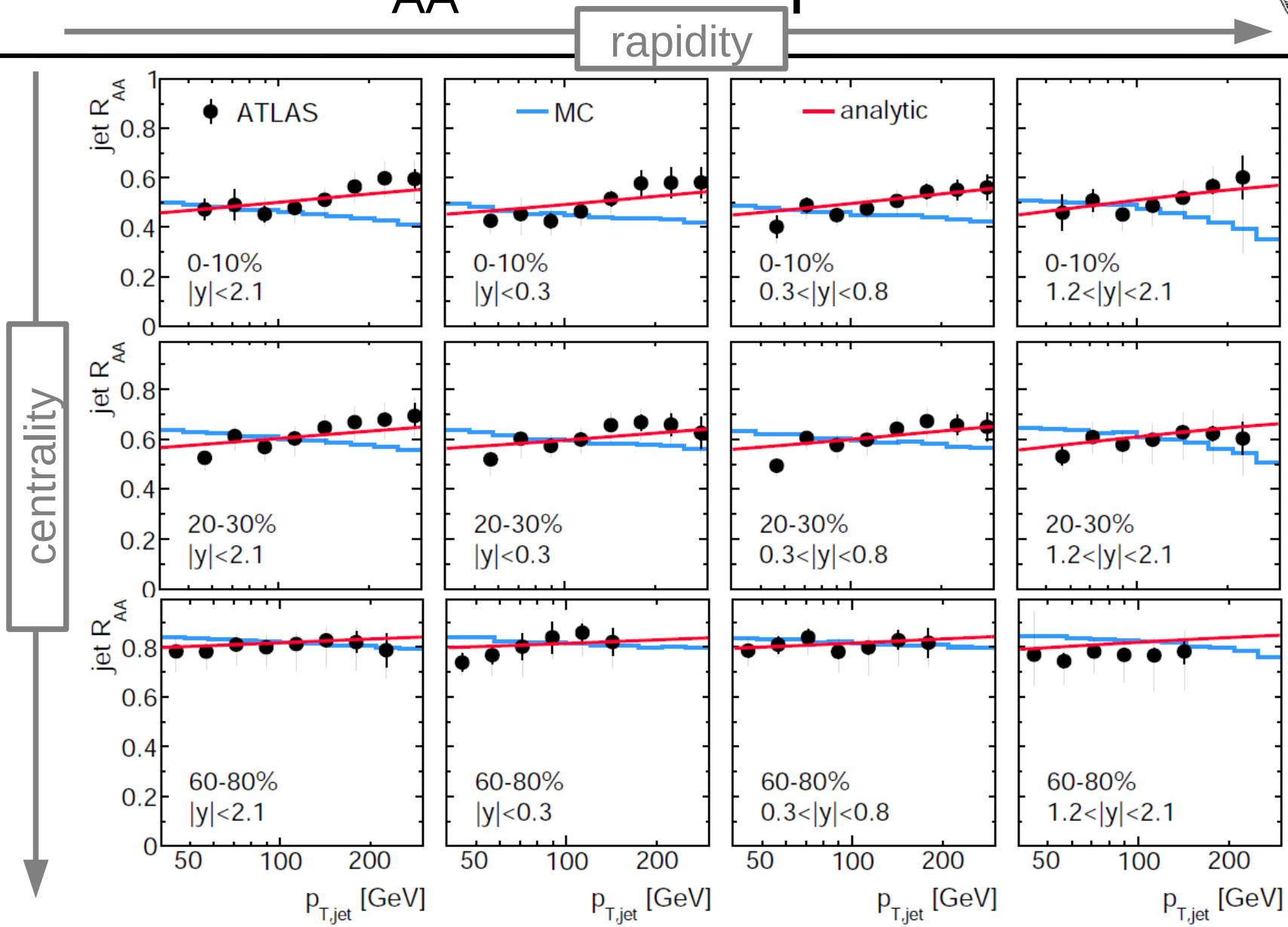
R_{AA} in the approximation of fractional energy loss

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

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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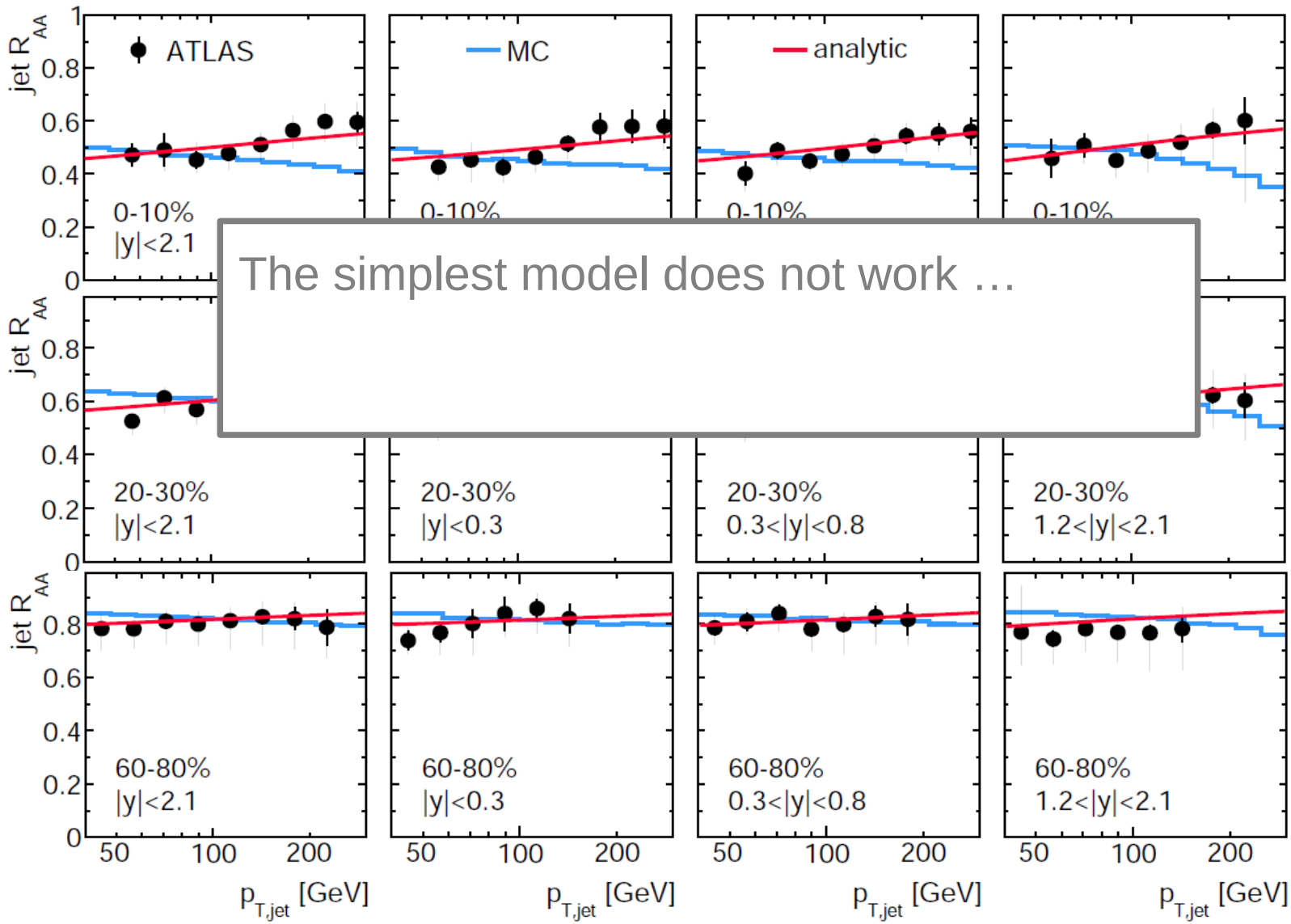
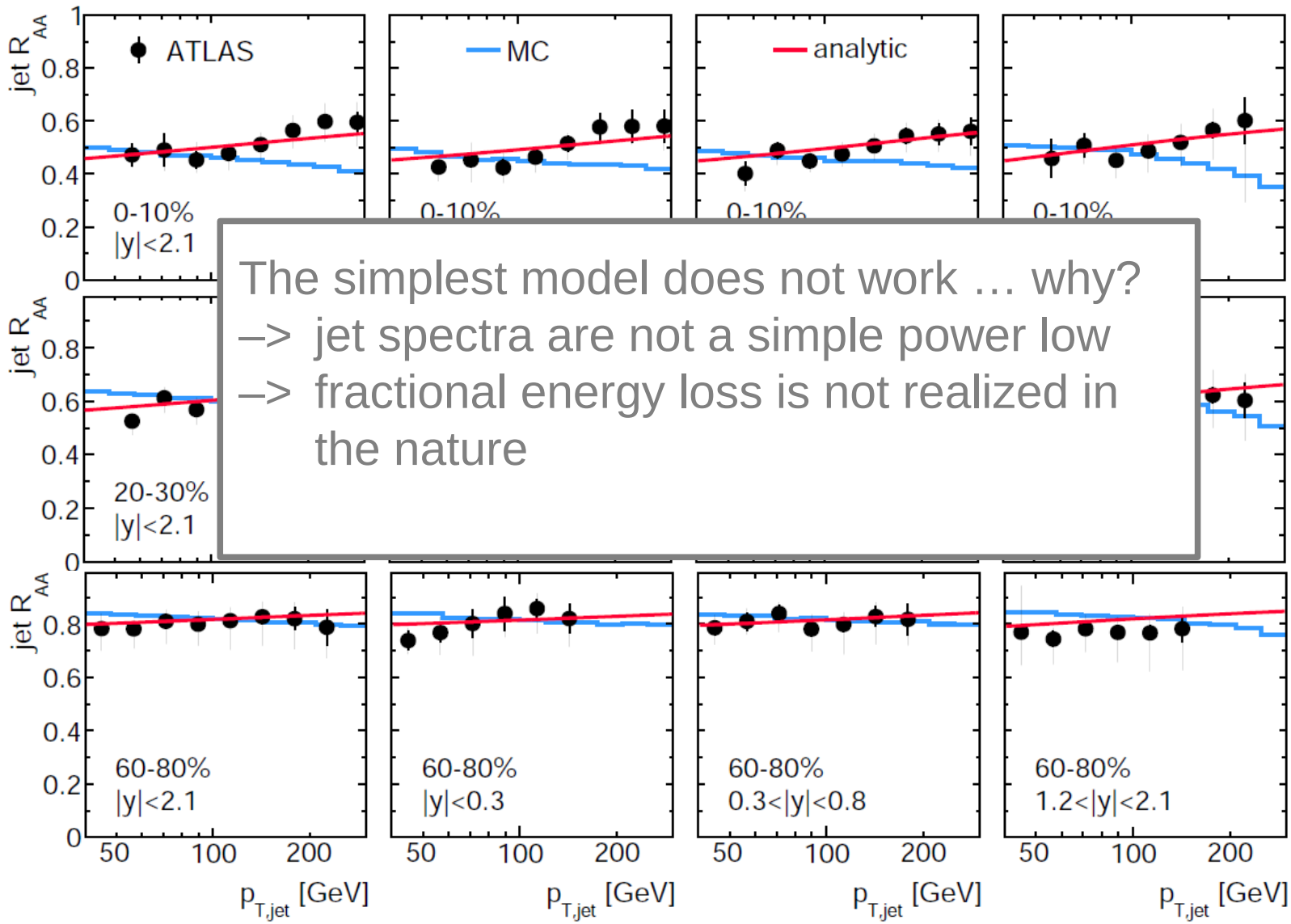


The simplest model does not work …

Jet R_{AA} in the simplest model

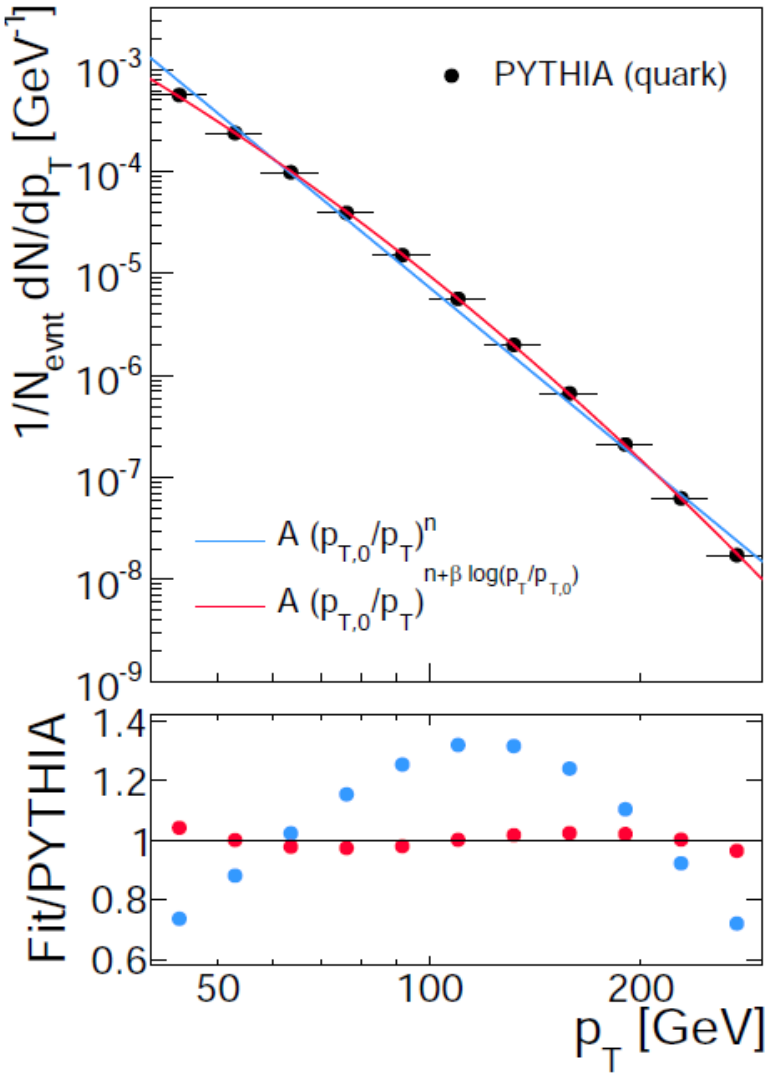


The simplest model does not work … why?

–> jet spectra are not a simple power low

–> fractional energy loss is not realized in the nature

Extending the model



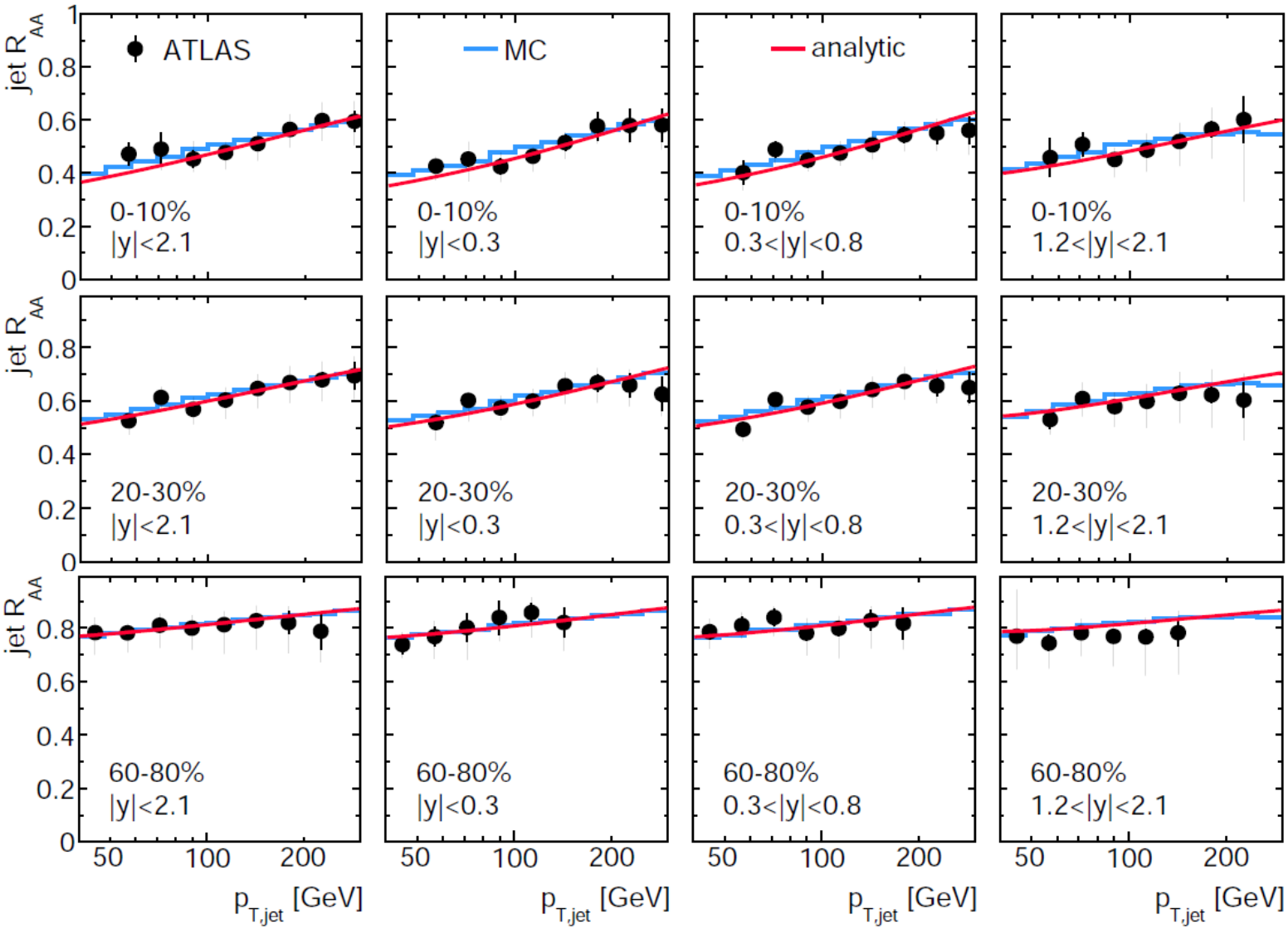
$$\frac{dn}{dp_{\mathrm{T}}^{\mathrm{jet}}} = A\left(\frac{p_{T0}}{p_{\mathrm{T}}^{\mathrm{jet}}}\right)^{n+\beta\log\left(p_T^{jet}/p_{T0}\right)}$$

More precise parameterization of input jet spectra

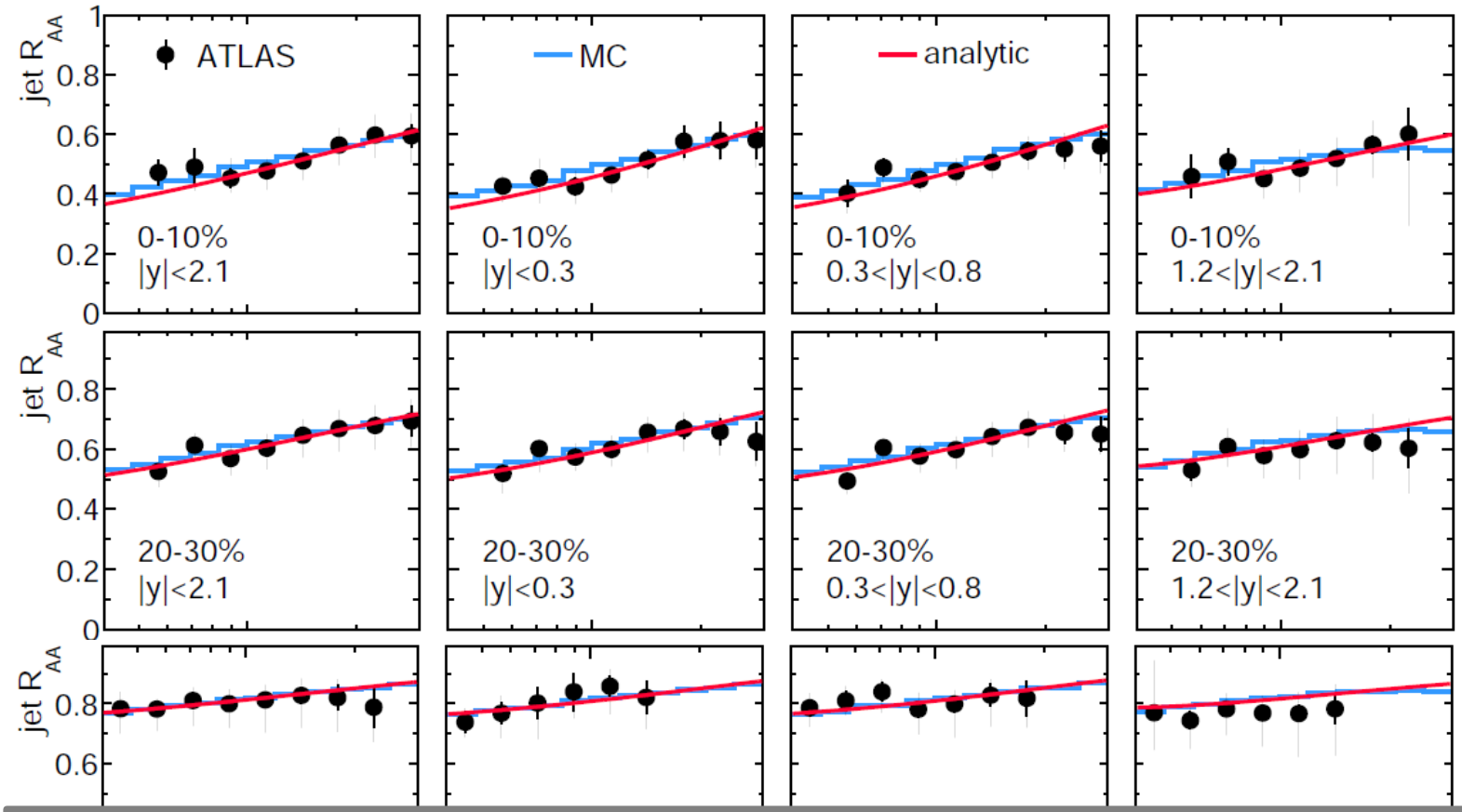
More general modeling of jet energy loss

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

Jet R_{AA} in extended model

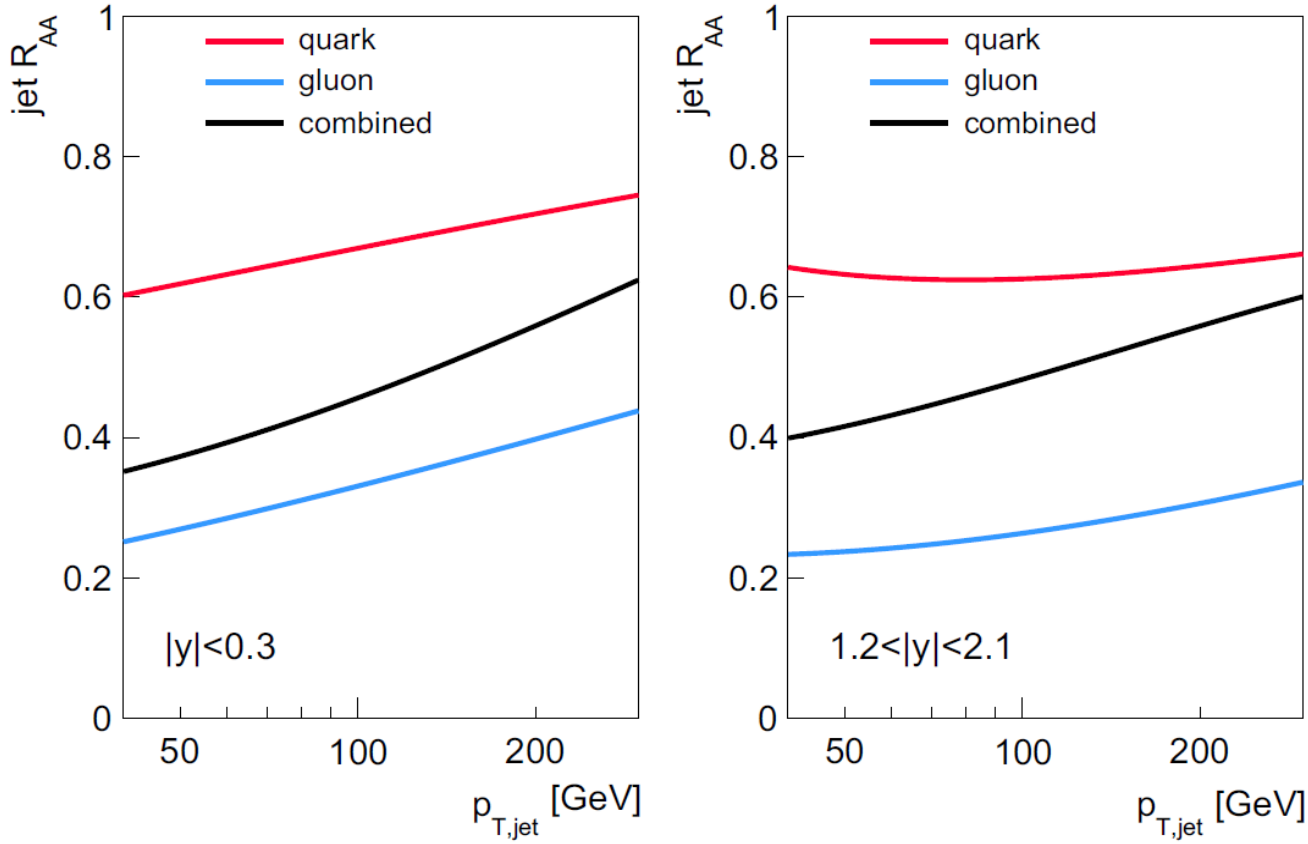


Jet R_{AA} in extended model



–> Flatness and no rapidity dependence of jet R_{AA} are due to different energy loss of quark and gluon initiated jets

Jet R_{AA} in extended model

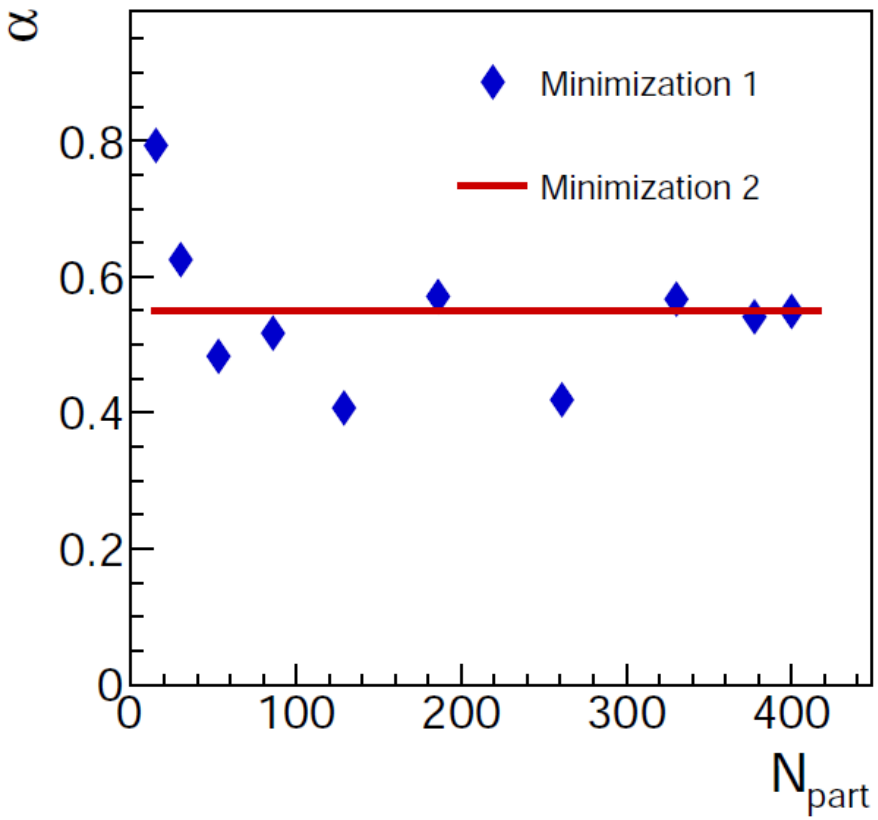


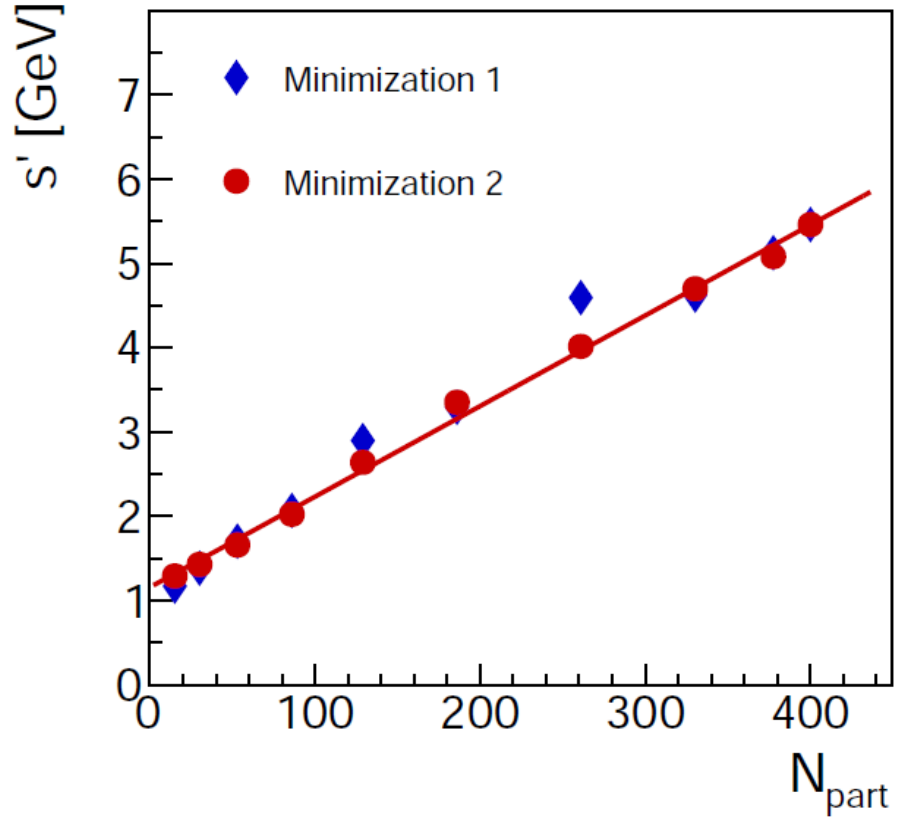
–> Flatness and no rapidity dependence of jet R_{AA} are due to different energy loss of quark and gluon initiated jets

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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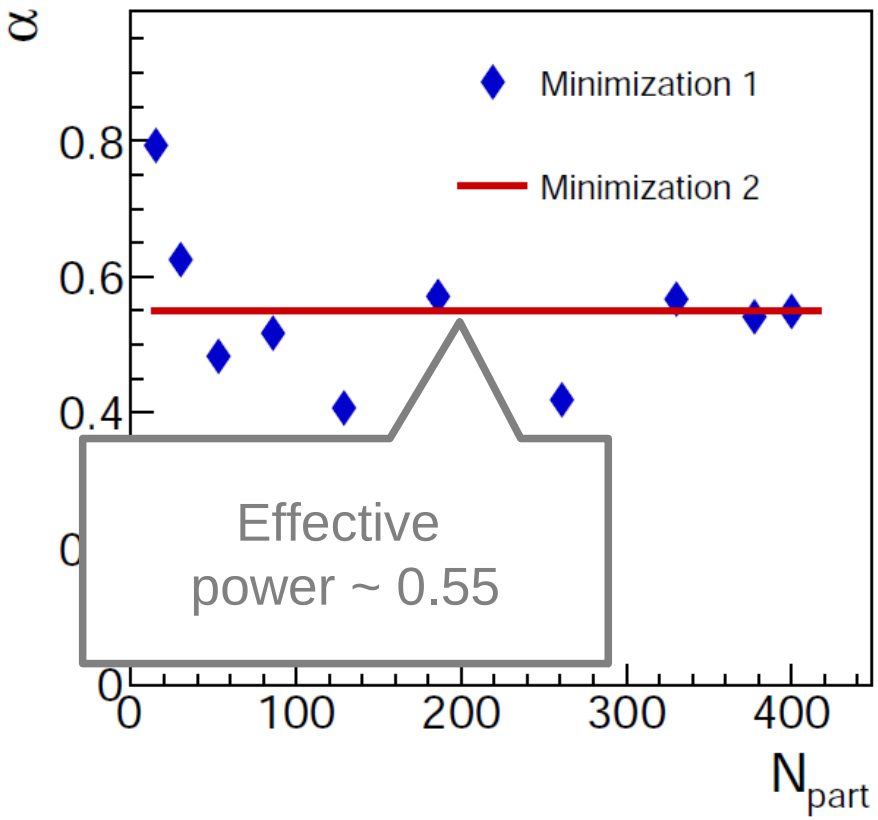
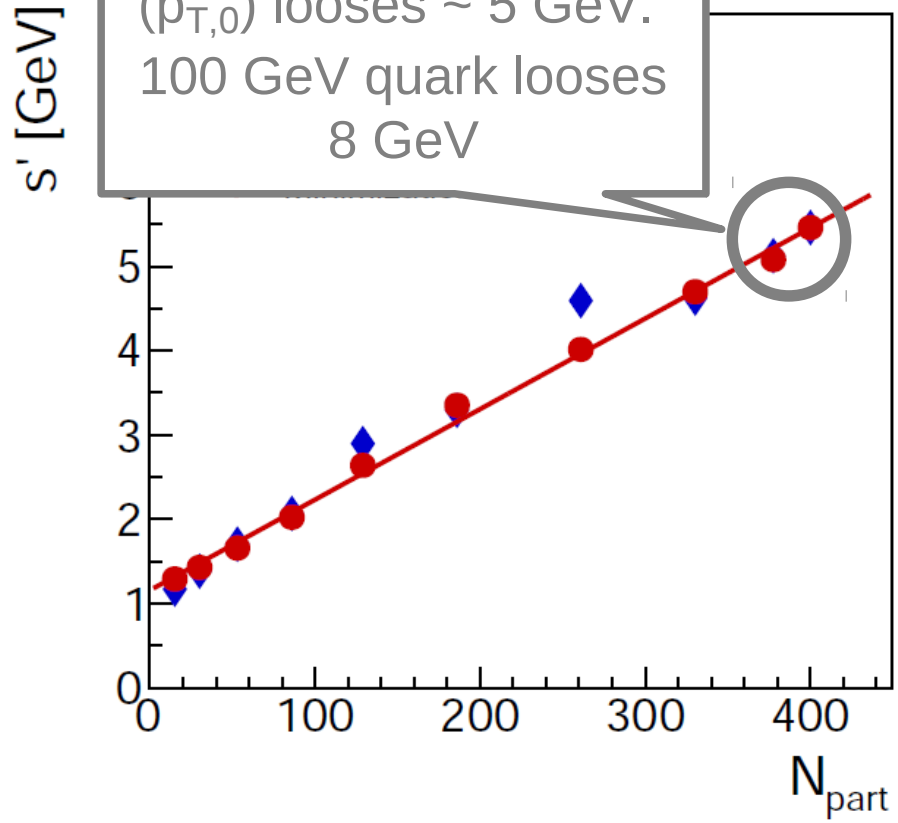


Effective power ~ 0.55

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



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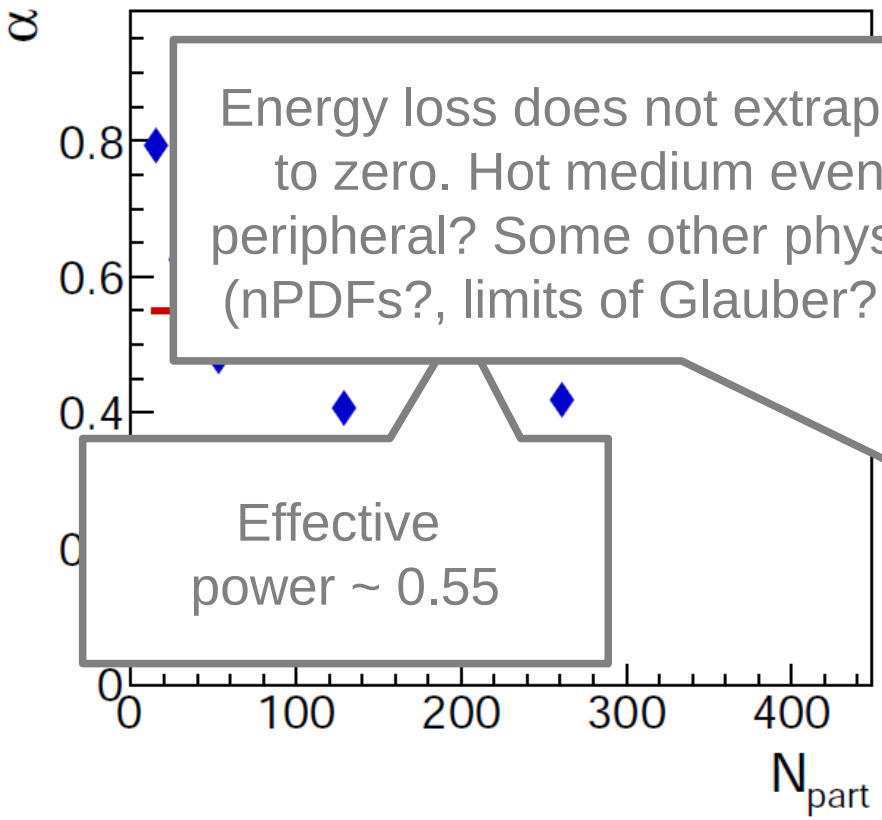
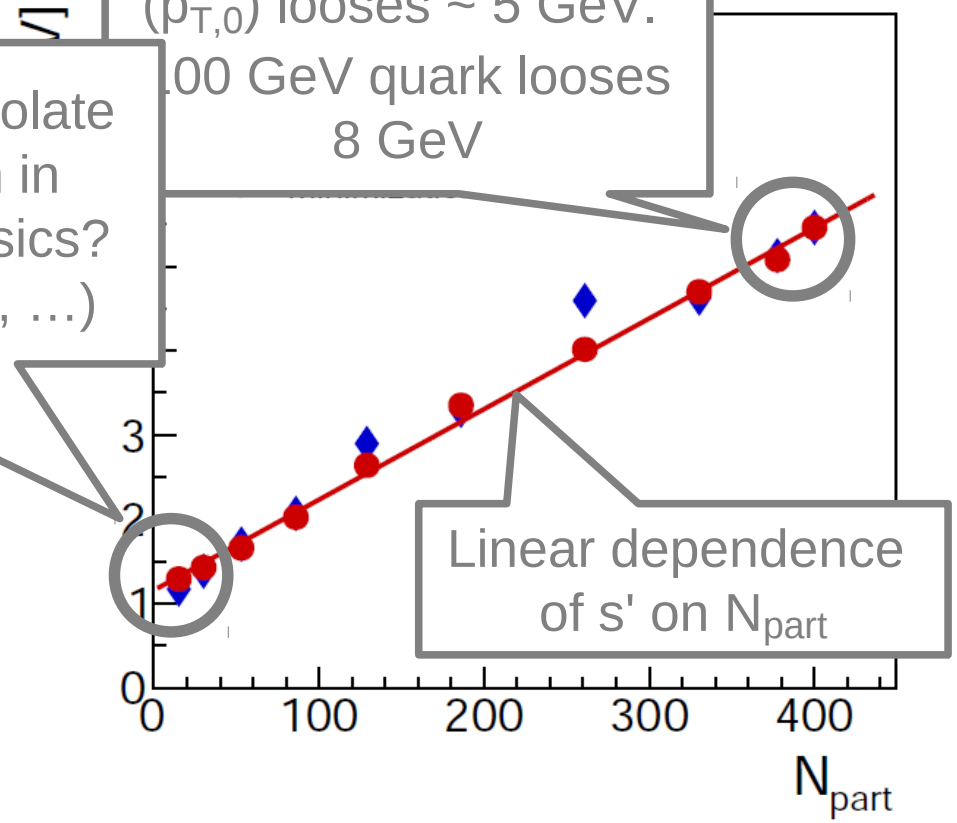
Energy loss does not extrapolate to zero. Hot medium even in peripheral? Some other physics? (nPDFs?, limits of Glauber?, …)

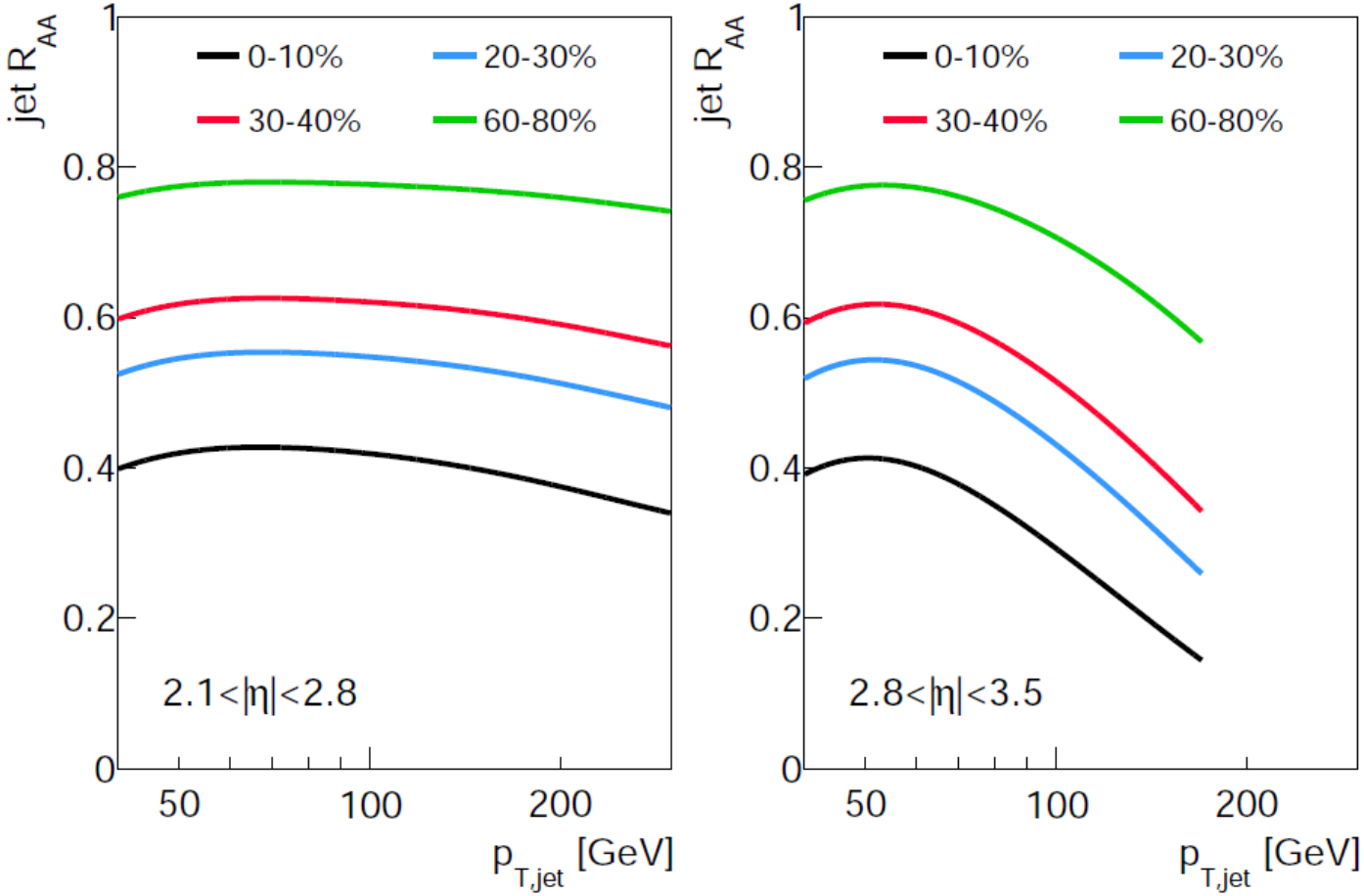
Effective power ~ 0.55

Linear dependence of s' on N_{part}



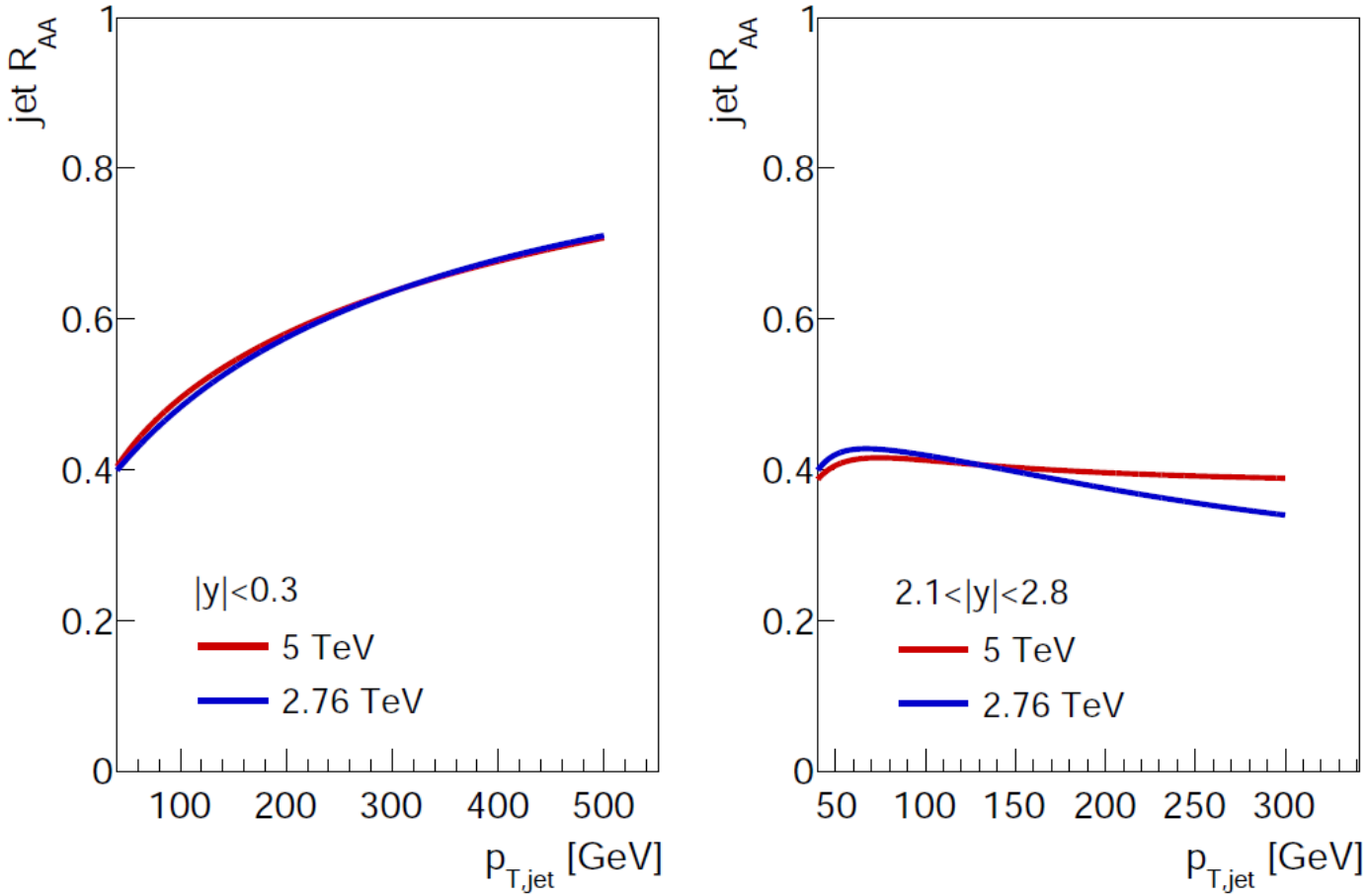


Predictions for 2.76 TeV



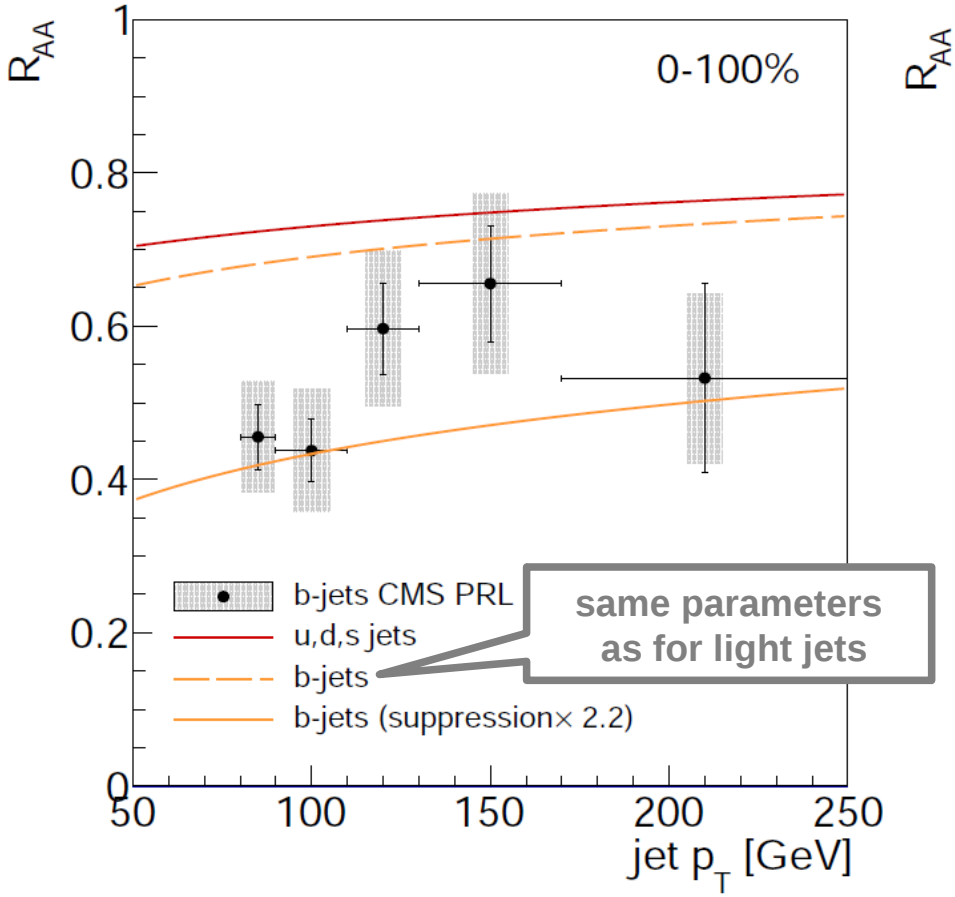
–> Forward should exhibit a decrease of R_{AA}

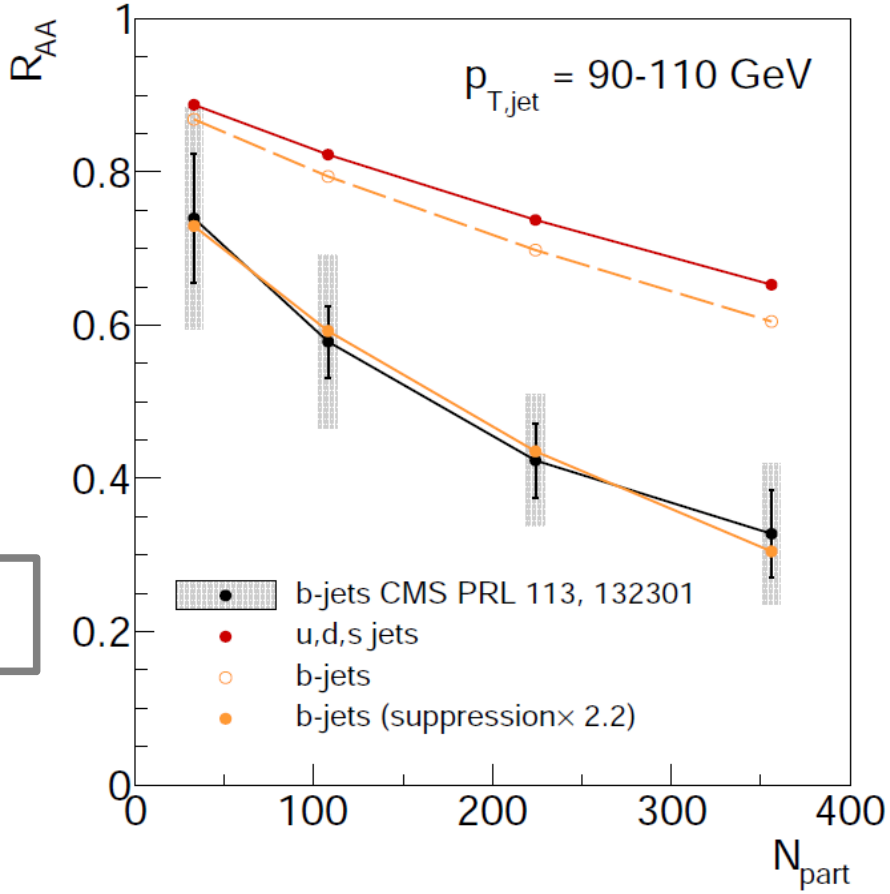
Predictions for 5 TeV



–> If the jet quenching is the same at 2.76 and 5 TeV, the jet R_{AA} will be very similar to that measured at 2.76 TeV

b-jets



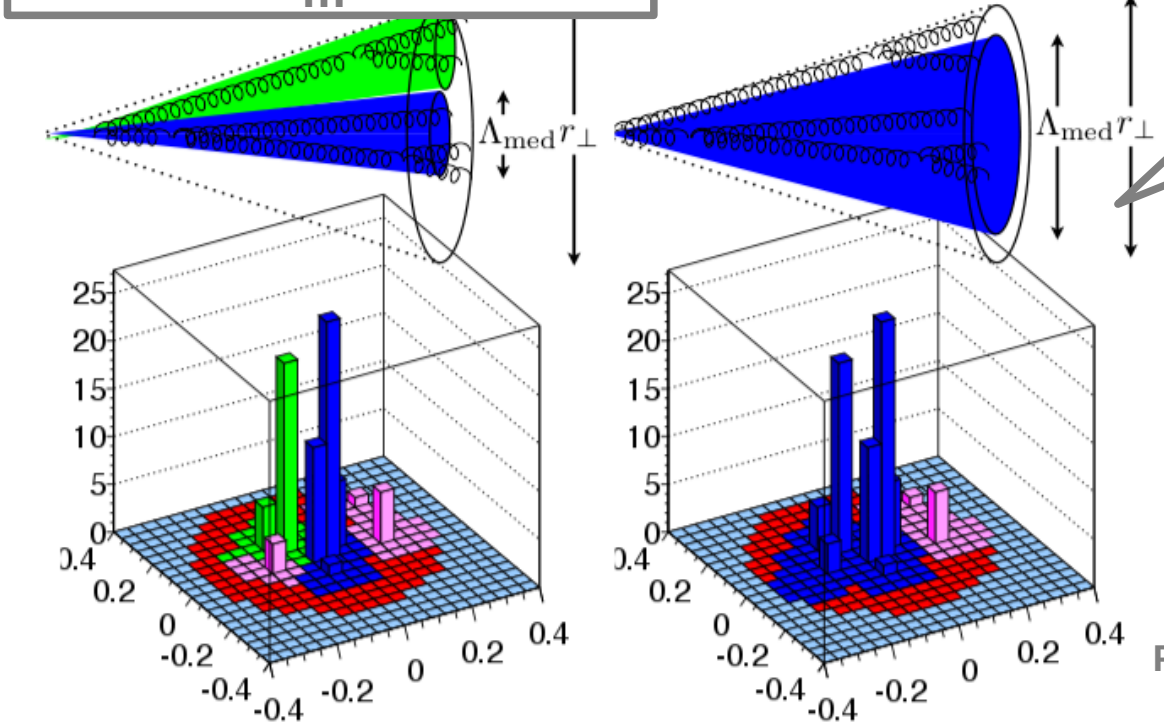


–> *b*-jets are suppressed more than light-quark jets

–> more precise data needed to quantify by how much

Modifications of fragmentation functions

Konrad Tywoniuk – Monday
Fabio Dominguez – Sunday
...



hardest resolved
next-to-hardest
soft fragments

… color coherence likely very important in the quenching physics

Figure from

Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, Phys. Rev. Lett. 106 (2011)
Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, Phys. Lett. B707 (2012)
J. Casalderrey-Solana, Y. Mehtar-Tani, C. A. Salgado,K. Tywoniuk, Phys. Lett. B725 (2013)
J.-P. Blaizot, E. Iancu, Y. Mehtar-Tani, Phys. Rev. Lett. 111 (2013) 052001.
...

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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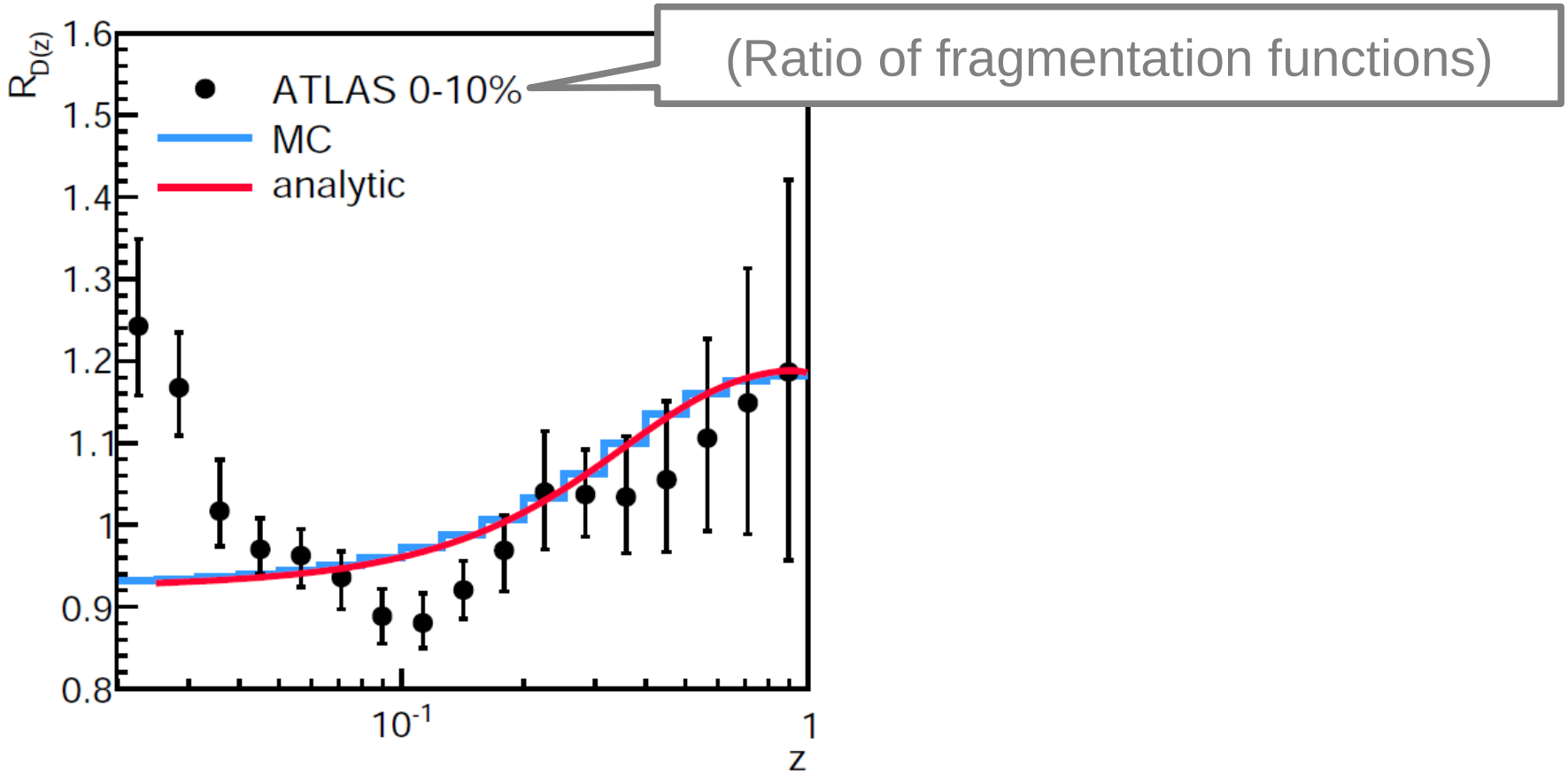

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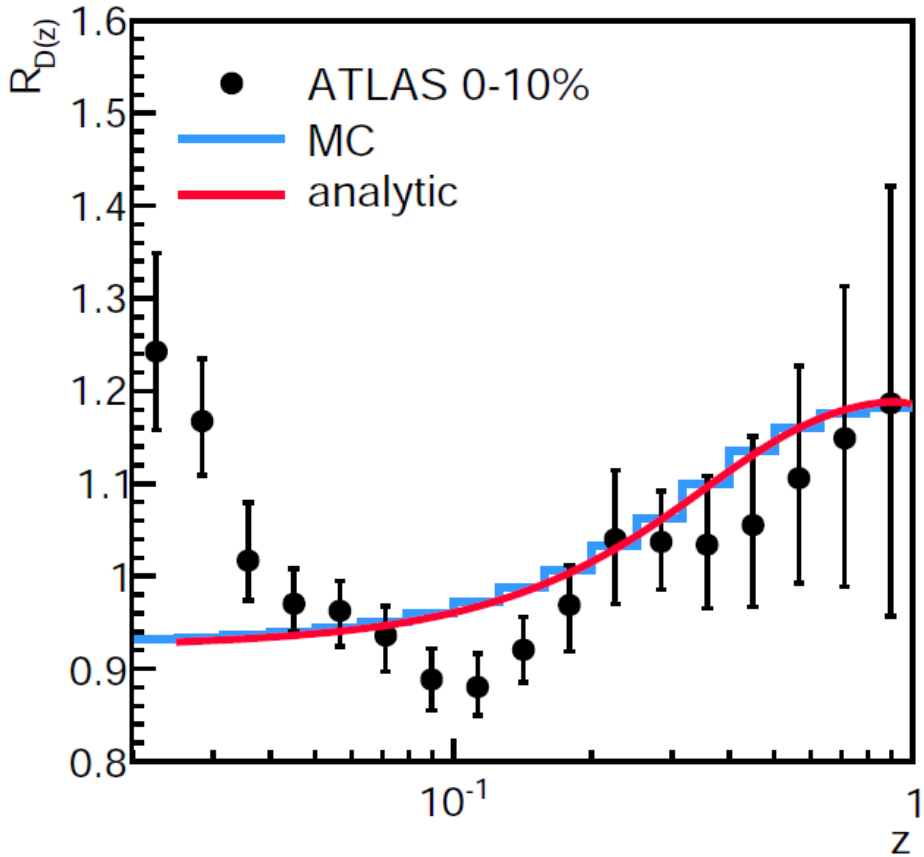
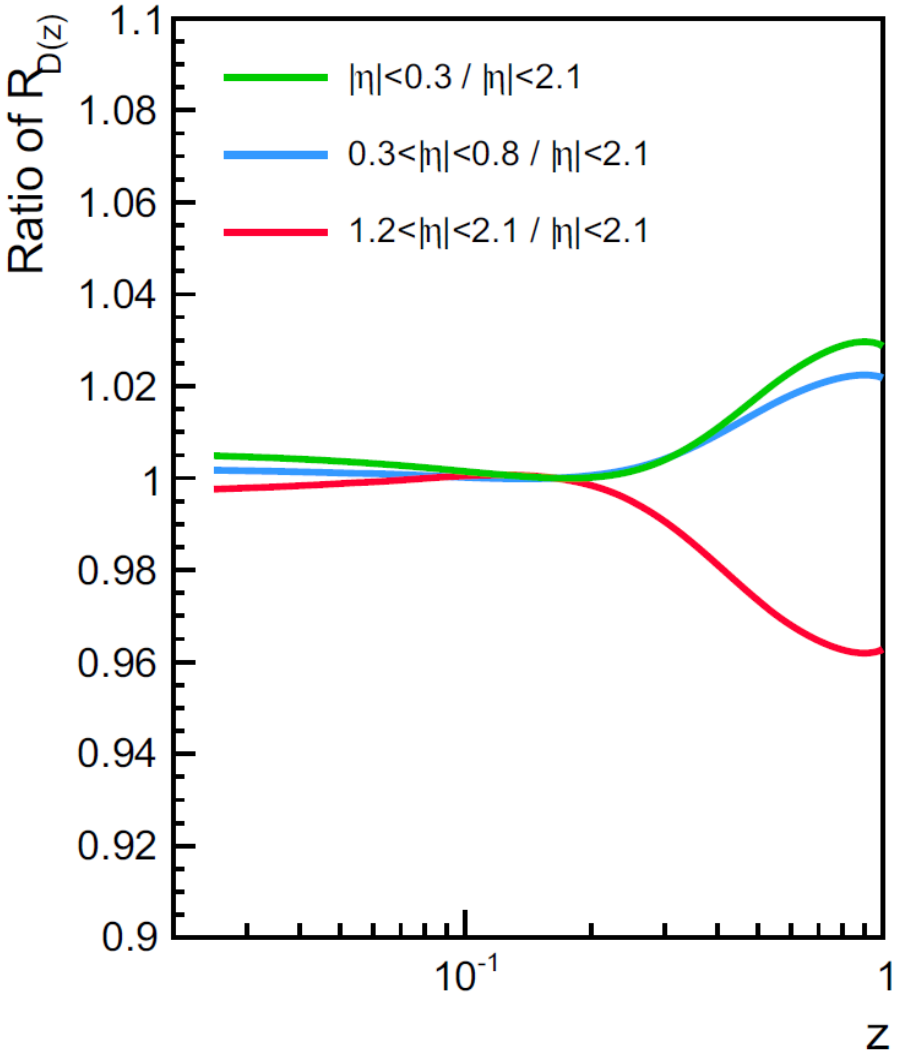


–> Structure seen at intermediate and high-z is due to the difference in quenching of quark and gluon initiated jets

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

Modifications of fragmentation functions – prediction



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

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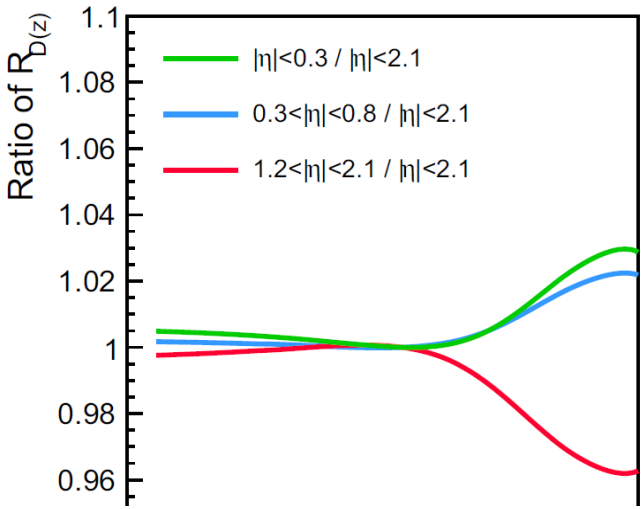

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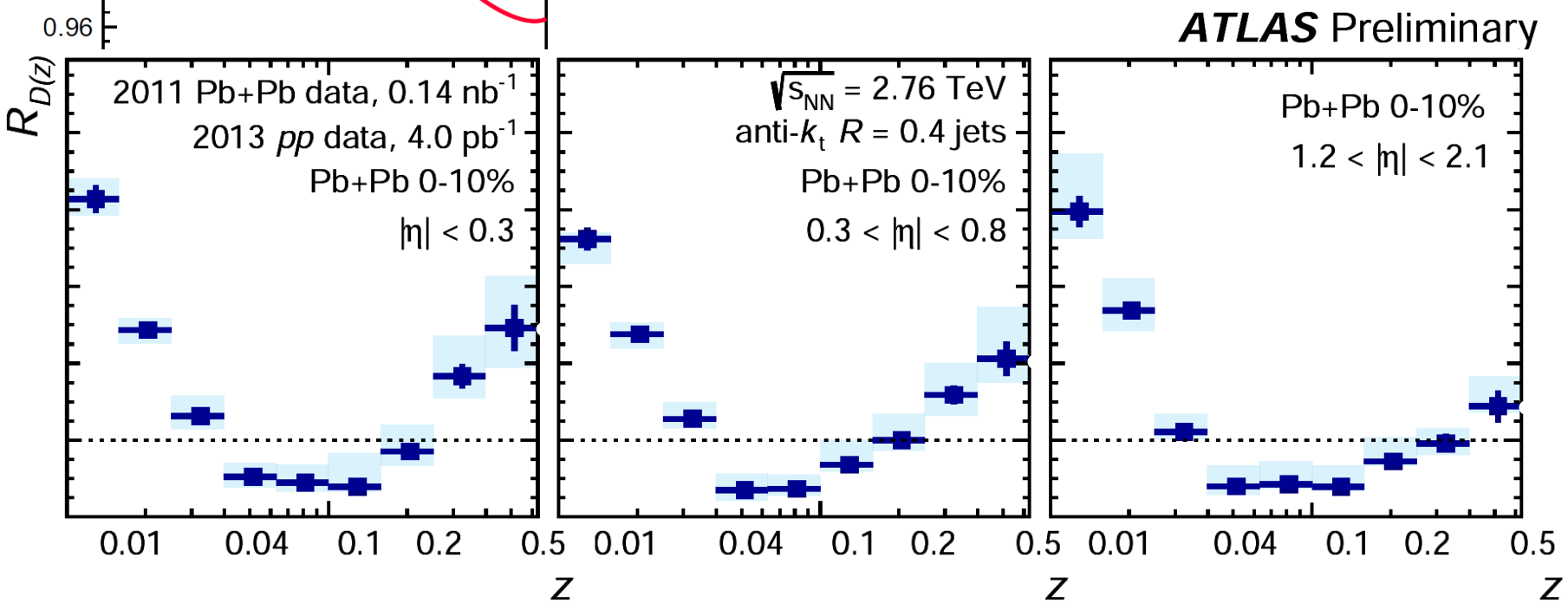

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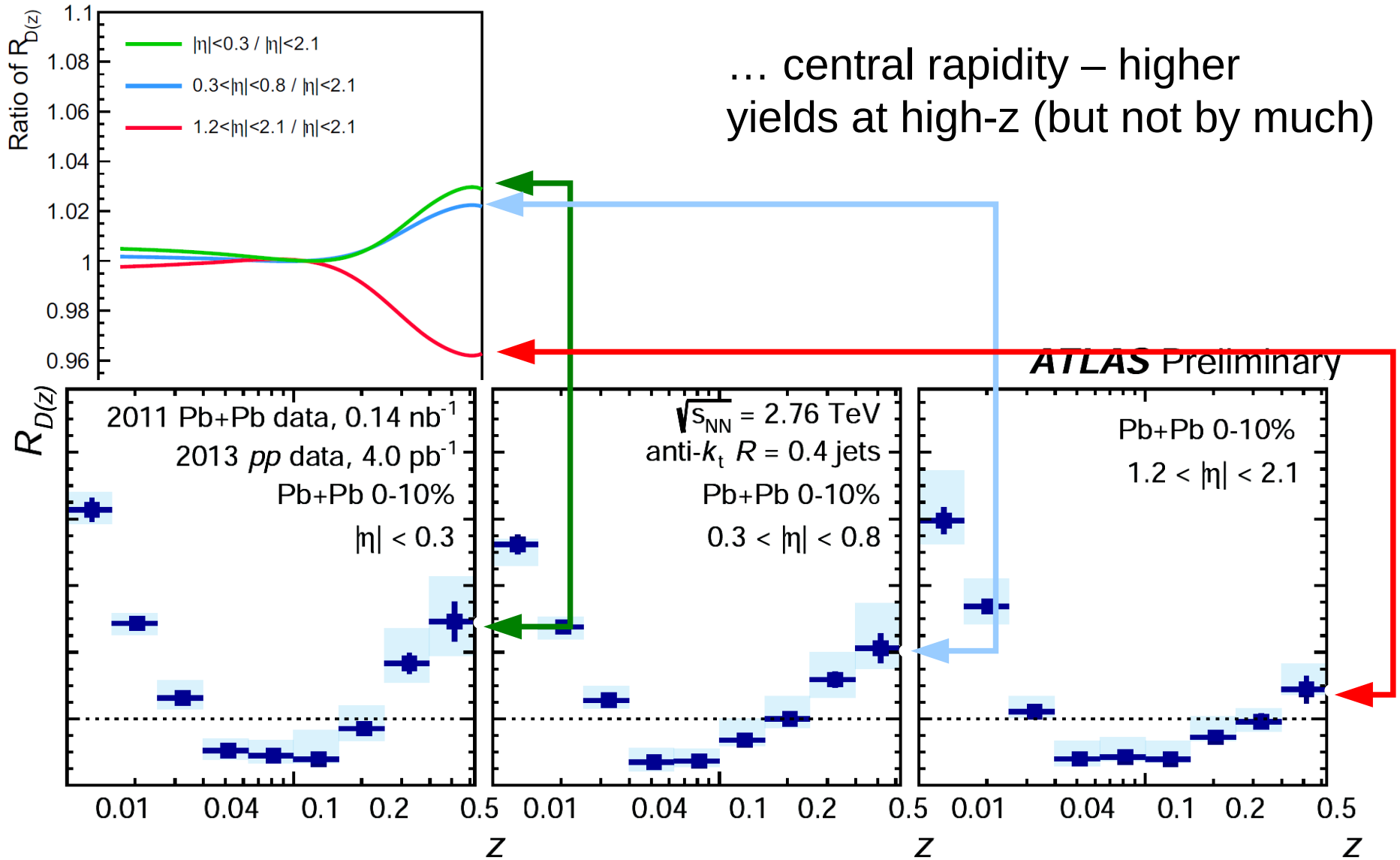
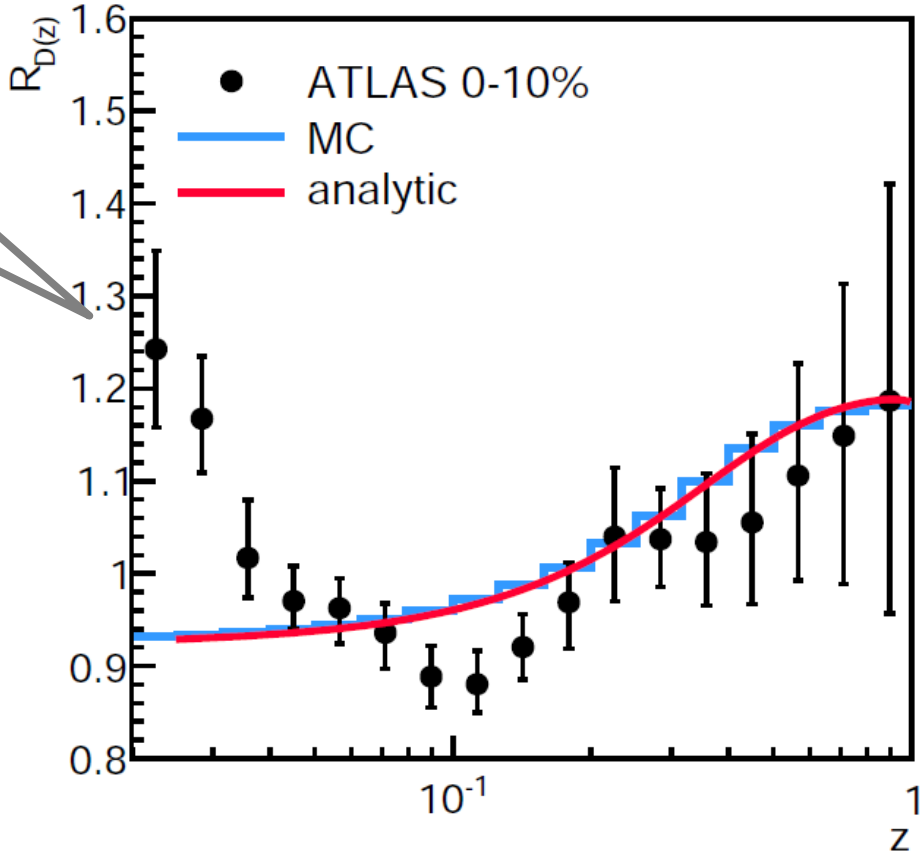


Modifications of fragmentation functions – a detail

Excess of low-*z* not due to flavor effects (maybe due to in-cone radiation, recoil, collective response, …)



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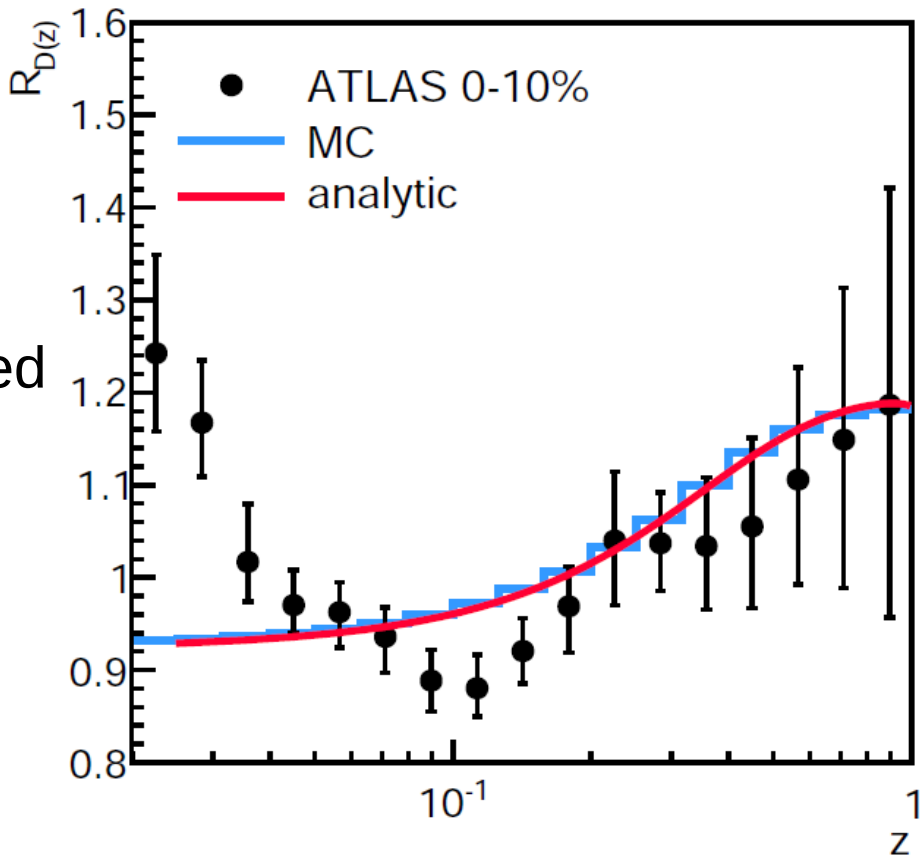
$$p_{\mathrm{T,jet}}^{\mathrm{measured}} = p_{\mathrm{T,jet}}^{\mathrm{quenched}} + p_{\mathrm{T}}^{\mathrm{soft}}$$

- 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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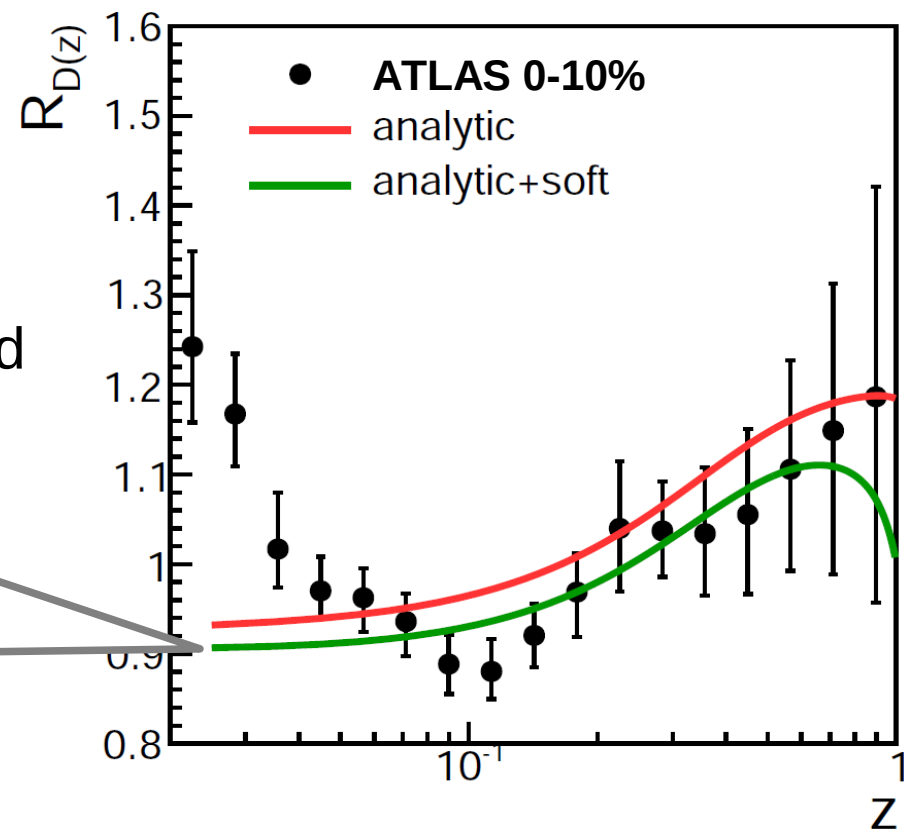
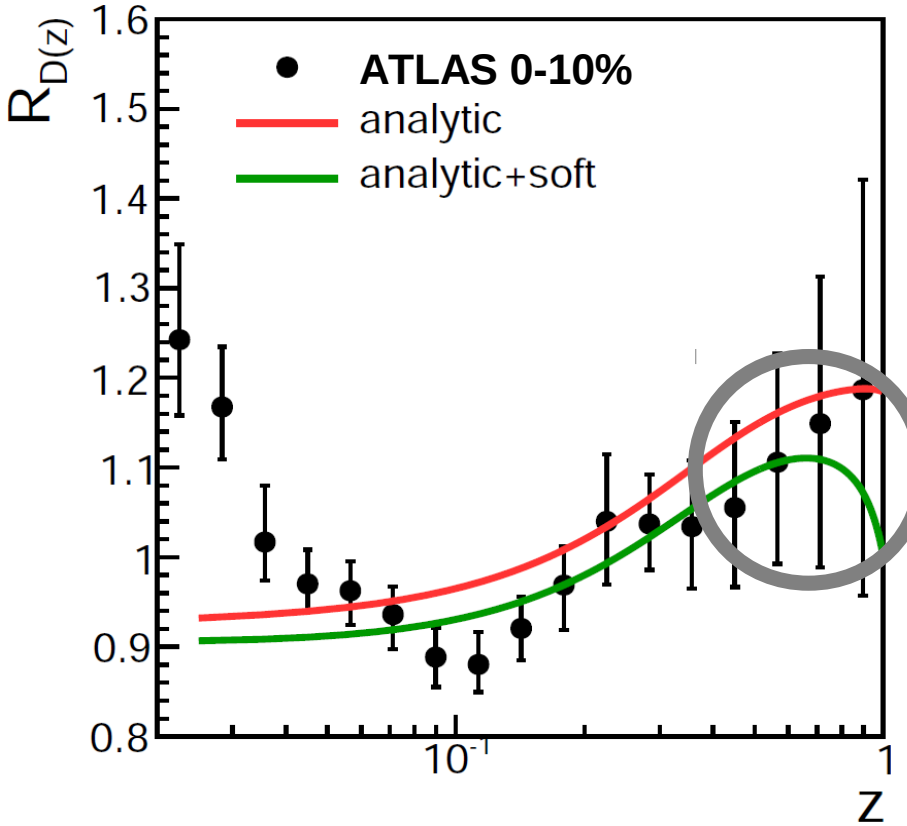


Contribution of soft hadrons to the jet energy can be estimated from the measurement at low-*z* => fragmentation distributions w/ correct soft contribution

Modifications of fragmentation functions – a detail

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

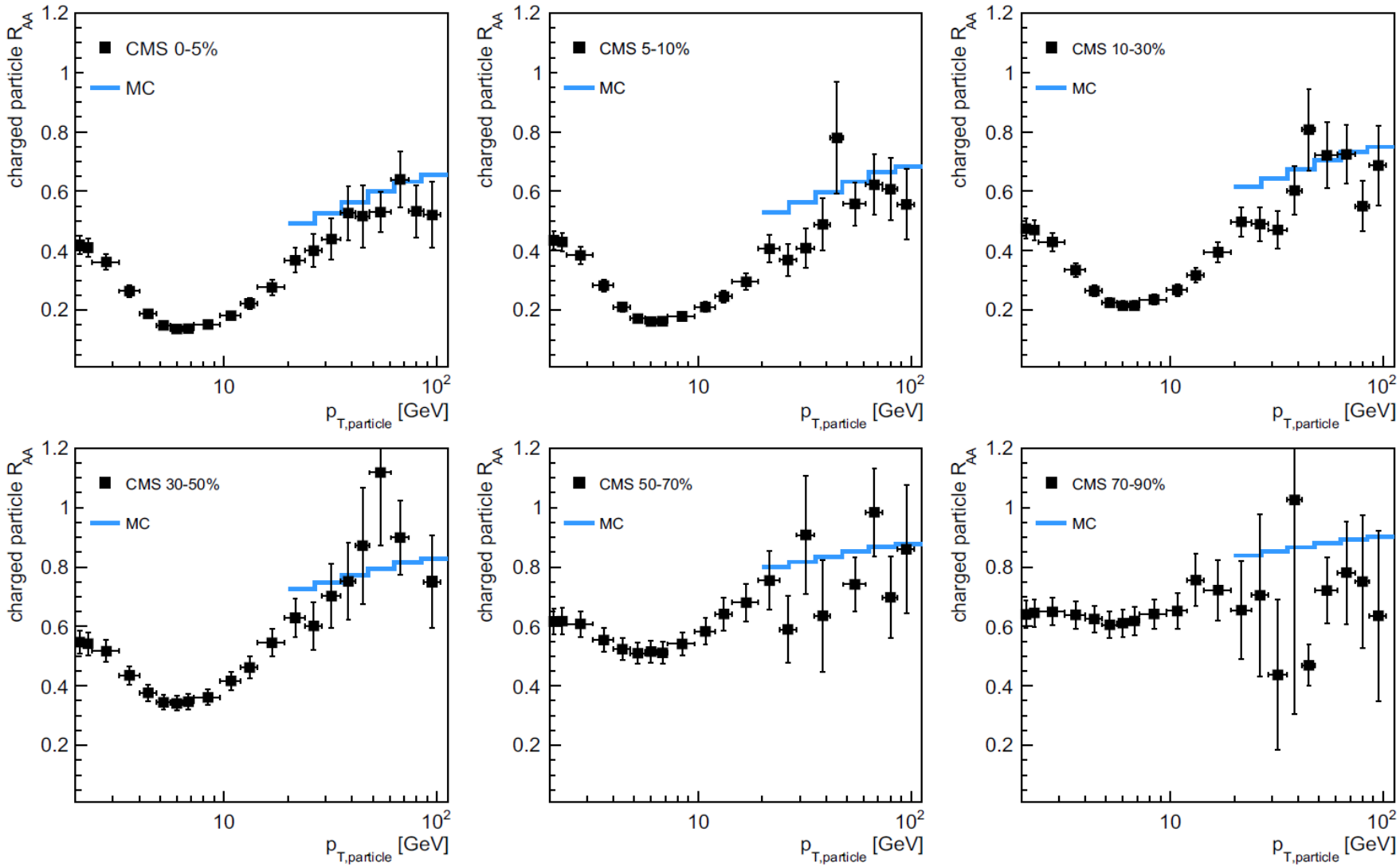
$$p_{\mathrm{T,jet}}^{\mathrm{measured}} = p_{\mathrm{T,jet}}^{\mathrm{quenched}} + p_{\mathrm{T}}^{\mathrm{soft}}$$



From jet internal structure to charged particle R_{AA}

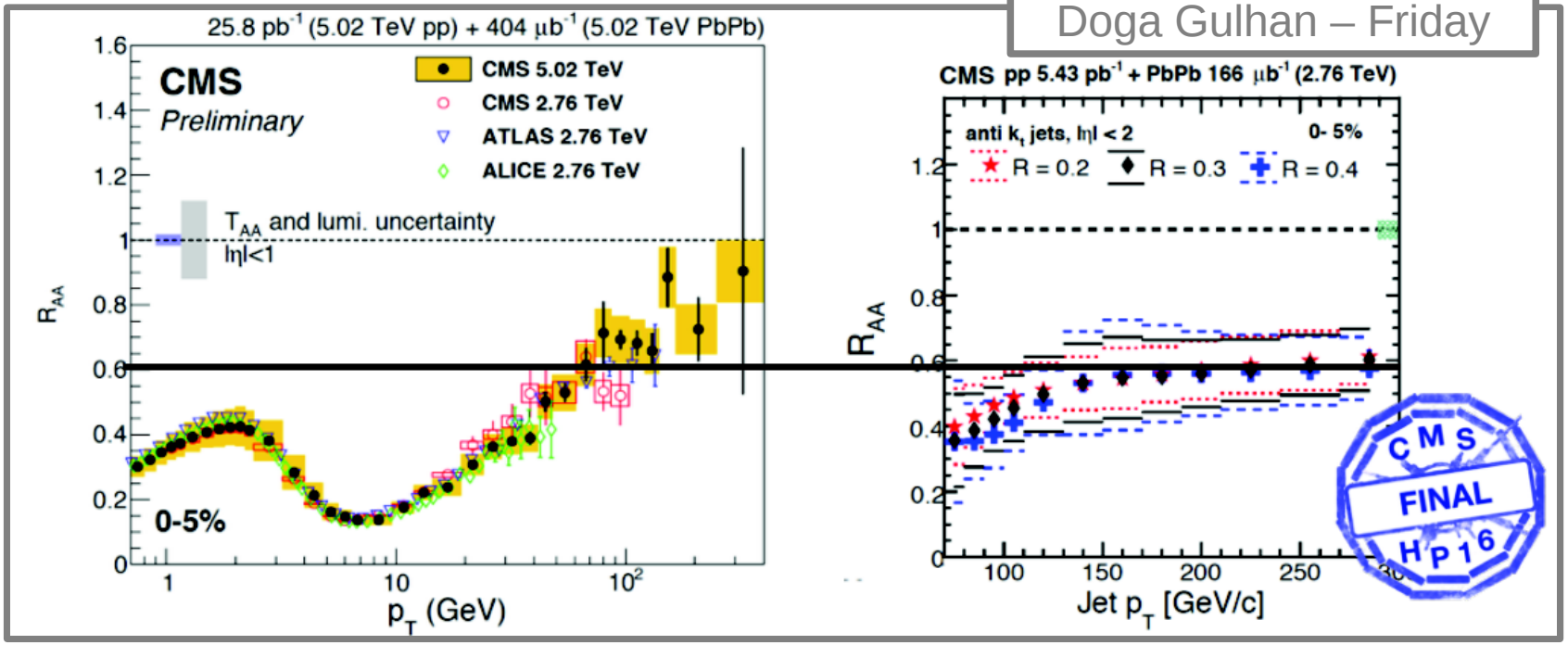
Each particle of a given p_T must be in a jet of the same or higher p_T
=> Charged particle R_{AA} (at high-p_T) = convolution of flavor dependent jet suppression and fragmentation functions

From jet internal structure to charged particle R_{AA}



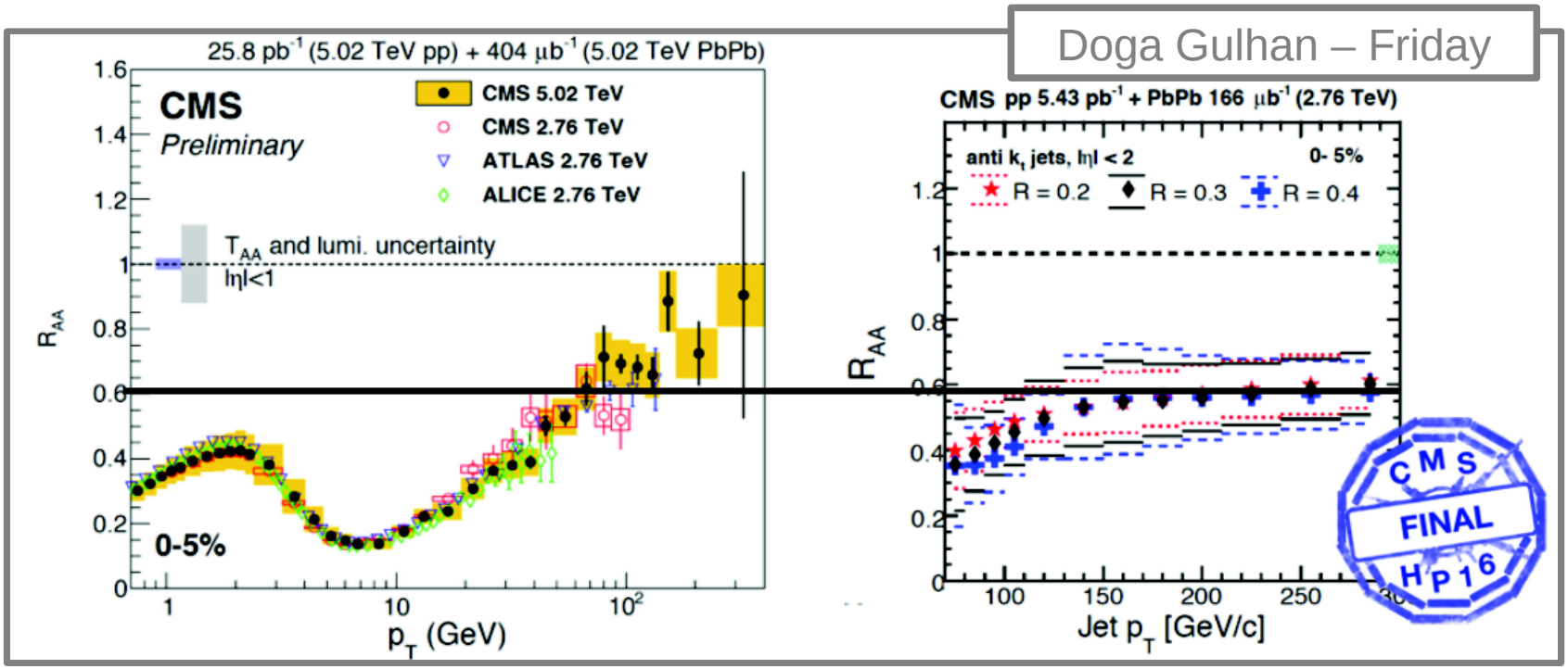
From jet internal structure to charged particle R_{AA}

Doga Gulhan – Friday



High-p_T jets are more suppressed than charged particles – a puzzle?

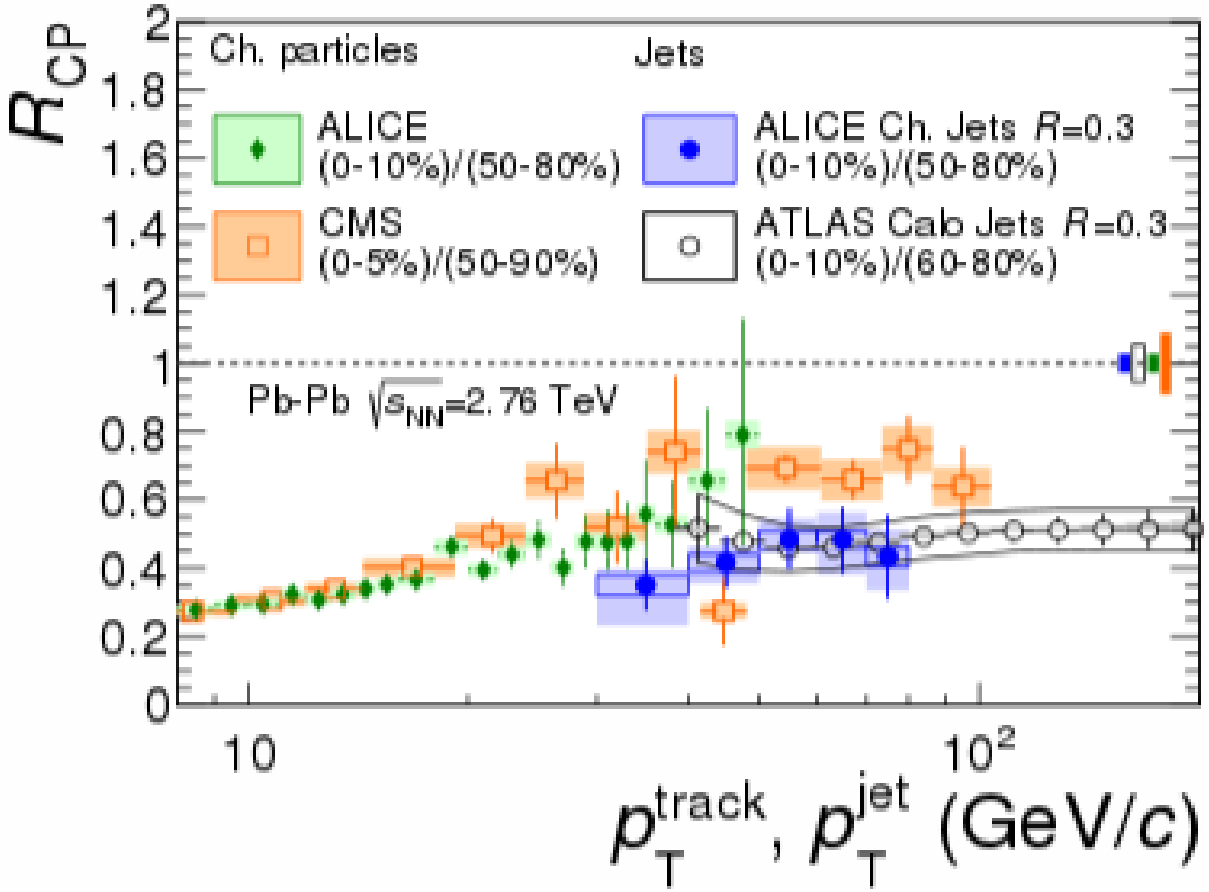
From jet internal structure to charged particle R_{AA}



High-p_T jets are more suppressed than charged particles – a puzzle?

– No, it is the same puzzle as the excess in D(z) at high z.
The 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}



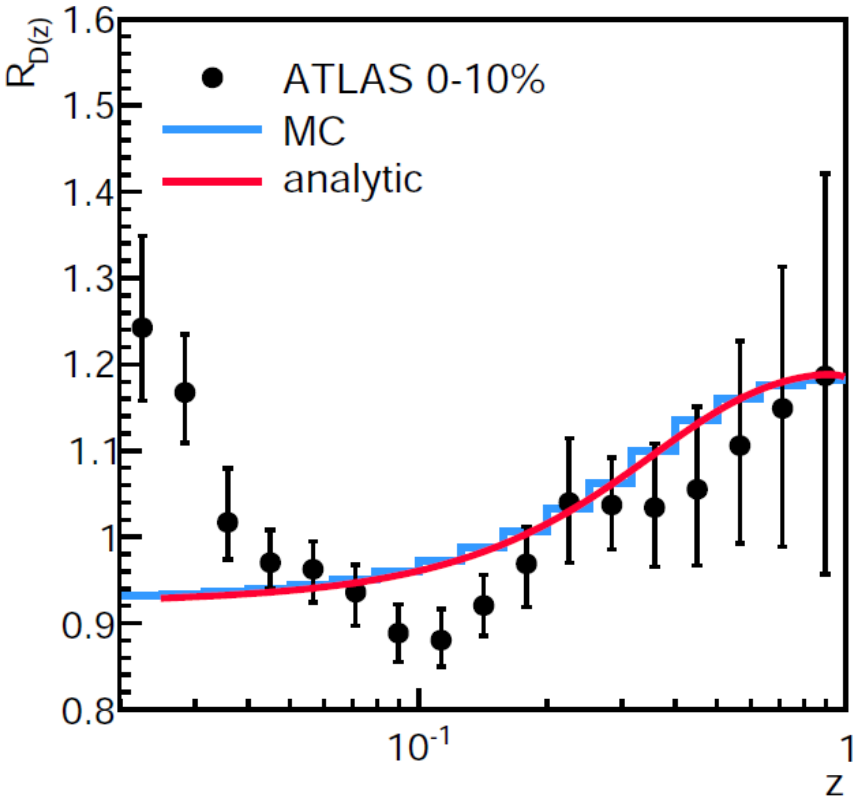
… we should not do this kind of plots – it is misleading

Flavor sensitivity

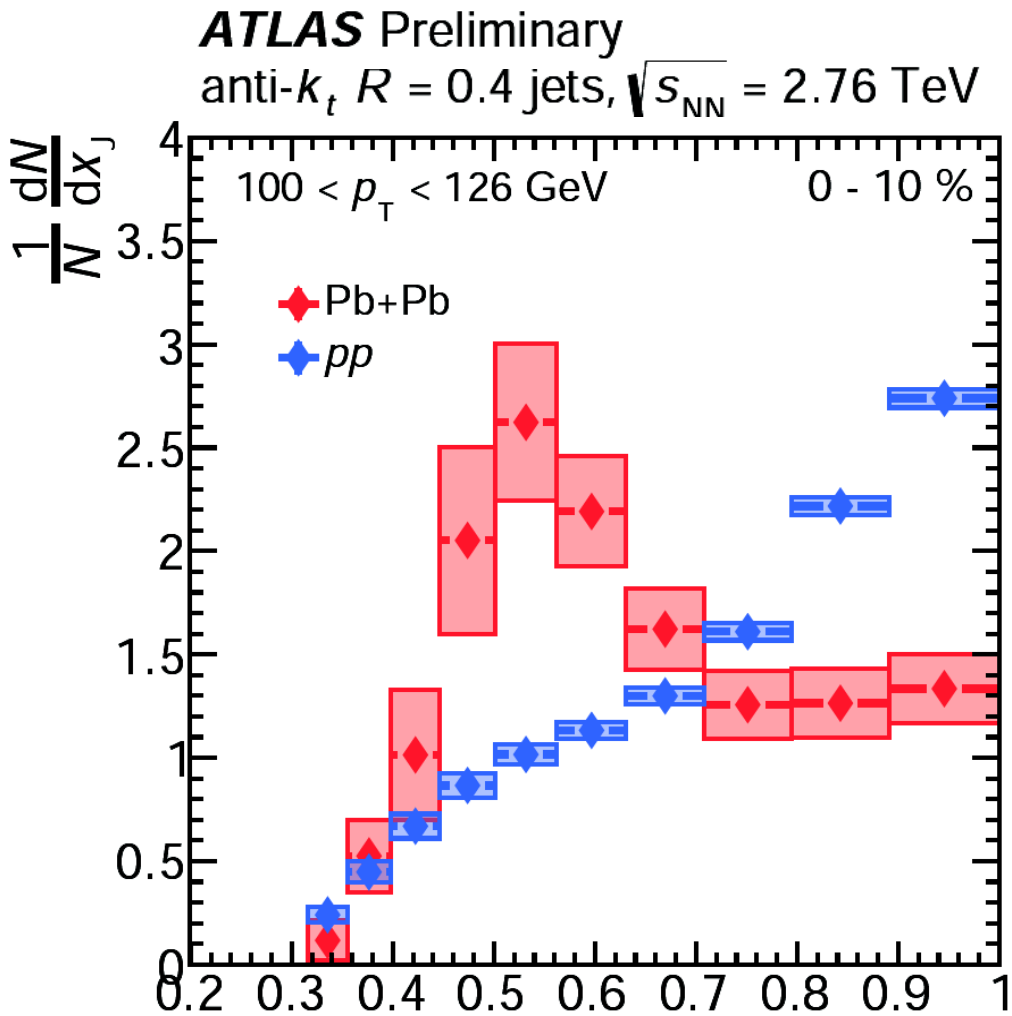
Definition: Flavor sensitivity = sensitivity of a given observable to the flavor (and spectra) of the initial parton leading to a possible incorrect interpretation of that observable.

Example: fragmentation functions at intermediate *z* and high *z*, charged particle R_{AA}

=> Checking other observables

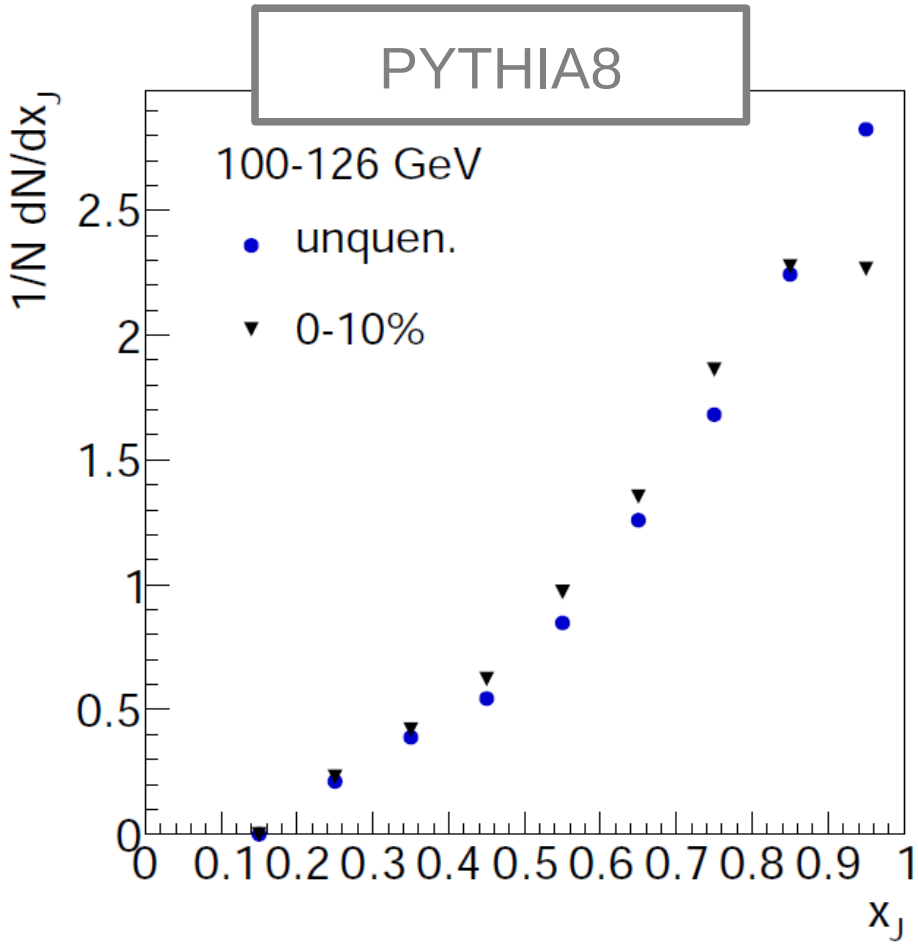


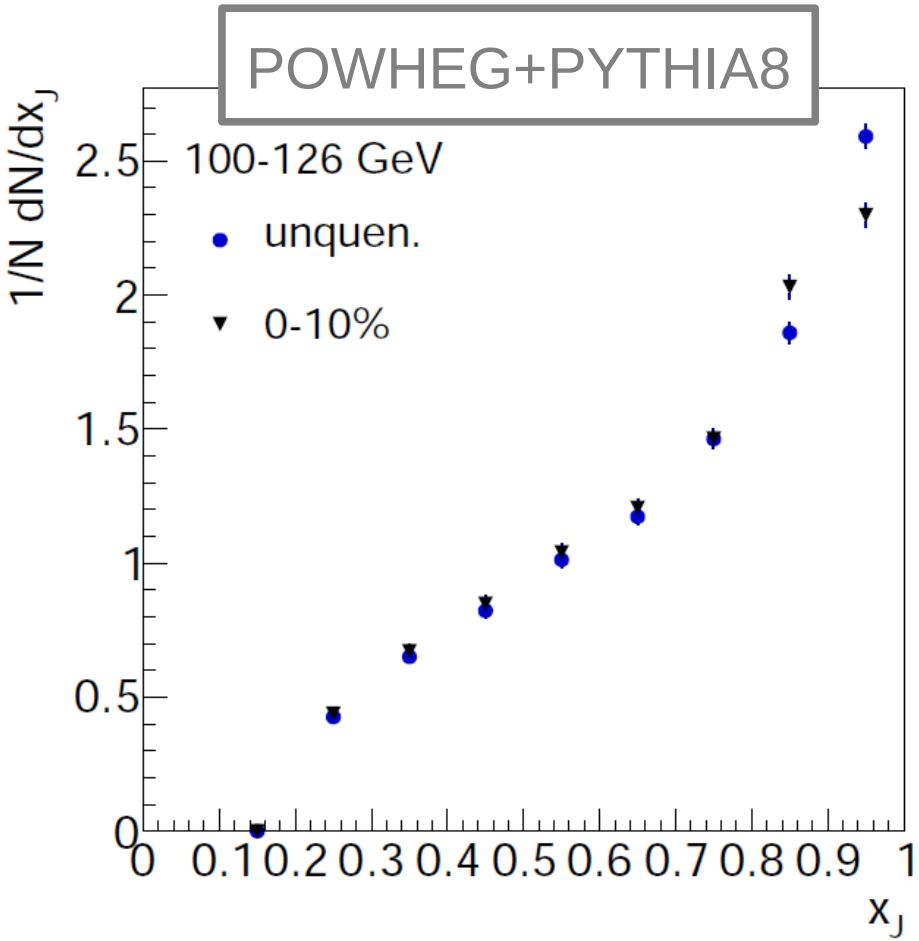
Dijet asymmetry



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

Dijet asymmetry





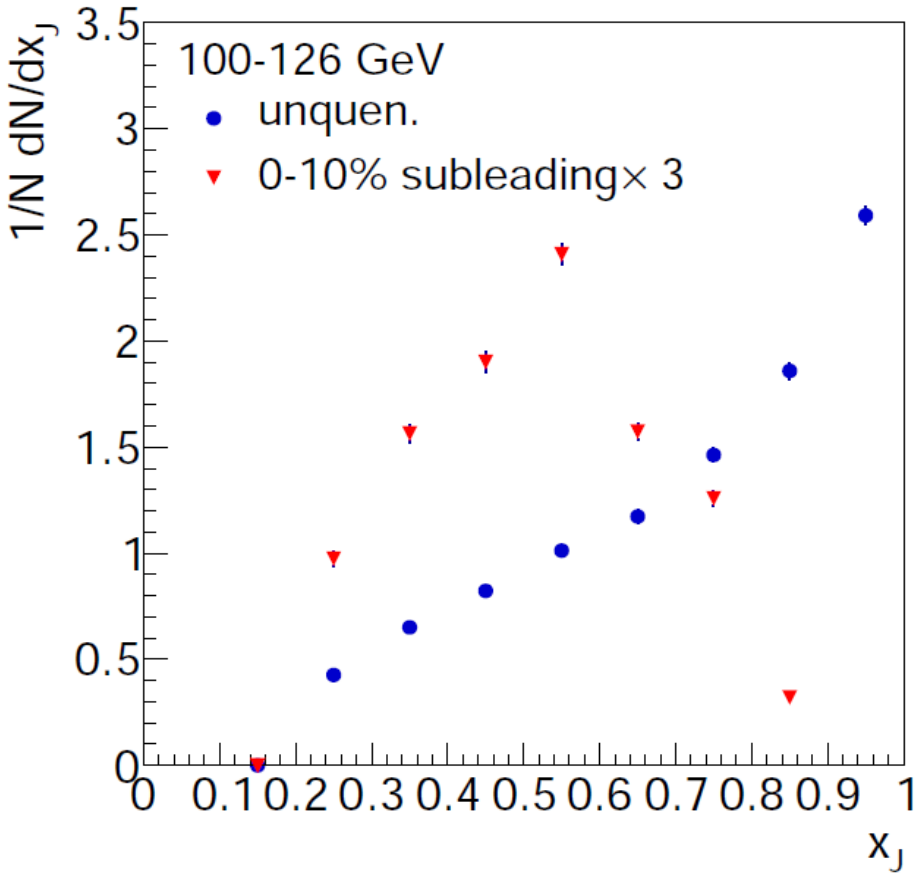
–> Measured asymmetry is not due to different quenching of q/g jets.

–> NLO generators may start to be important (shape matches w/ data).

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



Jet substructure using splitting

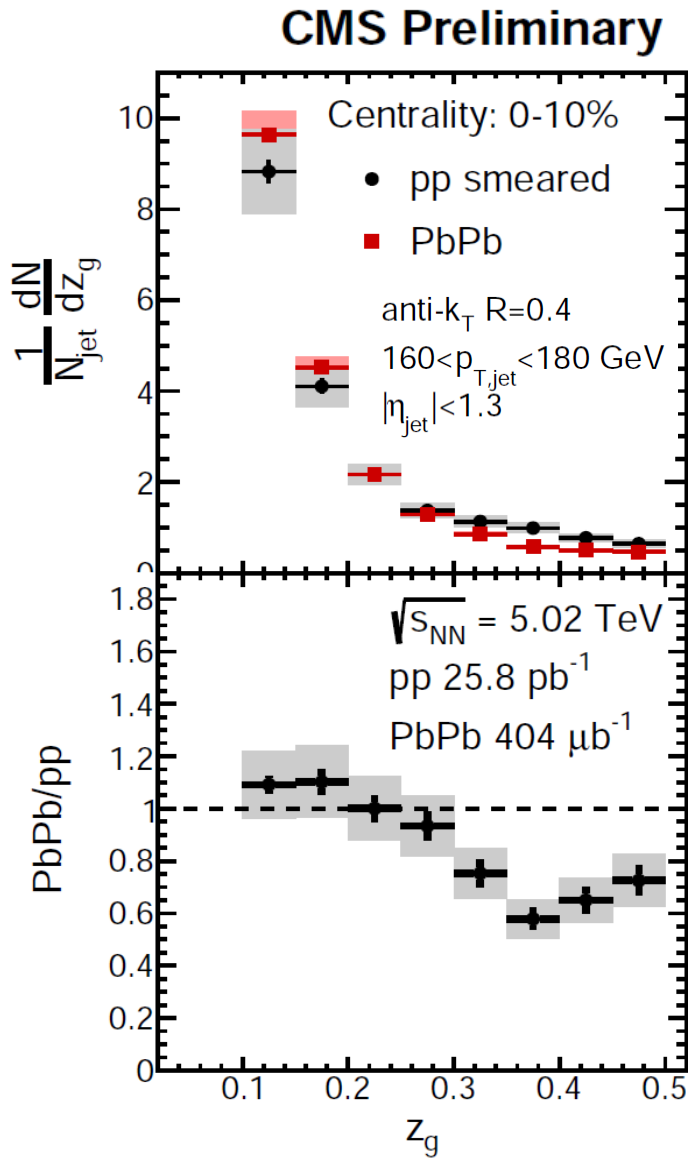
Splitting, z_g – defined by the 'Soft Drop' algorithm (used in pp studies of boosted objects):

- Run C/A algorithm in the jet
- Compare subjets; if

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} < 0.1$$

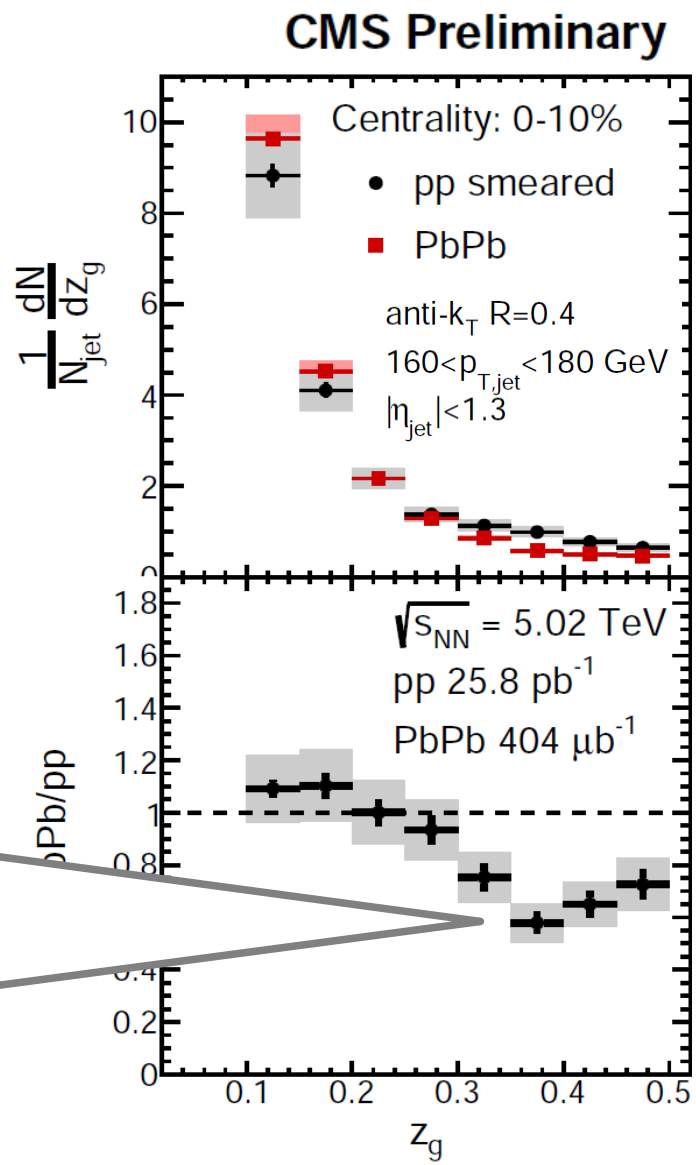
- drop the softer partner and repeat the same calculation with two "parents" of harder subject; else

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} = z_g$$



Matteo Cacciari (Fri), Marta Verweij (Sun)

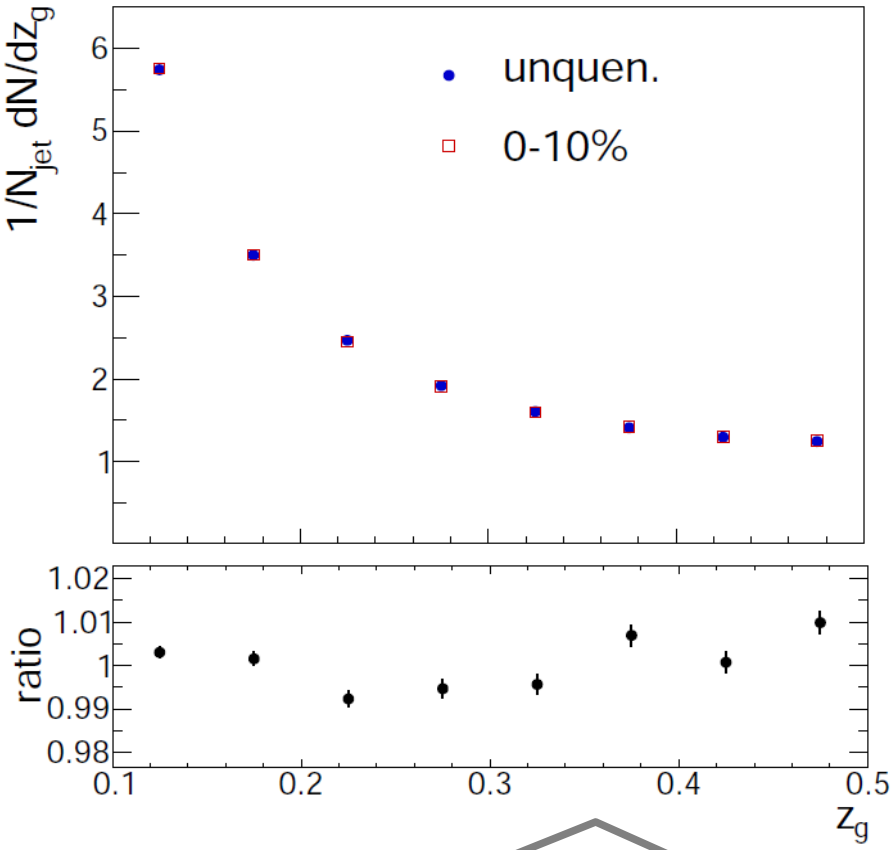
Jet substructure using splitting

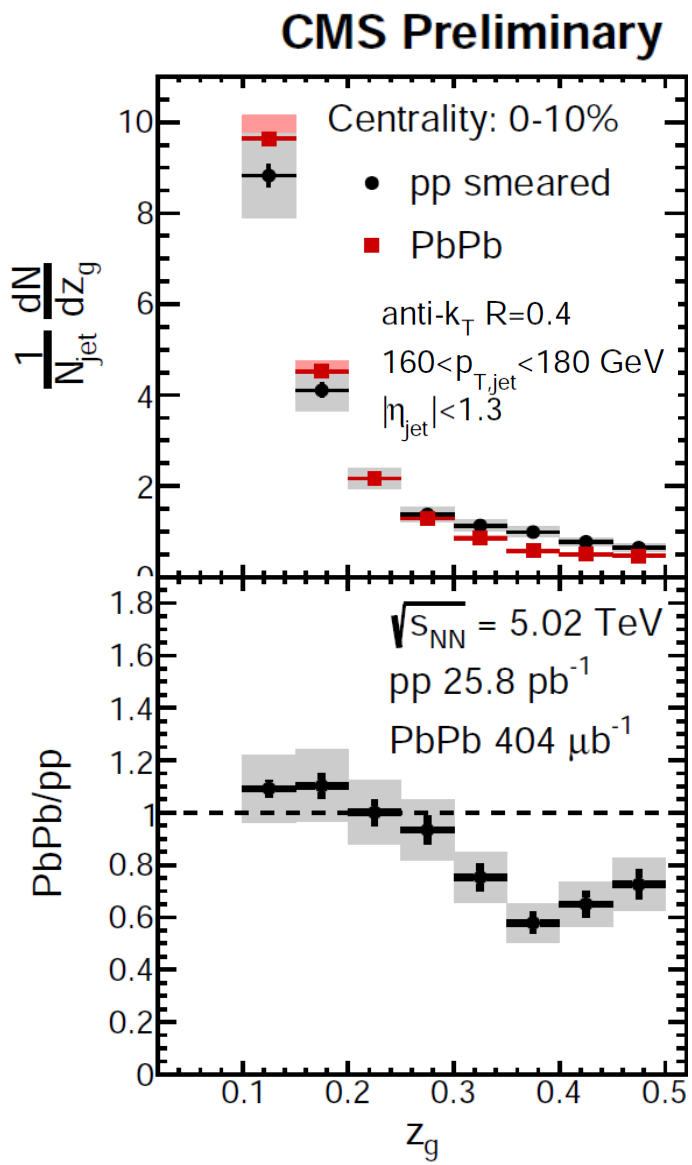


–> Jets with a distinct subject structure (p_{T1} closer to p_{T2}) quenched more (or more jets with less splitting)

–> Looks significant, but the change involves only 5-10% of jets

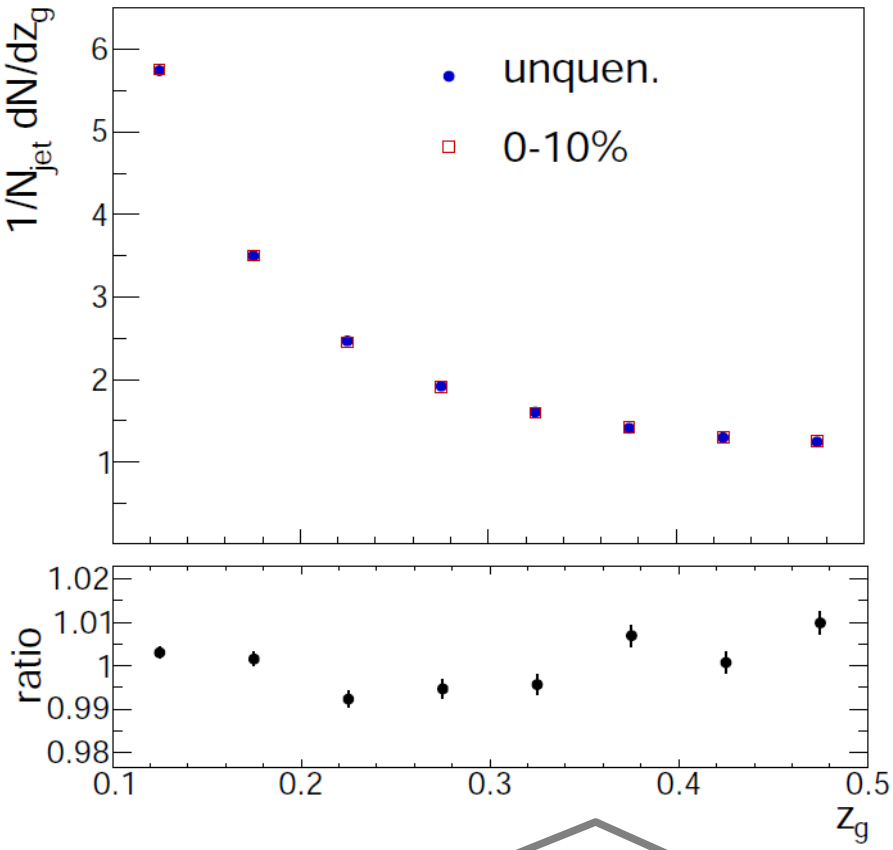
Jet substructure using splitting

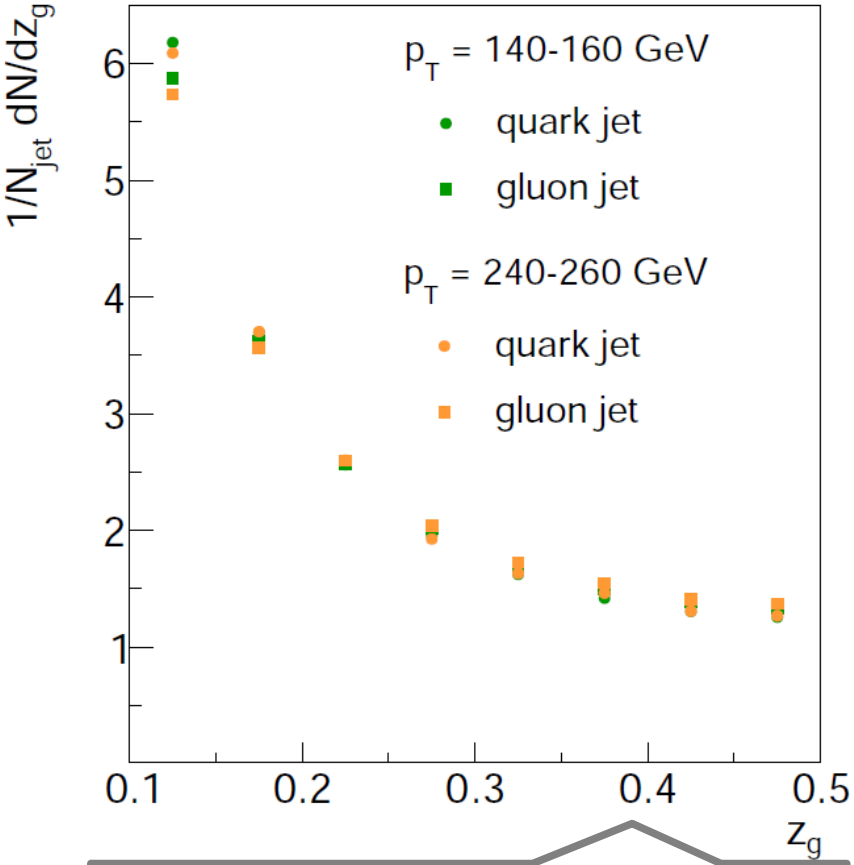




Use the quenching model in the same way as before for the fragmentation

Jet substructure using splitting

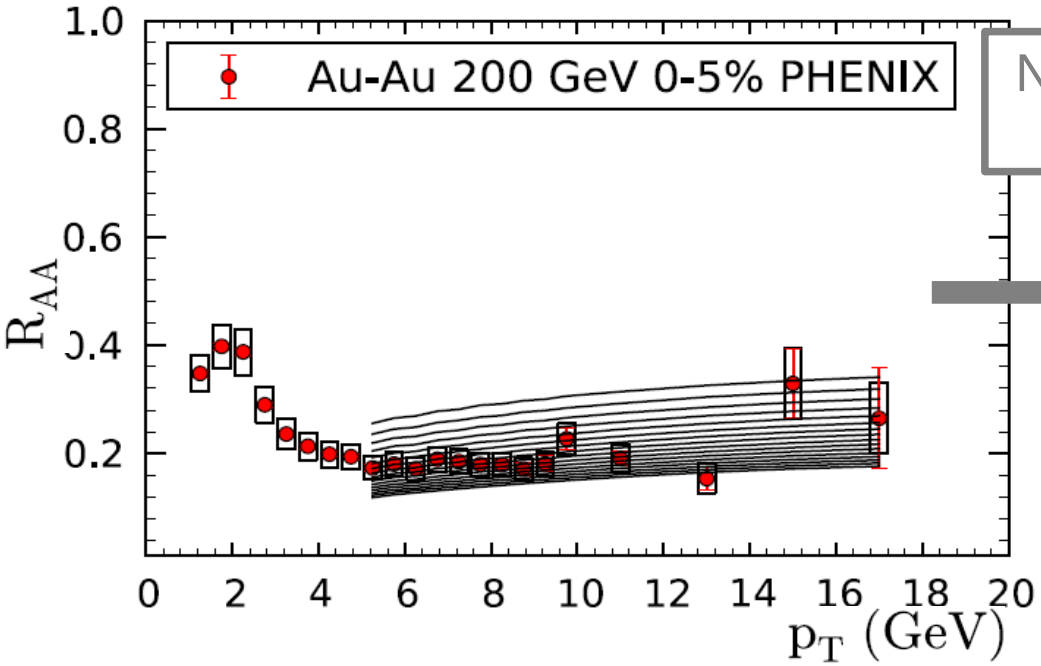




Modification not due to a simple flavor bias ...

… since z_g does not depend much on the flavor or jet p_T

Puzzling difference between RHIC and LHC



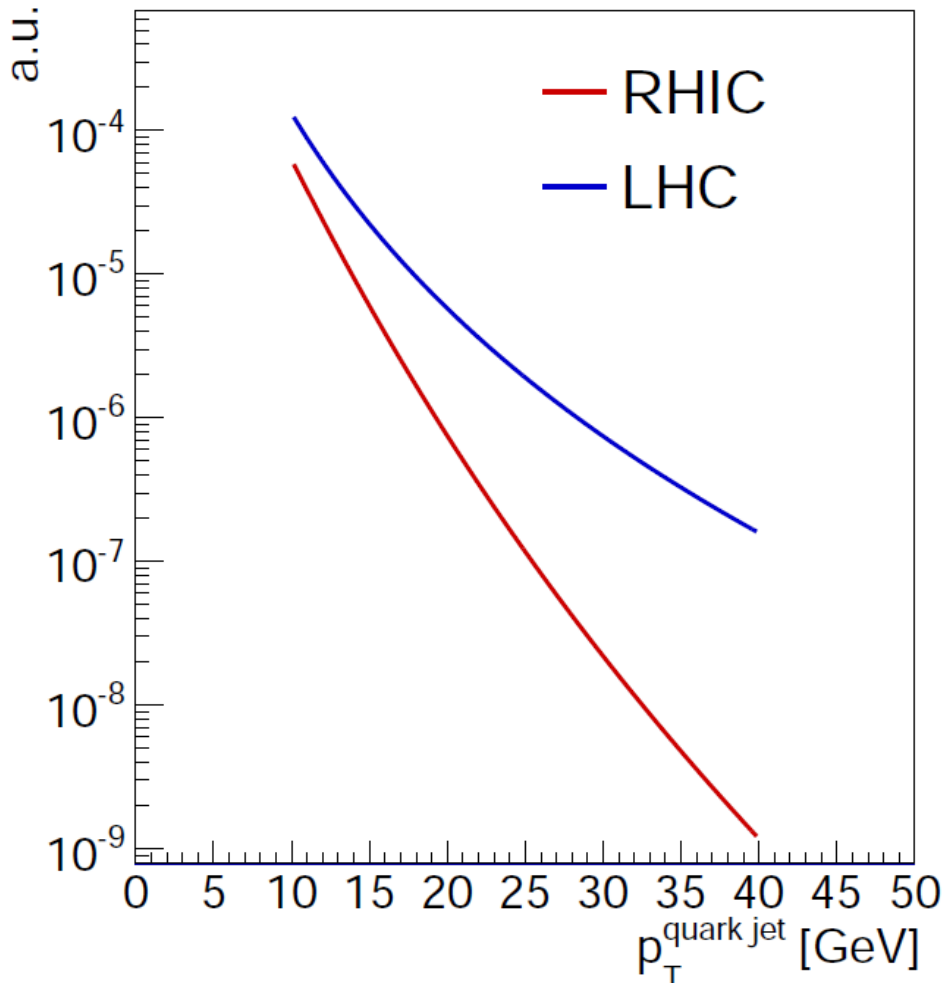
Nestor Armesto (Fri), Andres Casas (Sat)

$$\hat{q} = K \cdot \hat{q}_{ideal} = K \cdot 2\epsilon^{3/4}$$

- Andrés et. al (EPJ C76 (2016) 475) … K factor 2-3 times larger at RHIC than at the LHC, with only mild centrality dependence,...
- Horowitz, Gyulassy (Nucl.Phys. A872, 265) … suppression at RHIC is larger

=> How is the extraction of the quenching from charged particles influenced by the underlying parton/jet kinematics?

Jets at RHIC versus LHC

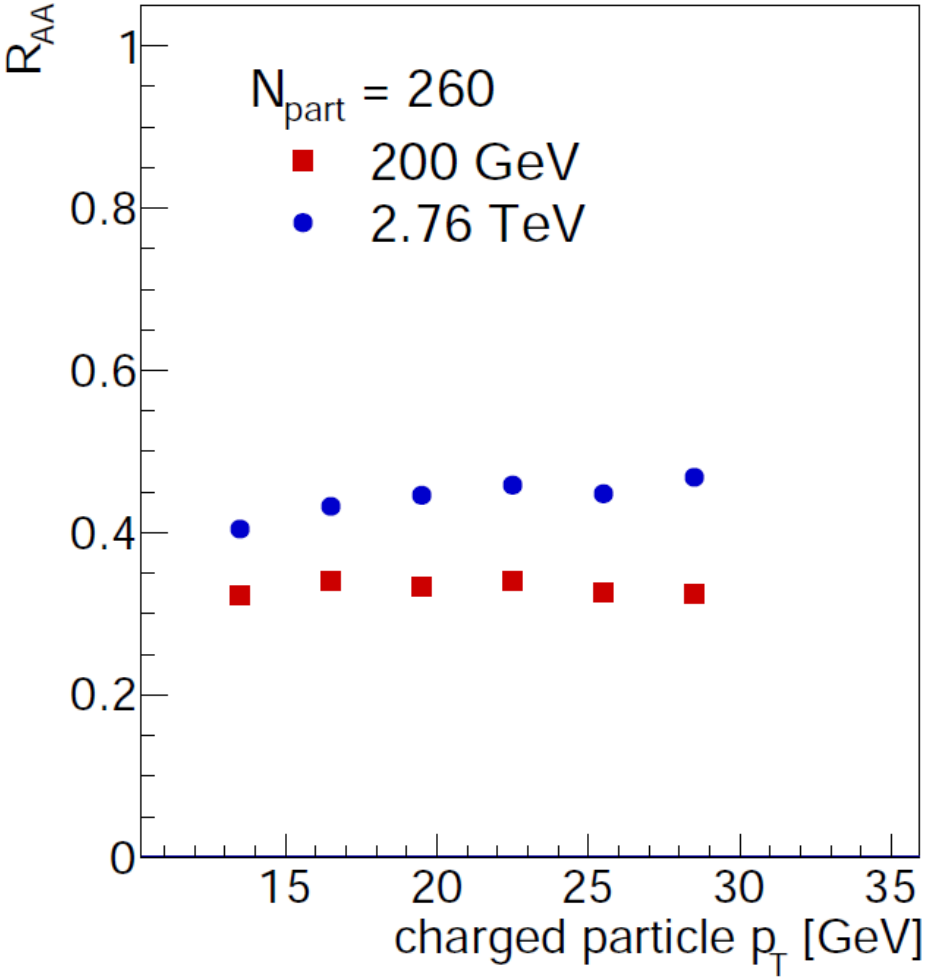


- Jets very different between LHC and RHIC
- Jet spectra for a given flavor more steep at RHIC
- Flavor composition also different

–> Will impact charged particle R_{AA}

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

Charged particle R_{AA} RHIC vs 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 crucial for the extraction of the size of jet quenching

Flavor sensitivity

Definition: Flavor sensitivity = sensitivity of a given observable to the flavor (and spectra) of the initial parton leading to a possible incorrect interpretation of that observable.

Flavor sensitive: jet R_{AA}, fragmentation functions at intermediate z and high z, charged particle R_{AA}

Likely flavor sensitive: jet width, jet mass, single particles

Almost flavor insensitive: z_g distribution, x_J distribution, fragmentation at low z (= high ξ)

Quantifying the parton energy loss (II.)

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

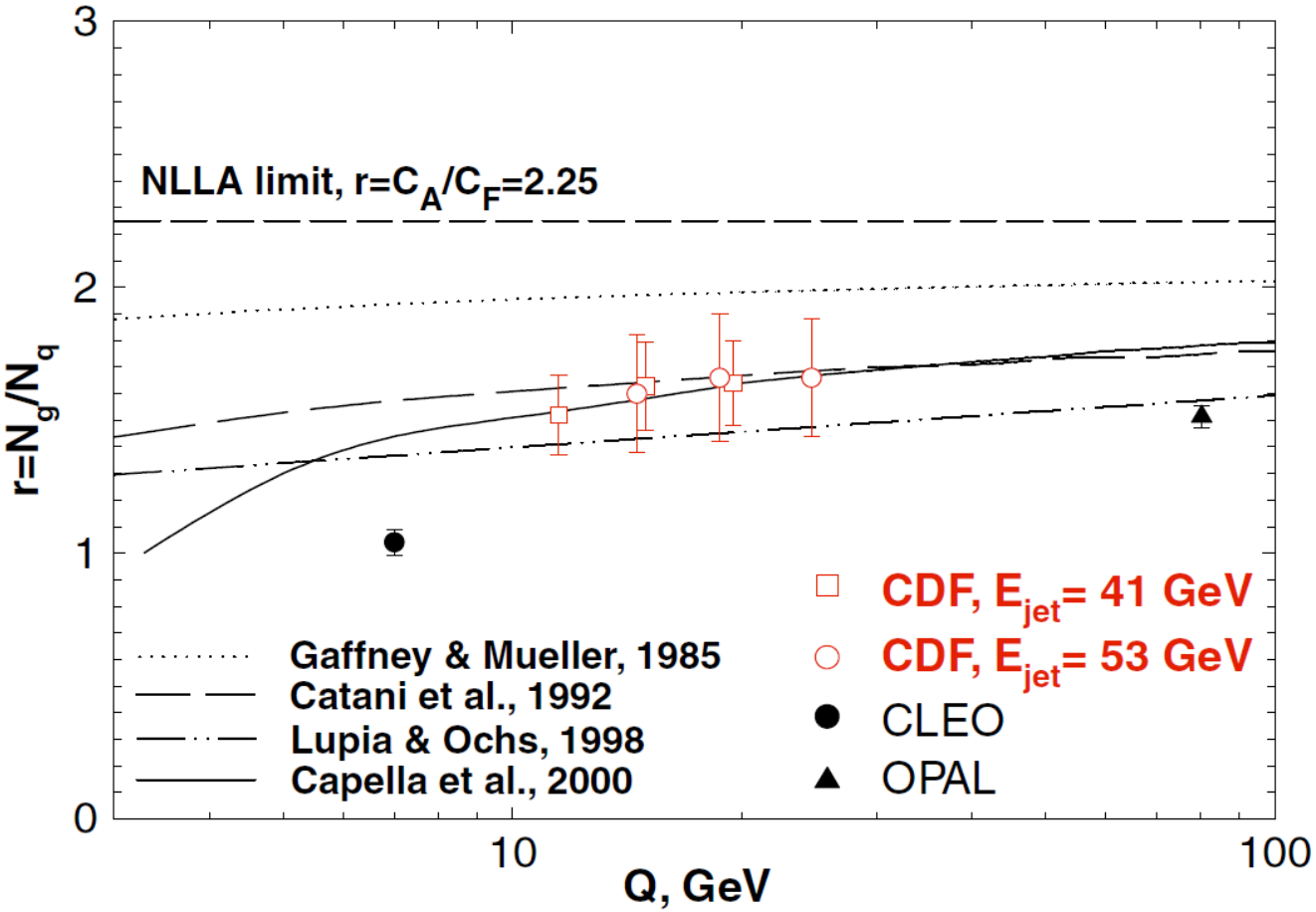
Yield of quenched jets of a given flavor at given pt

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

$$S_g = c_{\mathrm{F}} \times S_q$$

- So far α and s' free, c_F=9/4 fixed
- c_F=9/4 … difference in the probability to radiate a gluon from a gluon and quark source in the vacuum in large Q^2 limit or soft limit
- Vacuum value of c_F measured and calculated in pQCD (MLLA)

Quantifying the parton energy loss (II.)



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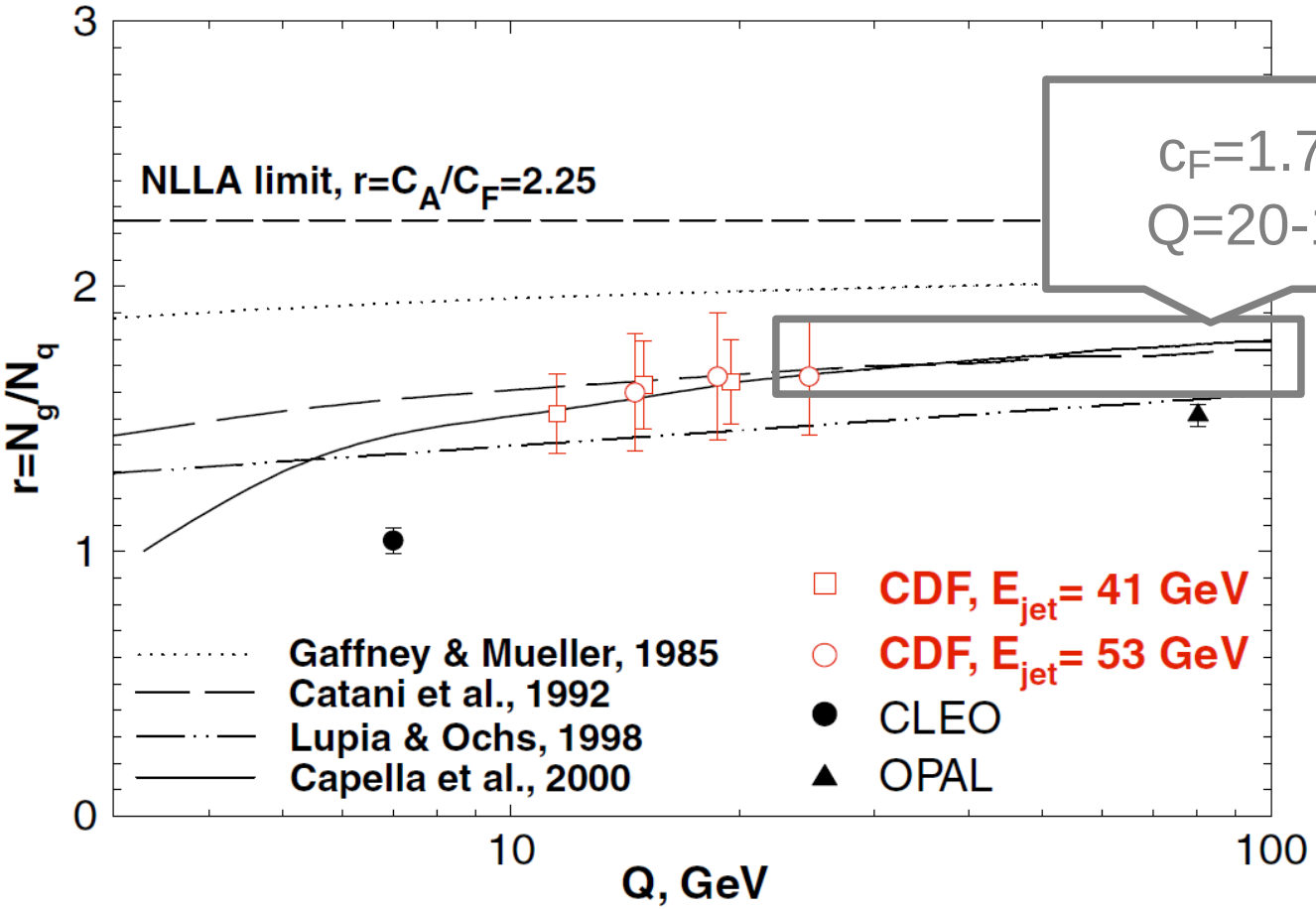
Quantifying the parton energy loss (II.)



c_F=1.7-1.8 for Q=20-100 GeV

- Vacuum value of c_F measured and calculated in pQCD (MLLA)

Quantifying the parton energy loss (II.)

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

- 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)

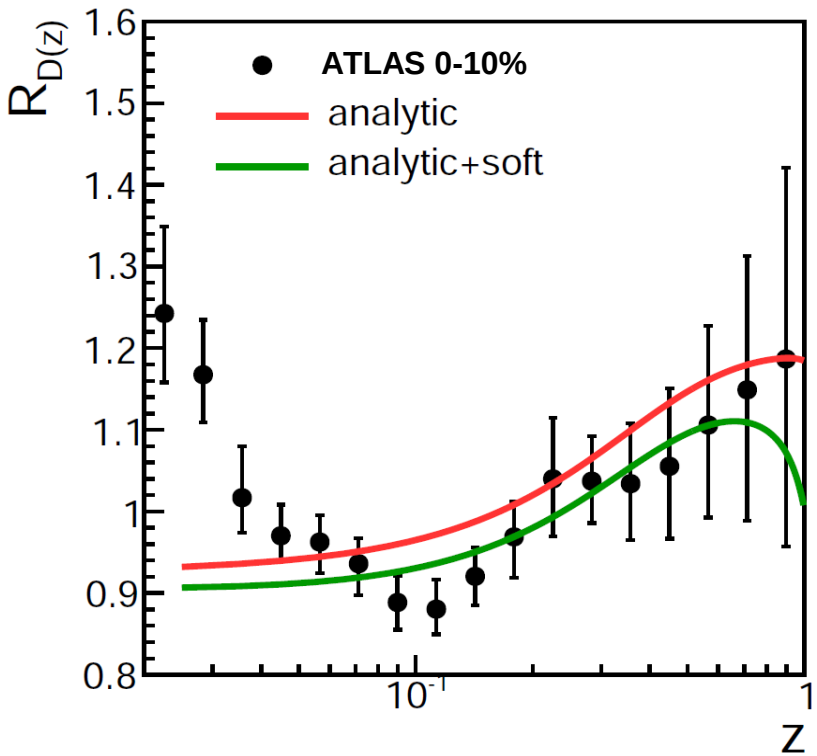
–> Result:

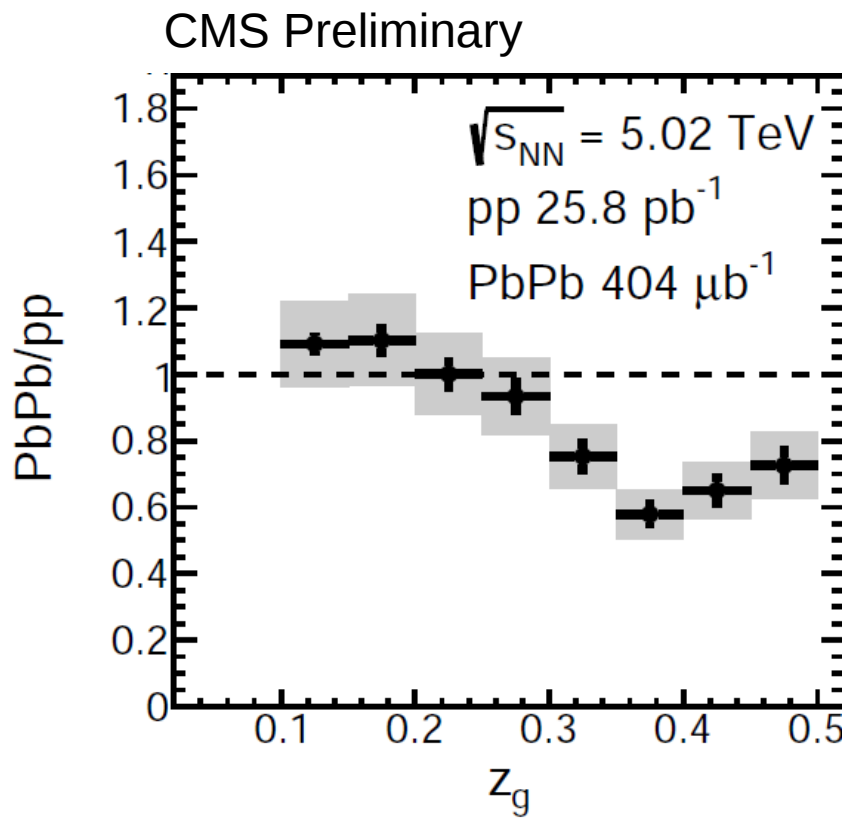
$s' = x \cdot N_{\mathrm{part}} + y$	$x = 12.3 \pm 1.4$ GeV, $y = 1.5 \pm 0.2$ GeV
α	0.52 ± 0.02
c_{F}	1.78 ± 0.12

–> 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?





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$$J/\Psi \ \& \ \Psi(2S)$$

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?

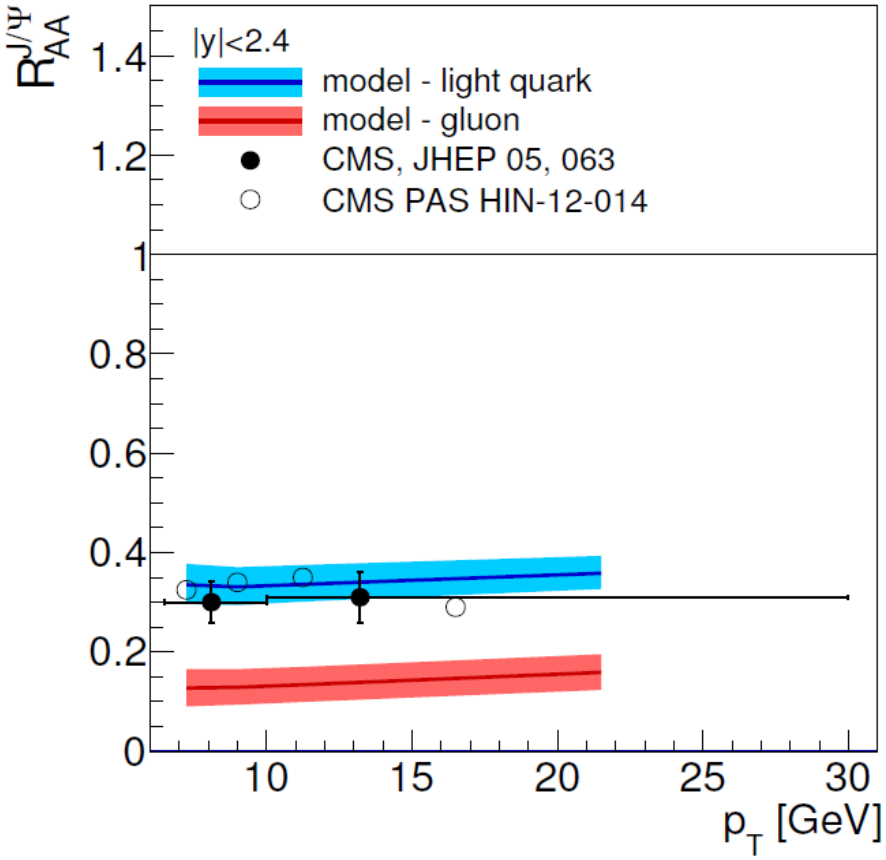
J/Ψ & $\Psi(2S)$

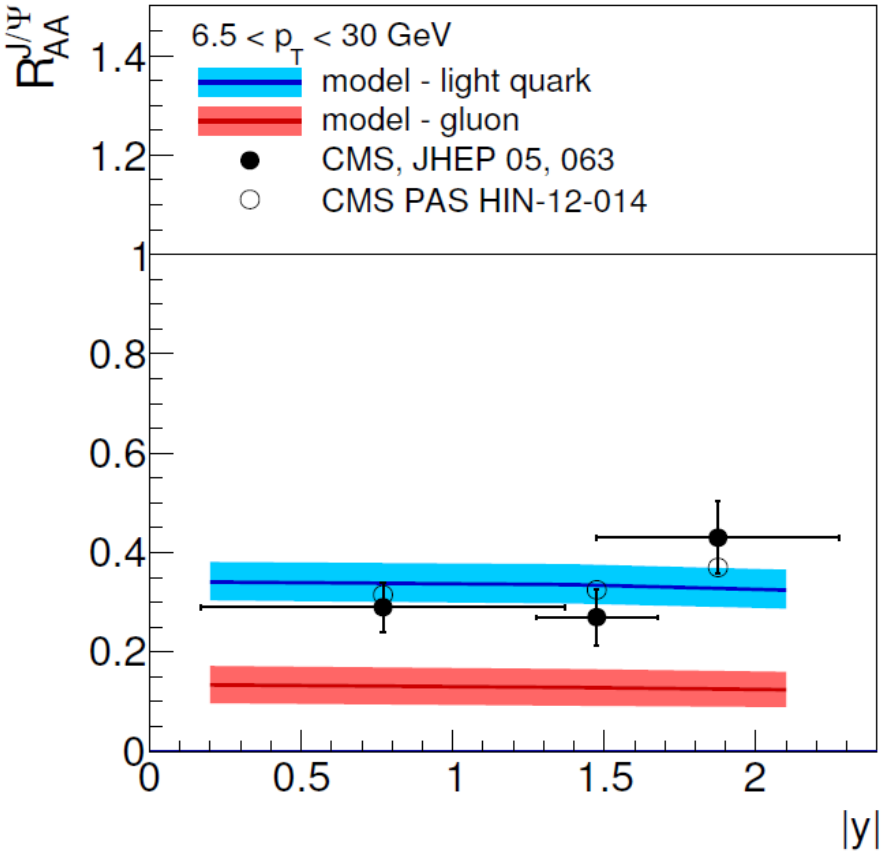
... check the differences between the suppression of jets and charmonia at high-p_T (at the LHC at mid-rapidity)

Input:

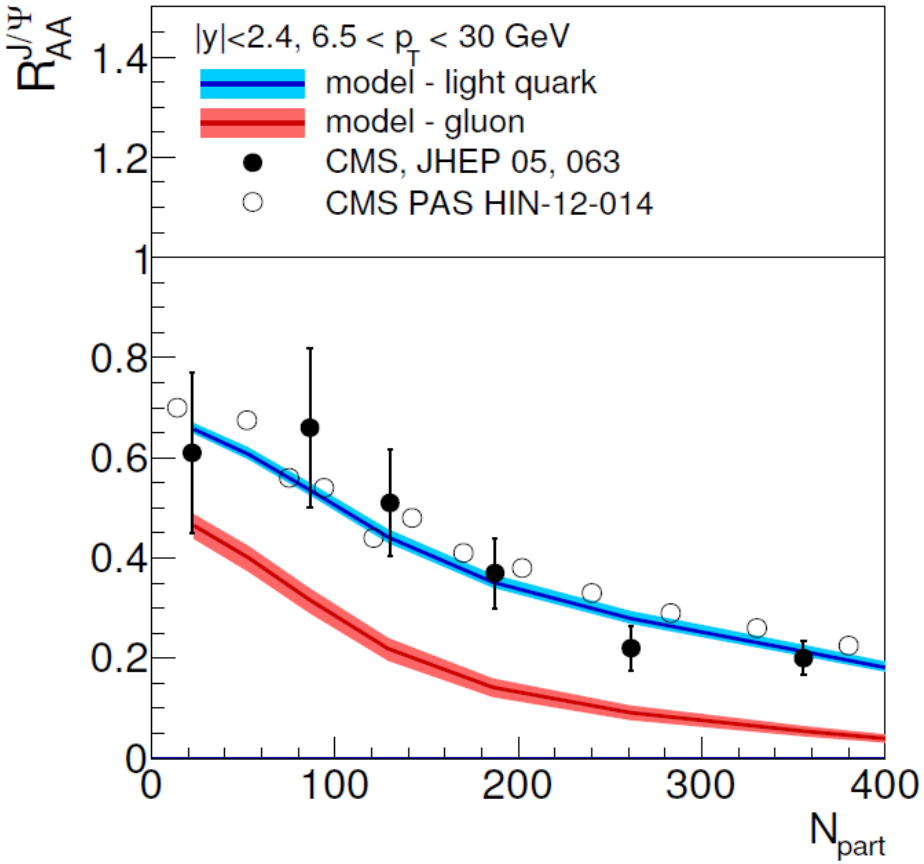
- Measured pp spectra of charmonia (cannot rely on out of the box PYTHIA or other generator)
- Energy loss extracted from jets

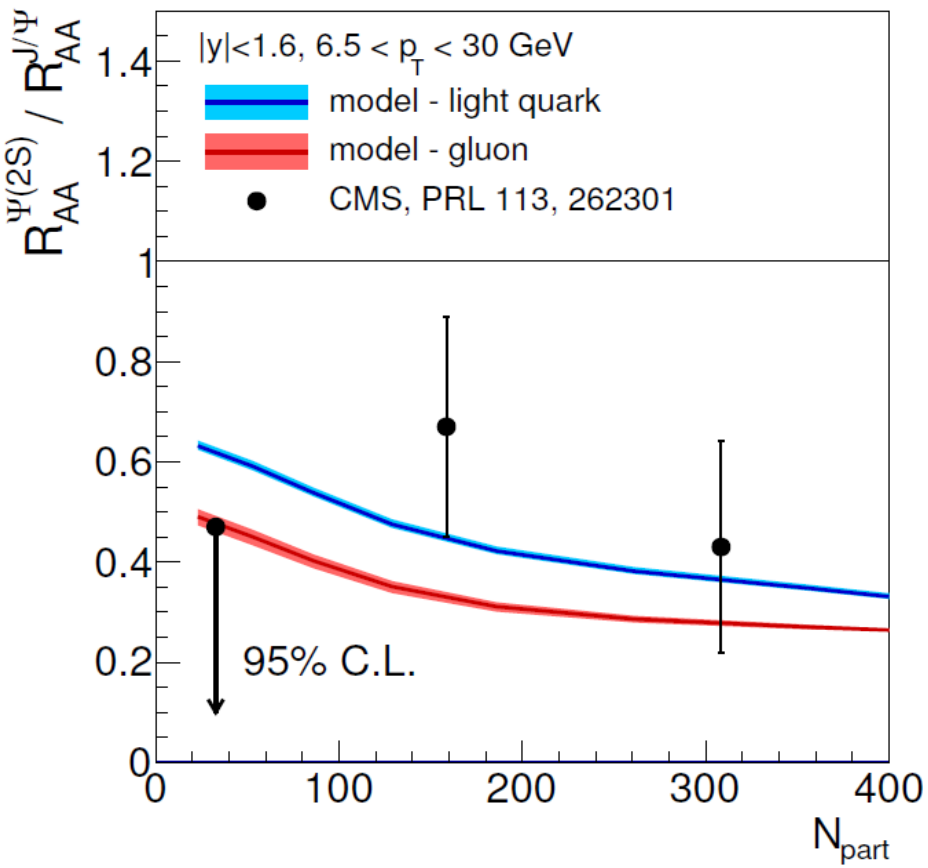
Charmonia


$R_{AA}^{J/\Psi}$
|y|<2.4
model - light quark
model - gluon
CMS, JHEP 05, 063
CMS PAS HIN-12-014
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10
15
20
25
30
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
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
|y|

Charmonia





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

Summary

- Absence of rapidity dependence and flatteness of jet R_{AA}, characteristic shapes of jet fragmentation at mid and high *z* are due to flavor dependent jet quenching.
- Data say that coherence effects are important (medium largely, but not fully sees R=0.4 jets as one radiating object).
- Recoil (or in-cone radiation) modifies also measured high-z fragmentation (same holds for all other observables).
- *b*-jets are quenched more than light quark jets.
- Dijet asymmetry: sub-leading jet is quenched ~3 times more then the leading jet.
- Charged particle R_{AA} @ RHIC vs LHC: initial parton spectra and flavor composition are important for the extraction of the size of quenching (for the same quenching R_{AA} at 200 GeV will be smaller than R_{AA} at 2.76 TeV)

Summary (cont'd)

- Average jet quenching can be parameterized as follows

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

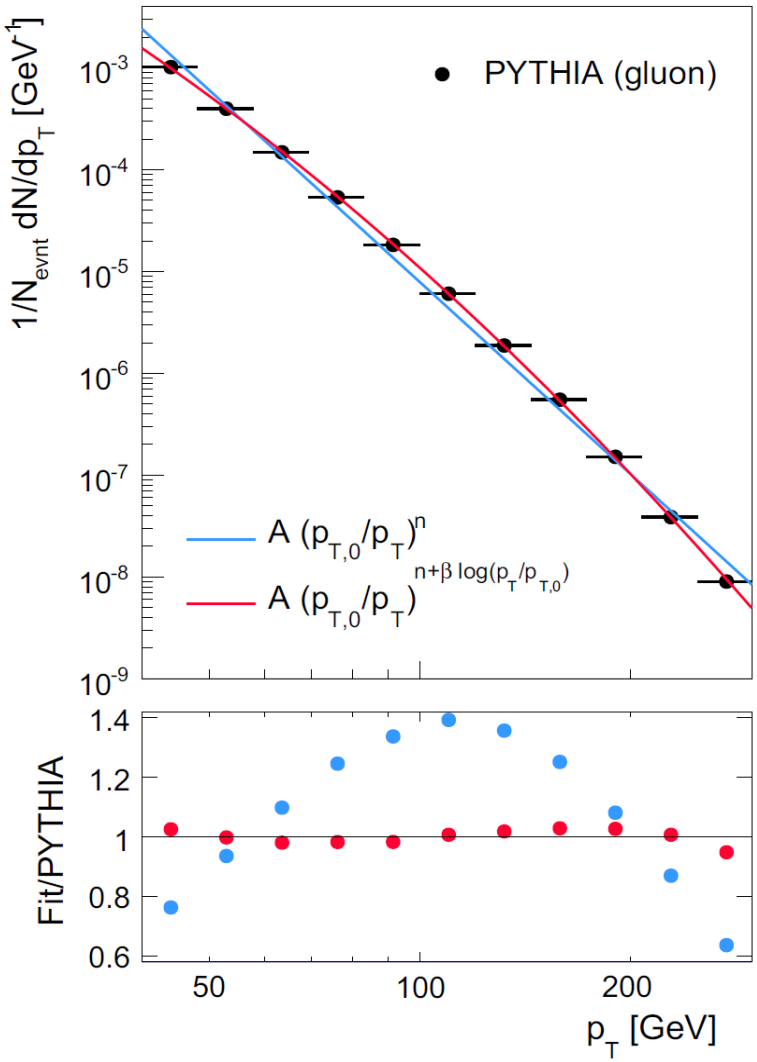
$$S_q = s' \left(\frac{p_T^{\mathrm{jet}}}{p_{T,0}} \right)^{\alpha}$$

(… can be used in simple modeling, checking observables, comparisons w/ full quenching models).

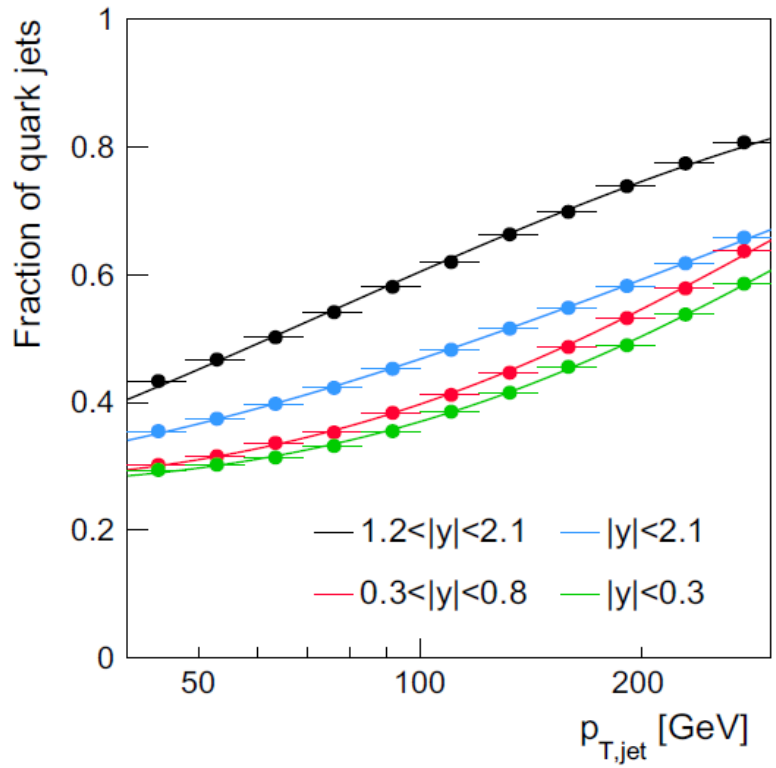
- Color factor, extracted for the first time in HI, seems not to be modified by the medium ($c_F = 1.78 \pm 0.12$).
- Parton energy loss does not extrapolate to 0 for $N_{part} \rightarrow 0$.
- Suppression of charmonia at p_T>6.5 GeV at midrapidity behaves like the suppression of light quark jets.

Backup slides

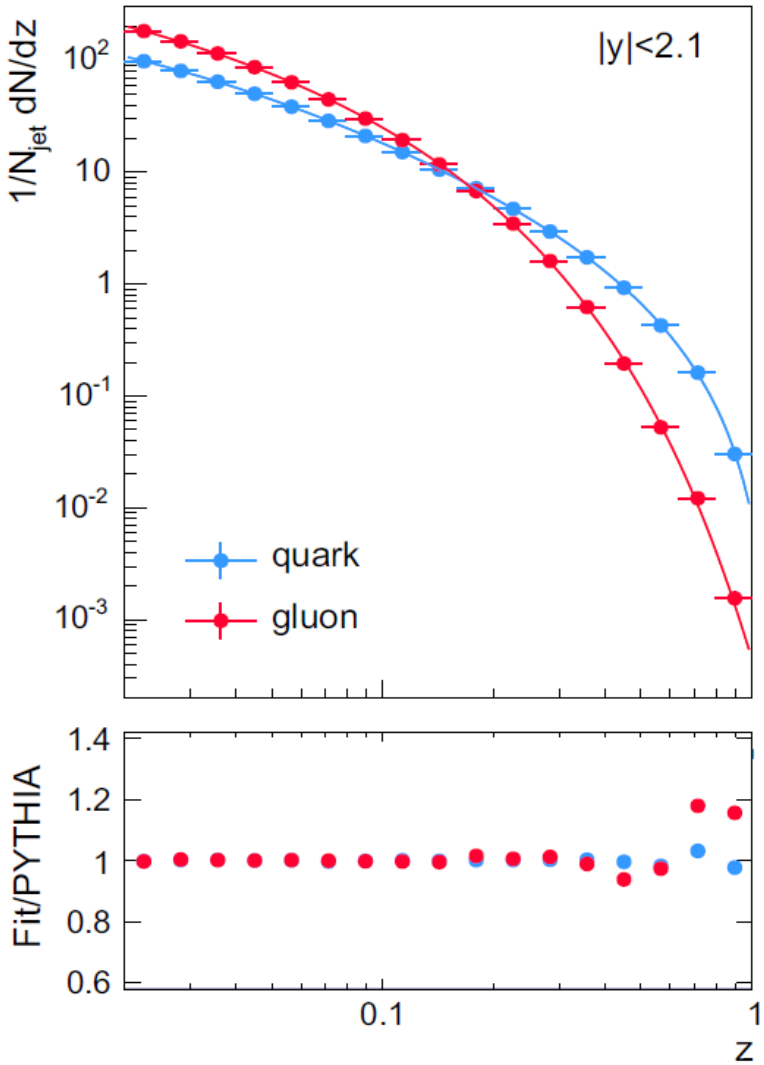
Flavor fractions and fit parameters



Fit type	Parameter	$\lvert y\rvert < 2.1$	$\lvert y\rvert < 0.3$	$0.3 < \lvert y\rvert < 0.8$	$1.2 < \lvert y\rvert < 2.1$
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

$$R_{AA} = f_q \left(\frac{1}{1 + S_q / p_T^{jet}} \right)^{n_q + \beta_q \log((p_T^{jet} + S_q)/p_{T0})}$$

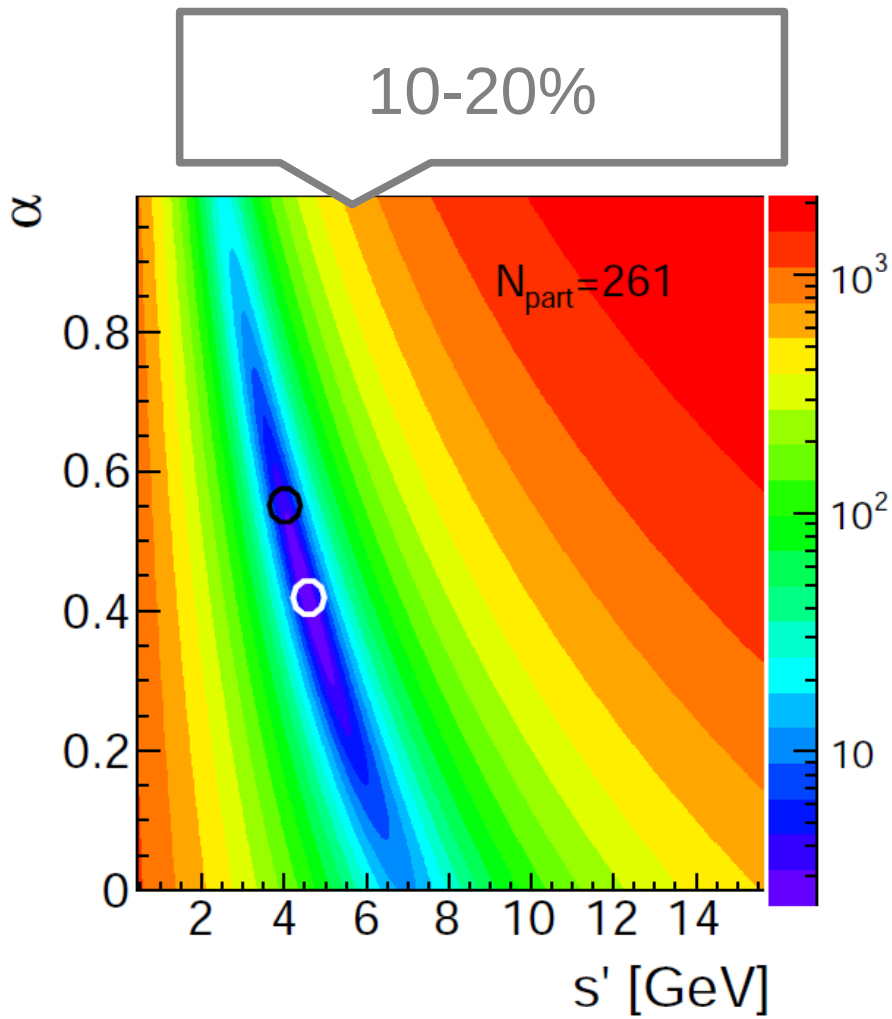
$$\times \left(\frac{p_{T0}}{p_T^{jet}} \right)^{\beta_q \log(1 + S_q / p_T^{jet})} \left(1 + \frac{dS_q}{dp_T^{jet}} \right)$$

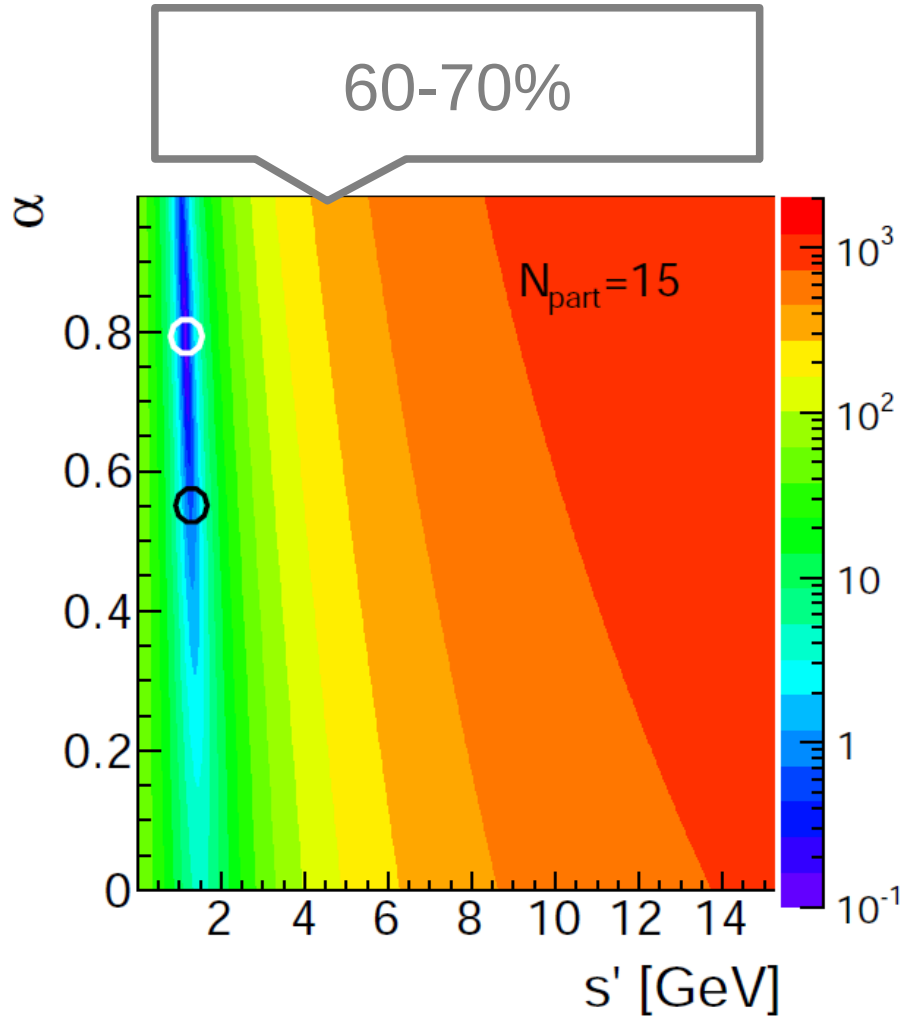
$$+ (1 - f_q) \left(\frac{1}{1 + S_g / p_T^{jet}} \right)^{n_g \beta_g \log((p_T^{jet} + S_g)/p_{T0})}$$

$$\times \left(\frac{p_{T0}}{p_T^{jet}} \right)^{\beta_g \log(1 + S_g / p_T^{jet})} \left(1 + \frac{dS_g}{dp_T^{jet}} \right),$$

$$f_q \left(p_T^{jet} \right) = \frac{1}{1 + \left(\frac{1 - f_{q0}}{f_{q0}} \right) \left(\frac{p_{T0}}{p_T^{jet}} \right)^{n_g - n_q + (\beta_g - \beta_q) \log \left(p_T^{jet} / p_{T0} \right)}}.$$

Minimization in (I.)





Modifications of fragmentation functions – a detail

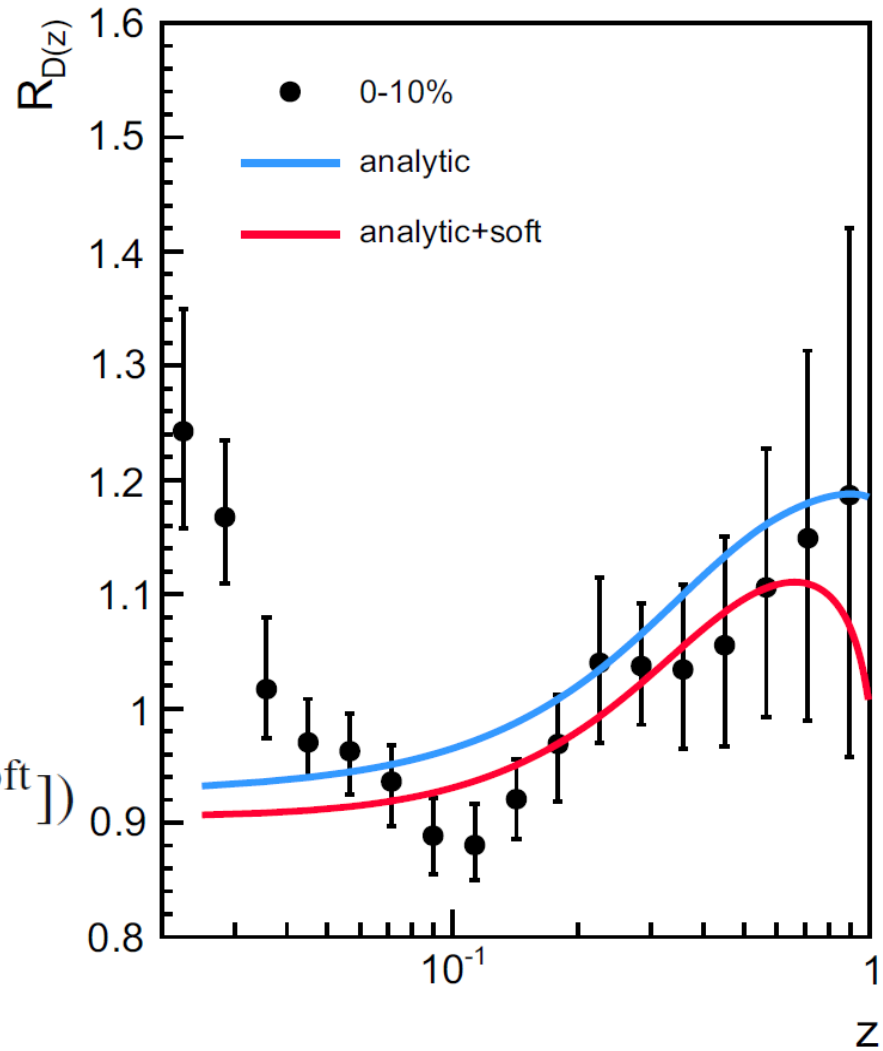
How the soft excess is estimated:

Measured
(at least partially)

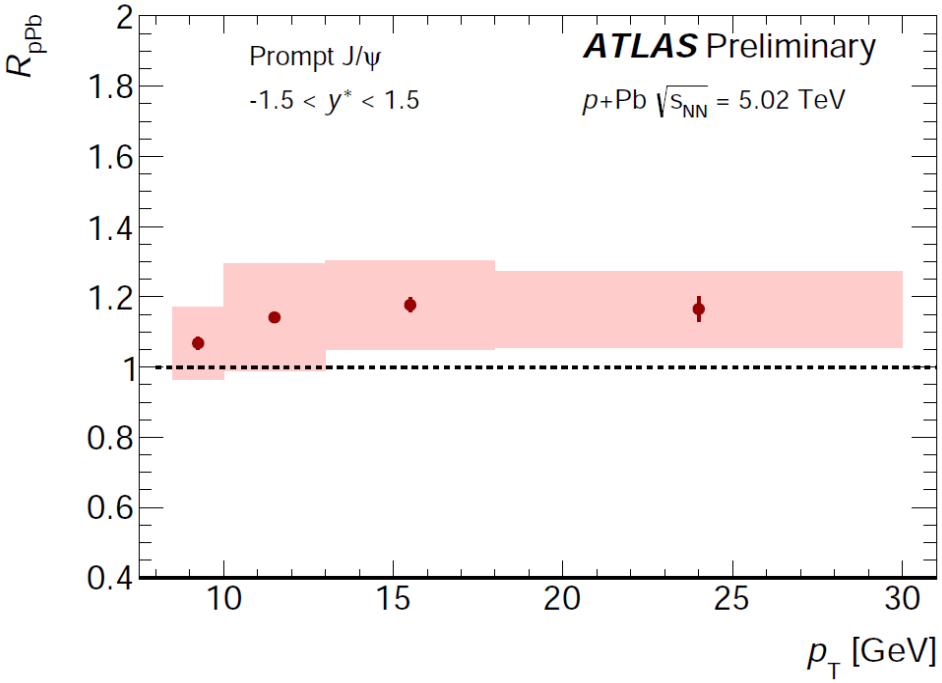
$$\Phi_{\rm inc}^{\rm soft} = f_q^{\rm int}\Phi_q^{\rm soft} + (1 - f_q^{\rm int})\Phi_{\rm g}^{\rm soft}$$

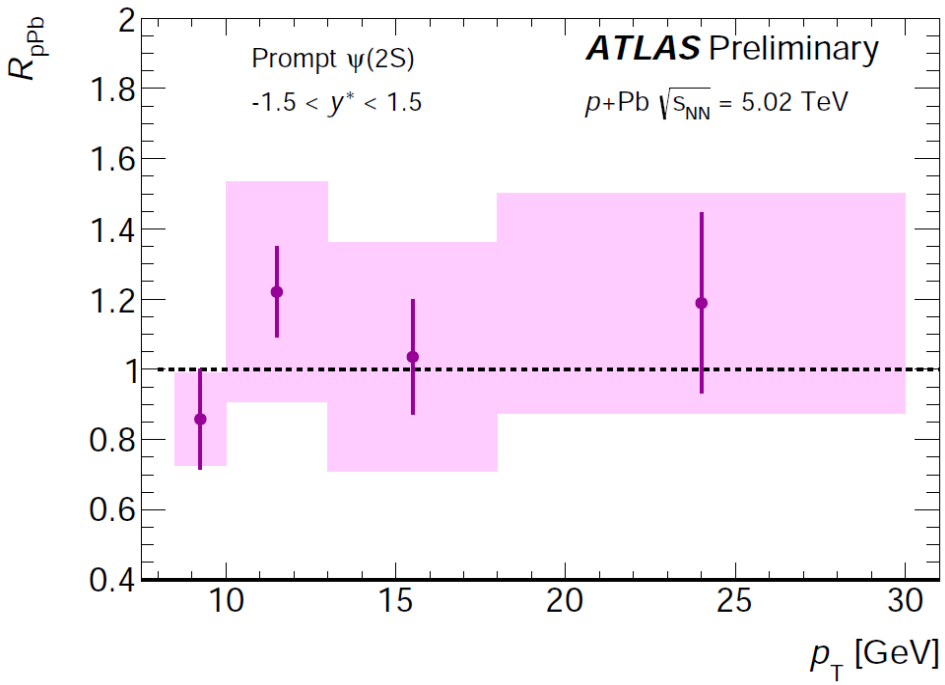
$$\Phi_{\rm g}^{\rm soft} = c_F\Phi_q^{\rm soft}$$

$$D^{\rm meas}(z) = f_q^{\rm int} D_q(z[1+\Phi_q^{\rm soft}]) + (1 - f_q^{\rm int}) D_g(z[1+\Phi_{\rm g}^{\rm soft}])$$

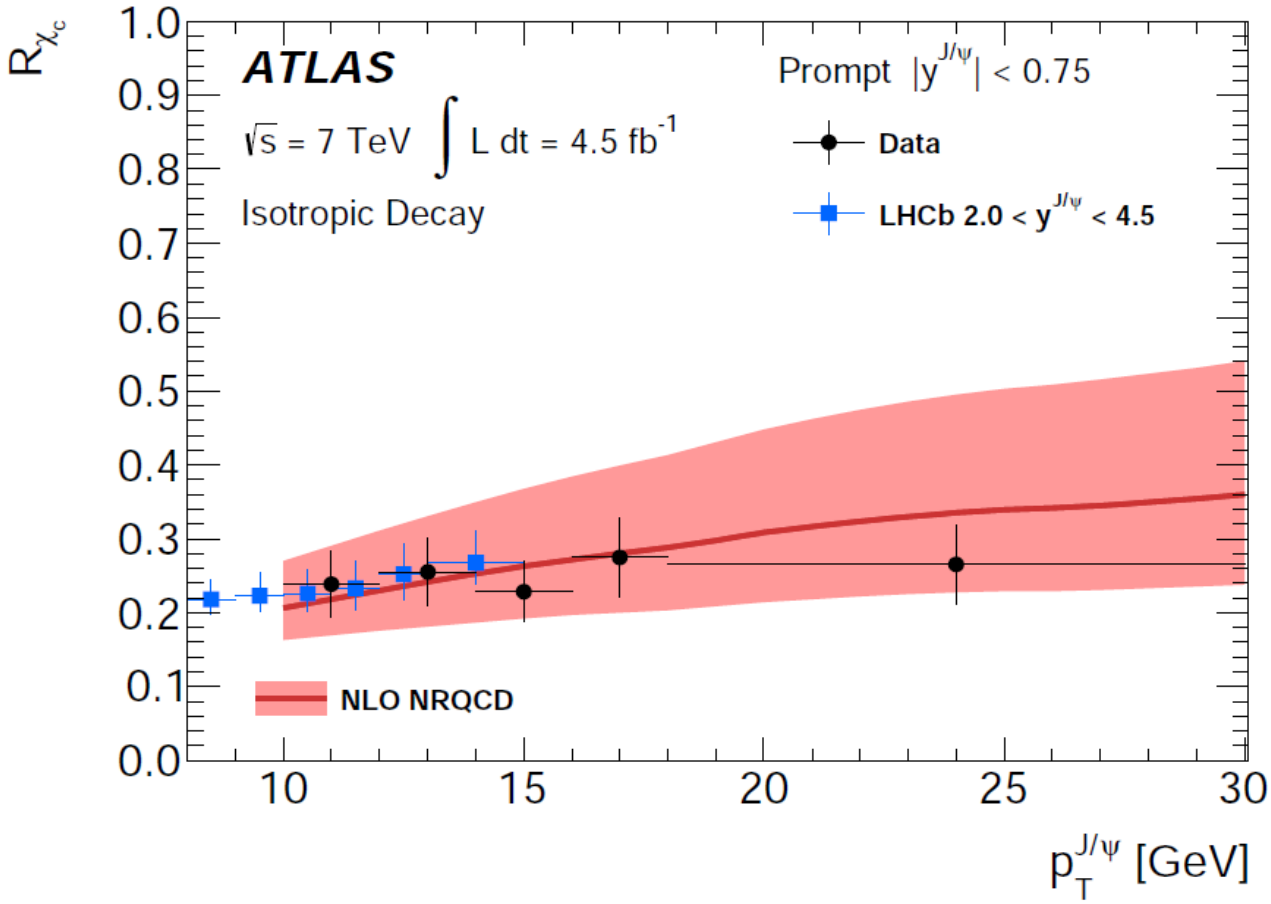


Charmonia in p+Pb



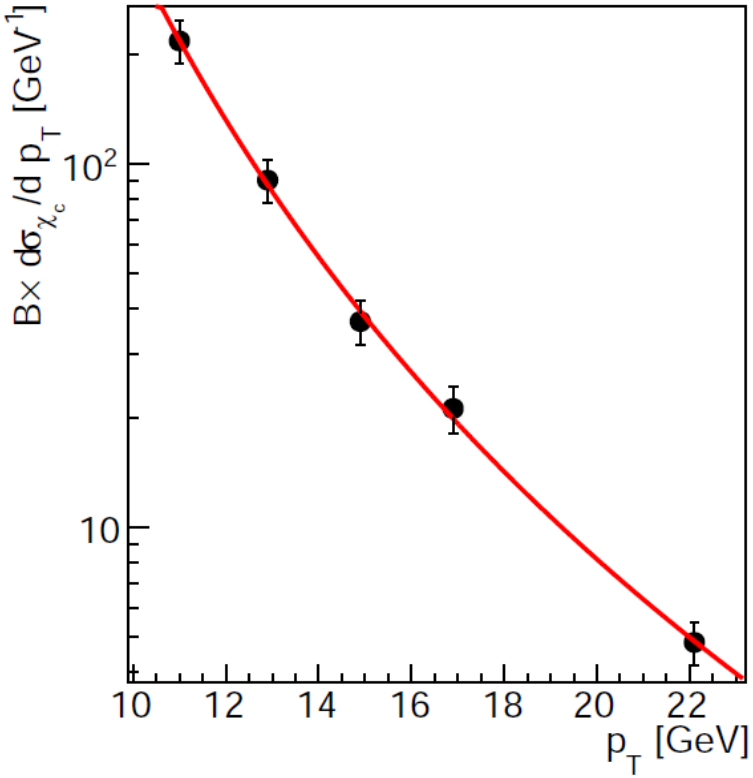


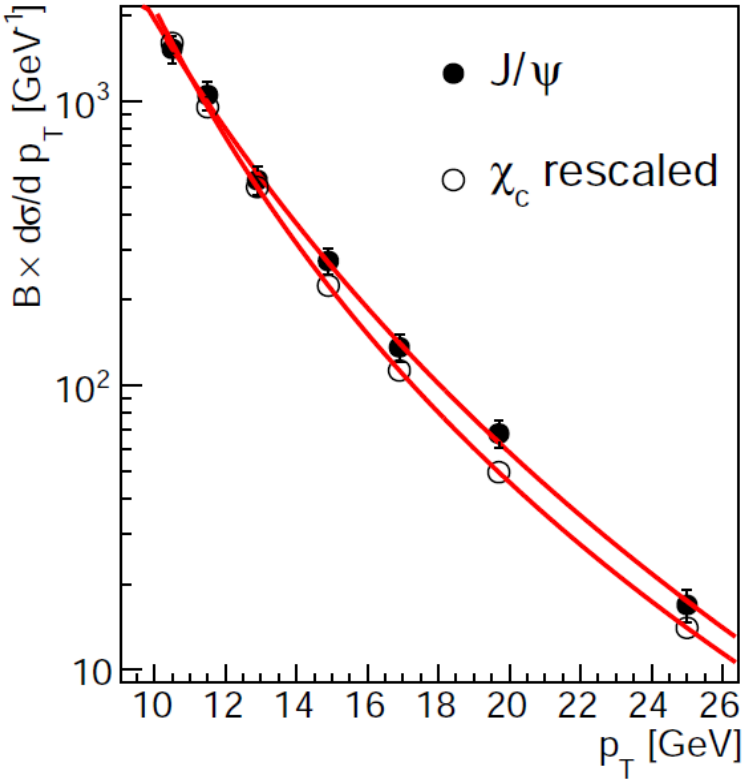
Feed down



ATLAS, JHEP 07 (2014) 154

Feed down





ATLAS, JHEP 07 (2014) 154

Modifications of fragmentation functions