QCD factorization of jet cross sections in heavy-ion collisions

Felix Ringer

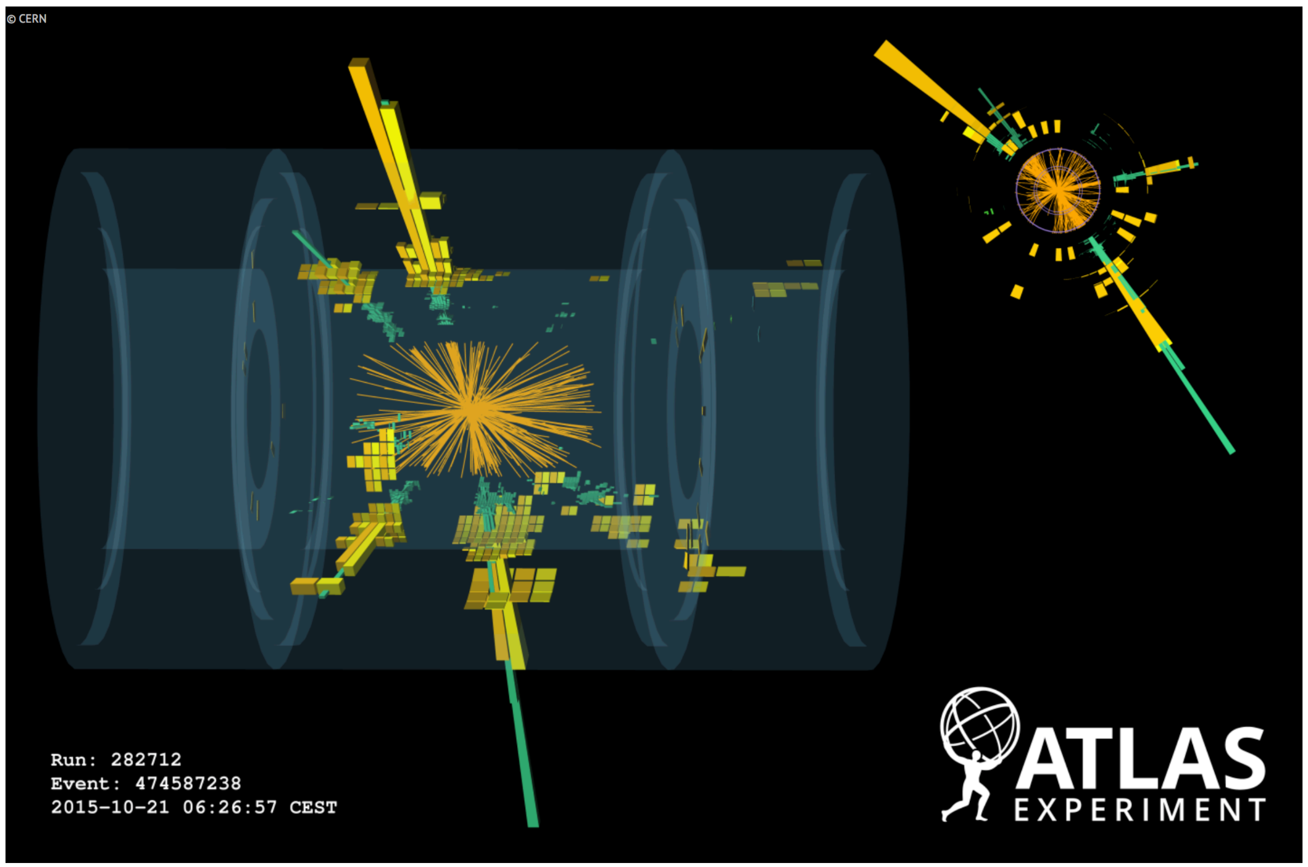
Lawrence Berkeley National Laboratory

In collaboration with Nobuo Sato, Pia Zurita

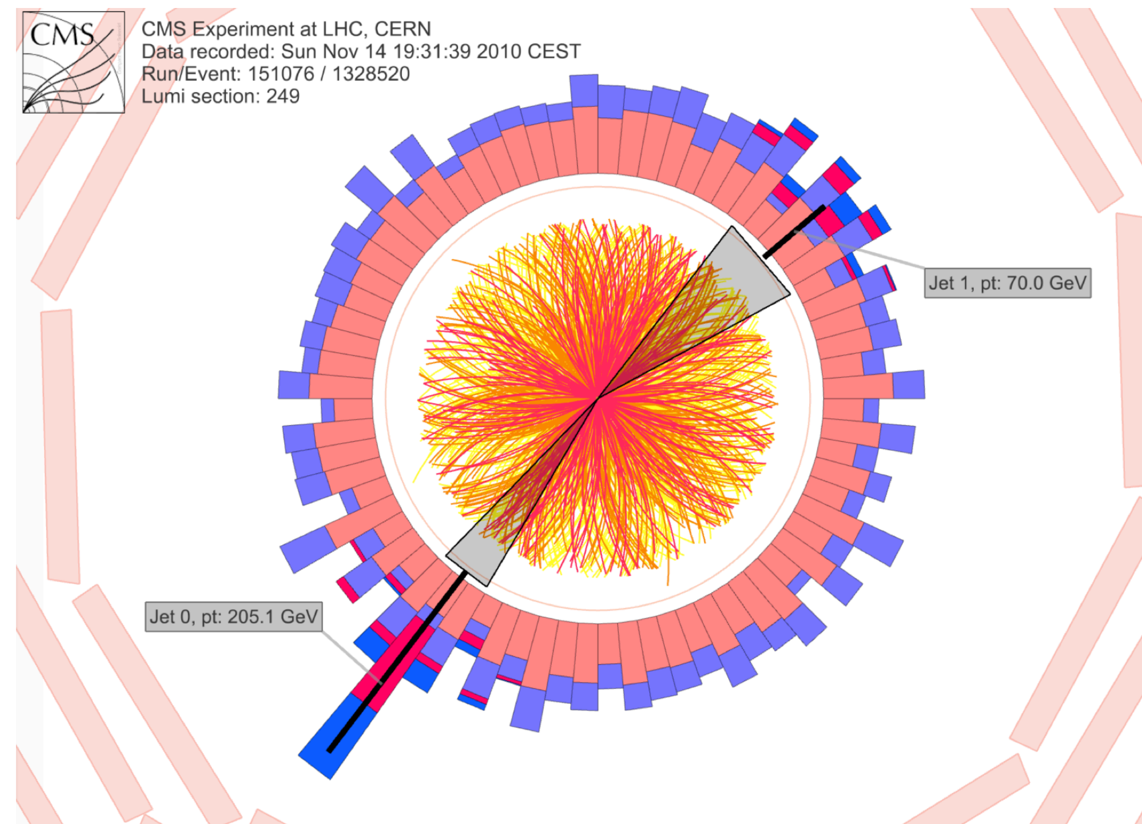
UCLA, 01/29/18

Inclusive jet production

$pp \to \text{jet} + X$



$AA \to \text{jet} + X$



Inclusive jet cross section

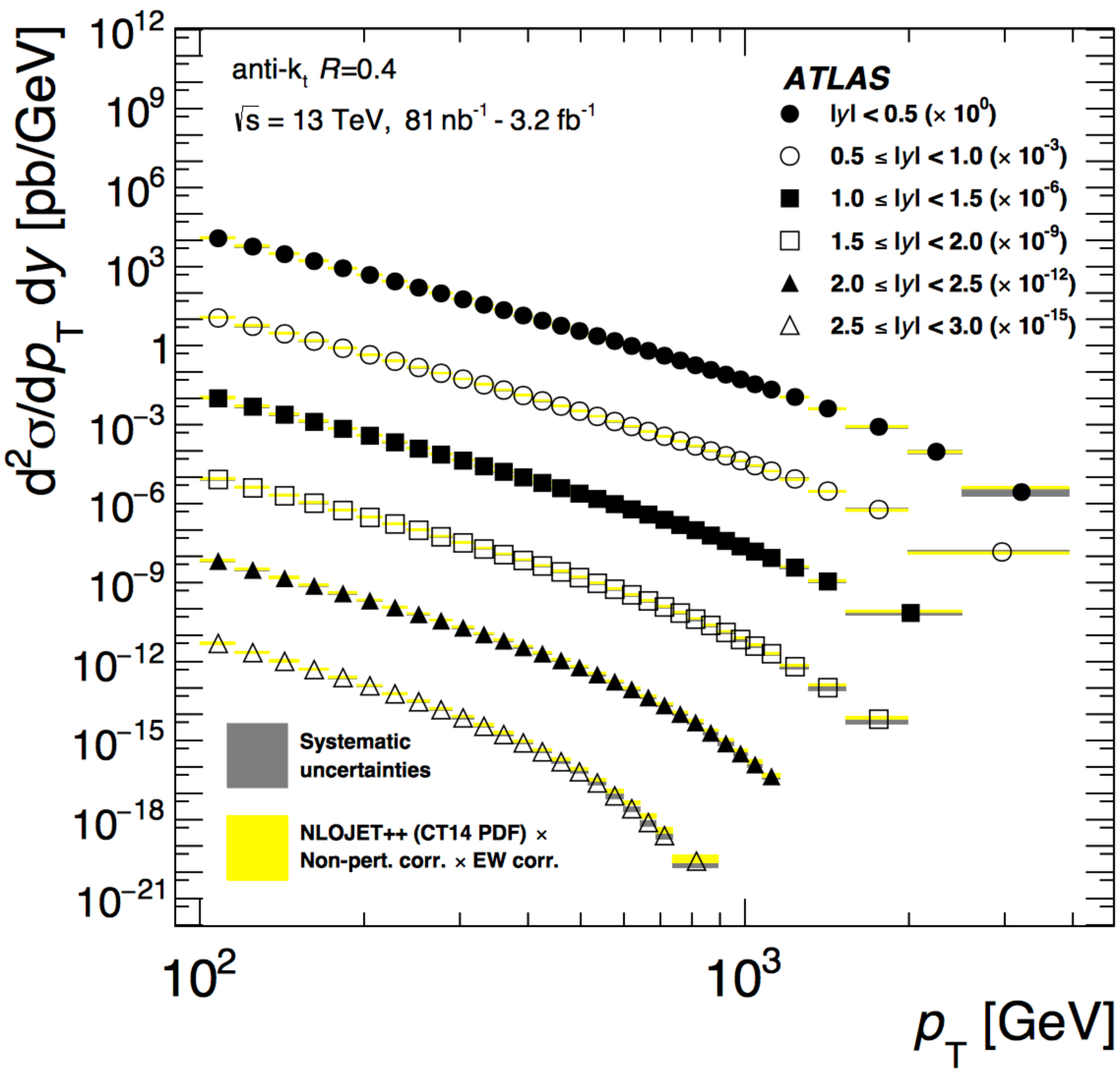
$$\frac{d\sigma^{pp\to\text{jet}+X}}{dp_T d\eta}$$

Nuclear modification factor

$$R_{\text{AA}} = \frac{d\sigma^{\text{PbPb}\to\text{jet}+X}}{\langle N_{\text{coll}}\rangle \, d\sigma^{pp\to\text{jet}+X}}$$

Inclusive jet production at the LHC

- Proton-proton



- Fixed order - NNLO

  Currie, Glover, Pires `16, …

  → *see talk by Frank Petriello*

- All order resummation

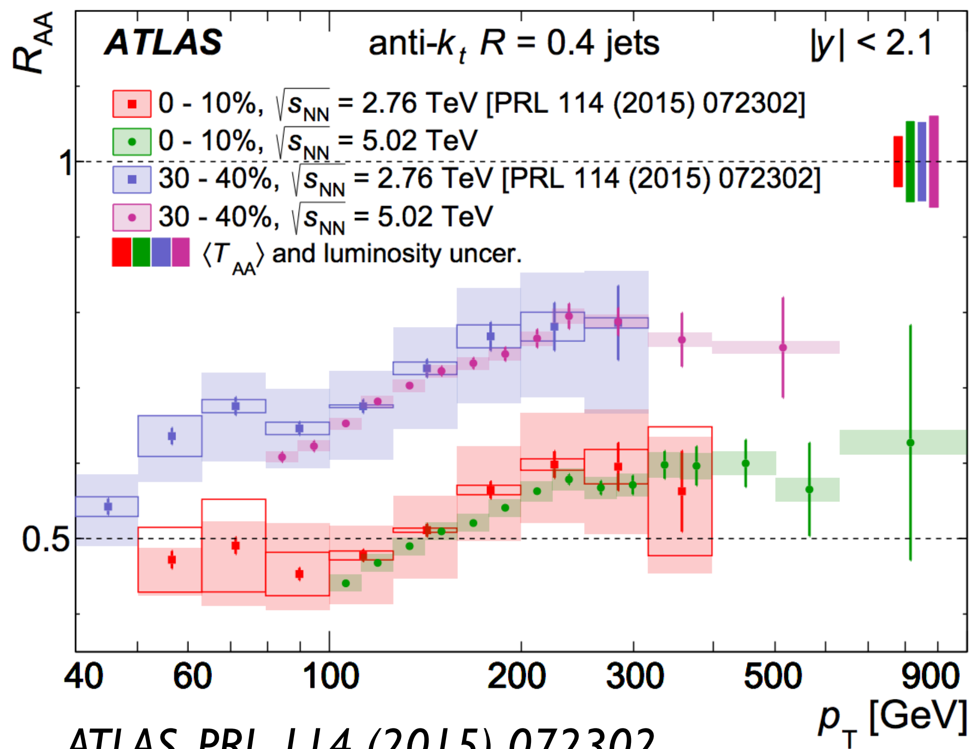
  Threshold and jet radius

  → *see talk by Dave Soper*

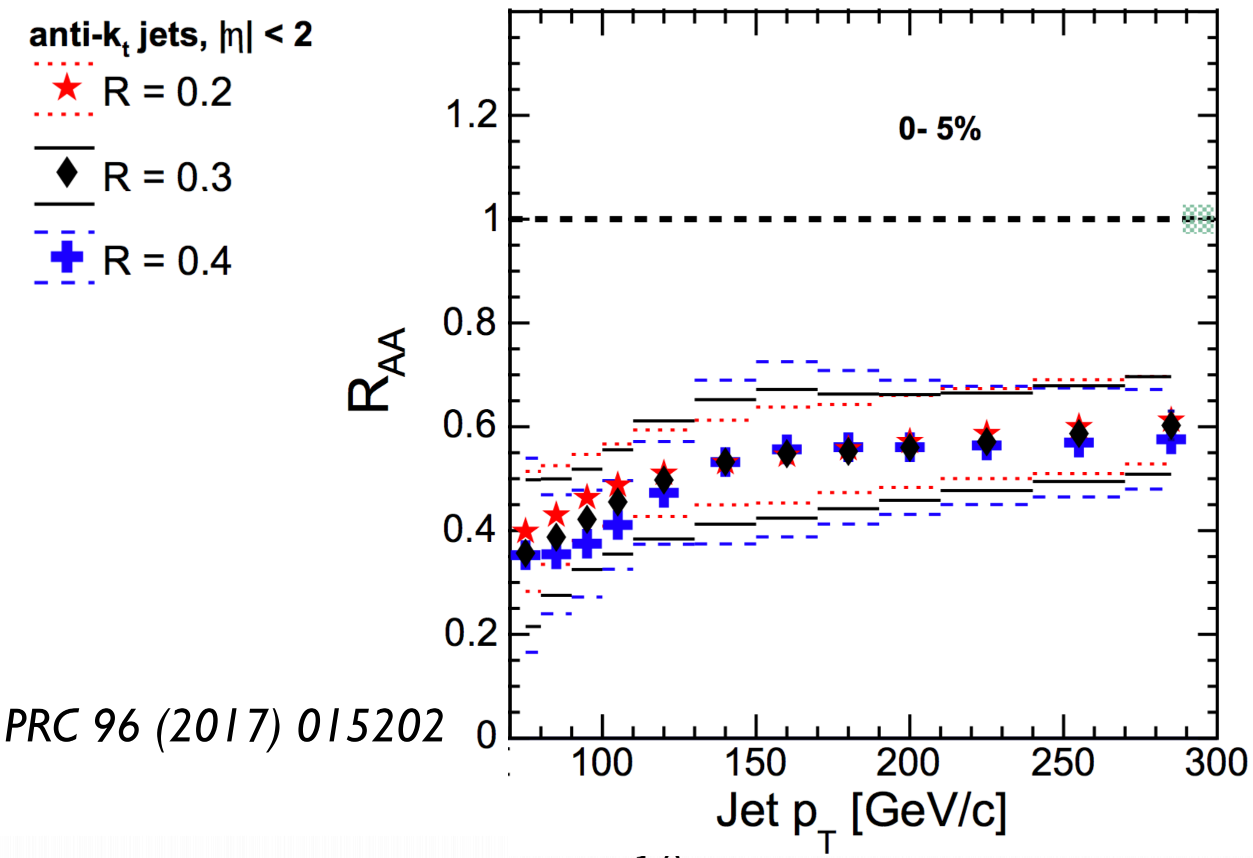
→ Precision physics

ATLAS, JHEP 1805 (2018) 195

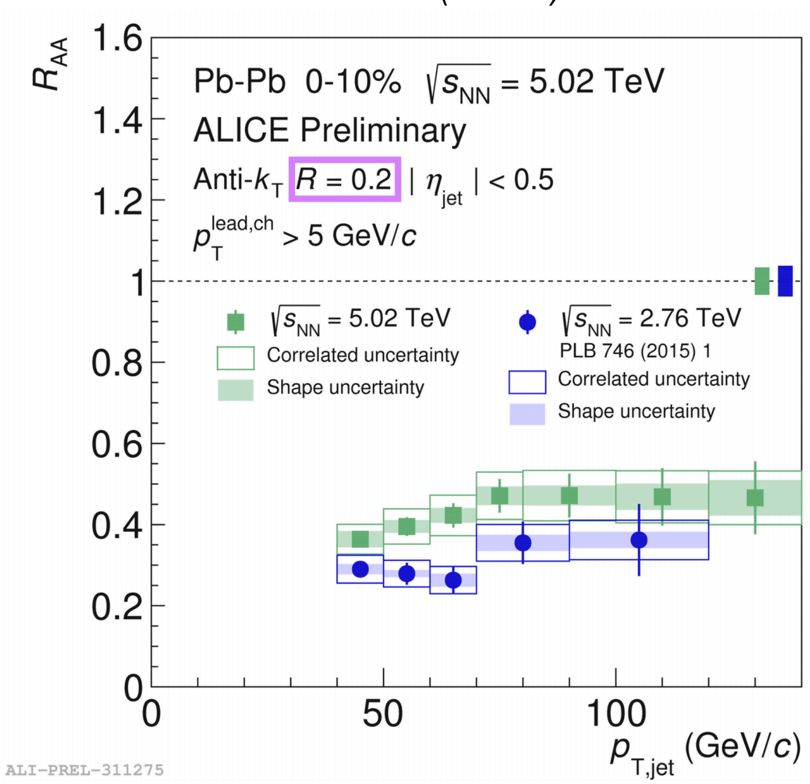
Inclusive jet production at the LHC



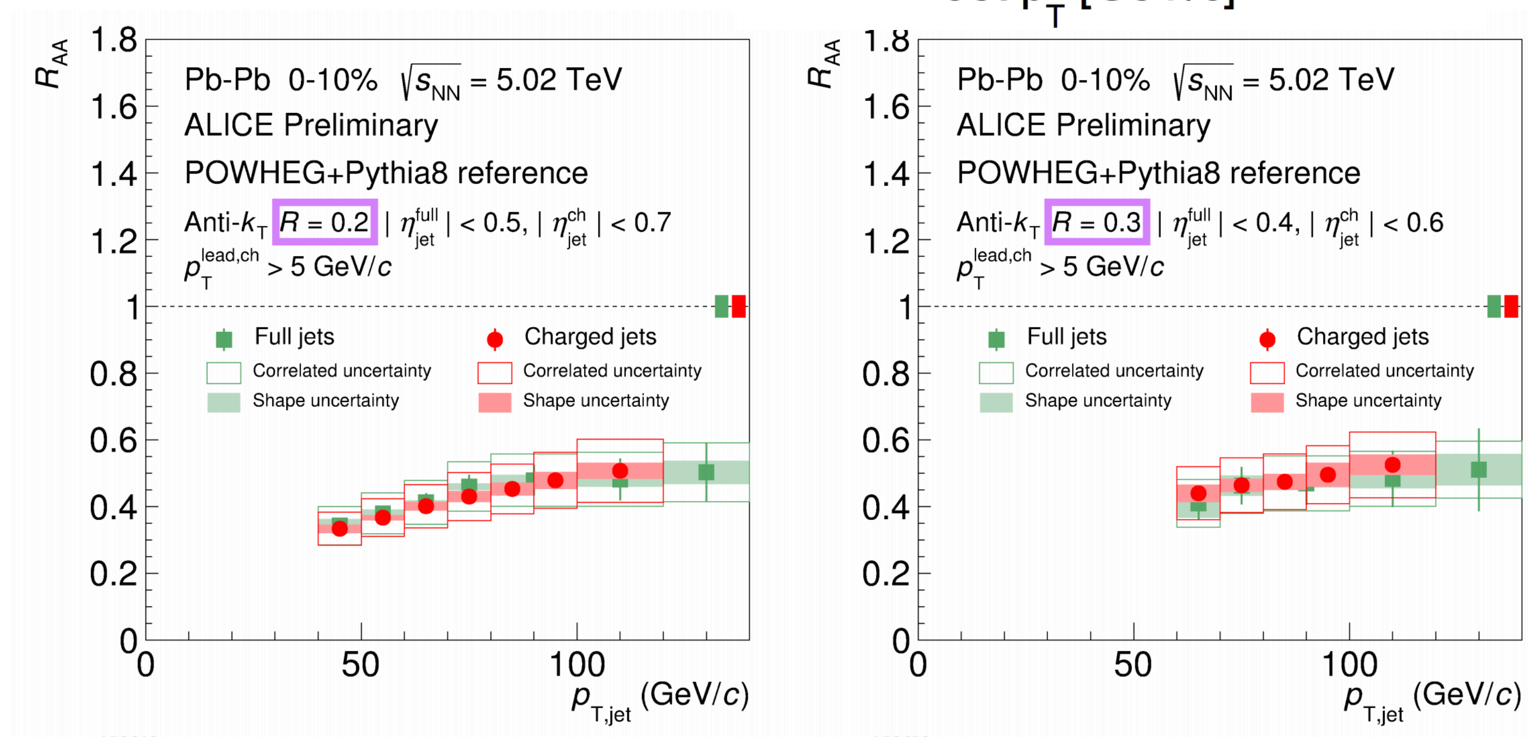
ATLAS, PRL 114 (2015) 072302, PLB 790 (2019) 108



CMS, PRC 96 (2017) 015202

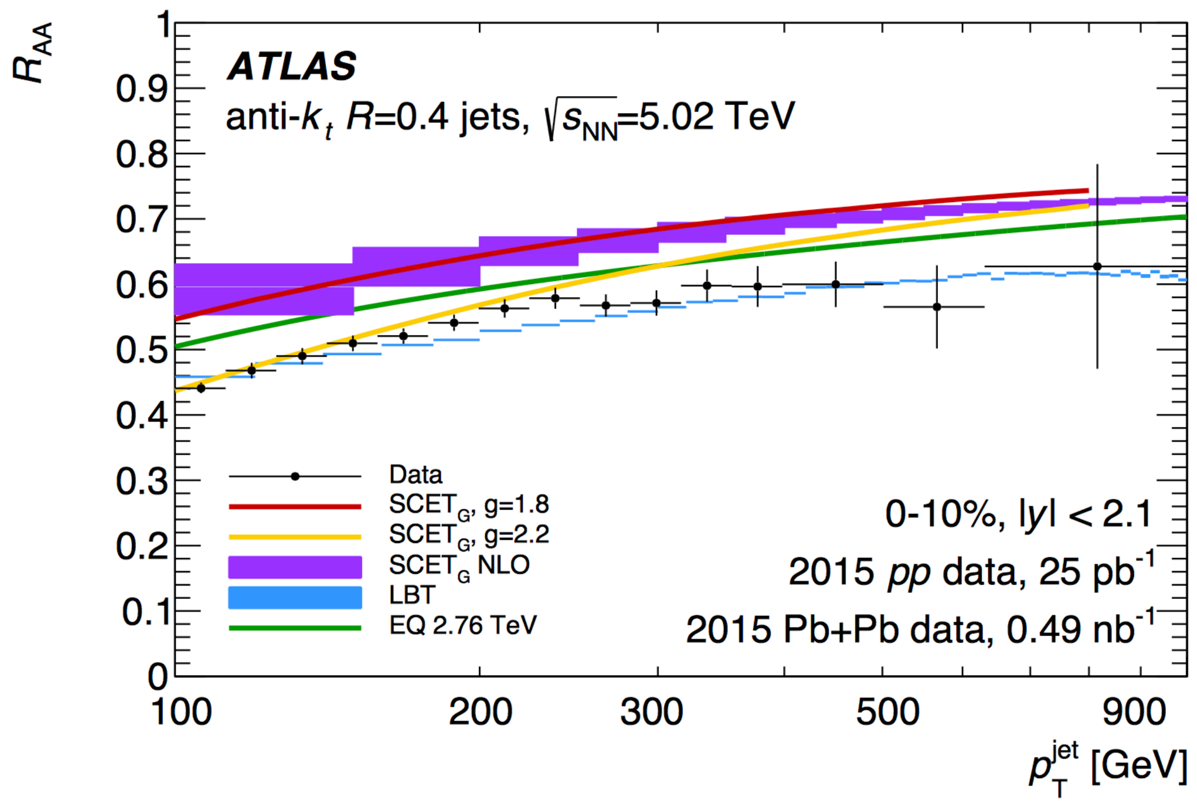


ALICE, PLB 746 (2015) 1

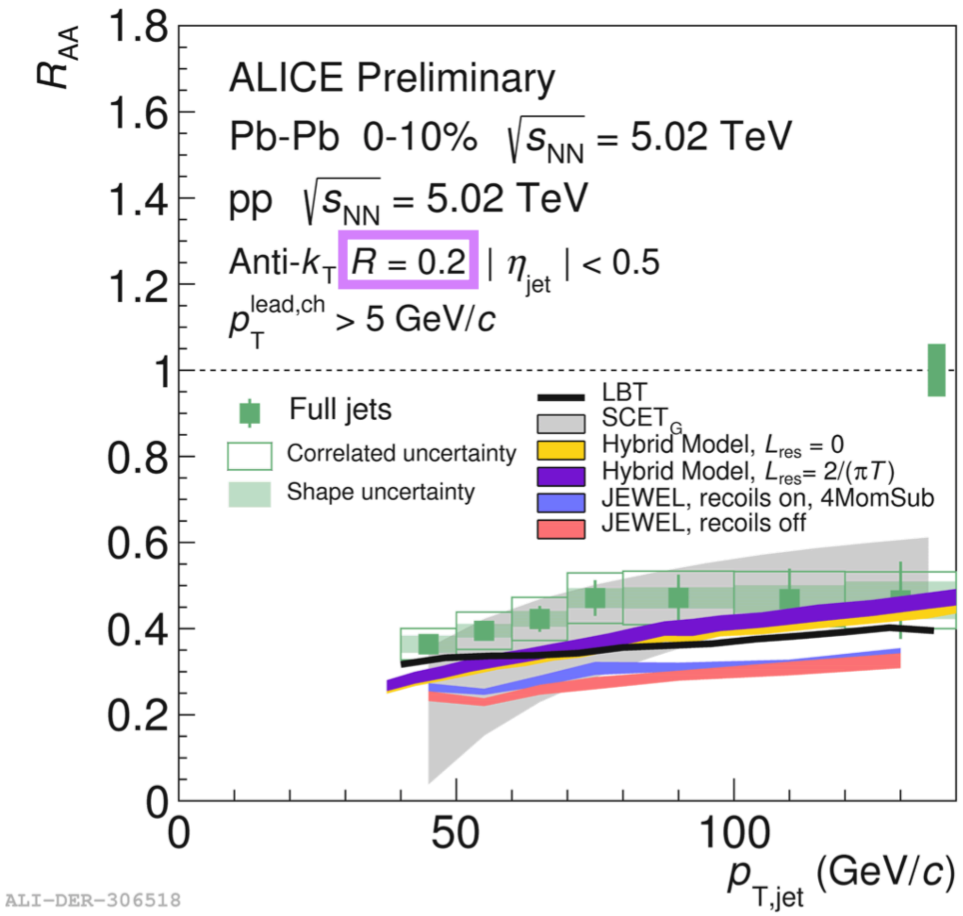


ALICE preliminary, J. Mulligan, HardProbes18

Inclusive jet production at the LHC



ATLAS, PLB 790 (2019) 108



ALICE preliminary, J. Mulligan, HardProbes18

This talk …

- Phenomenological approach
- Minimal theory input/approximations
- QCD factorization

Outline

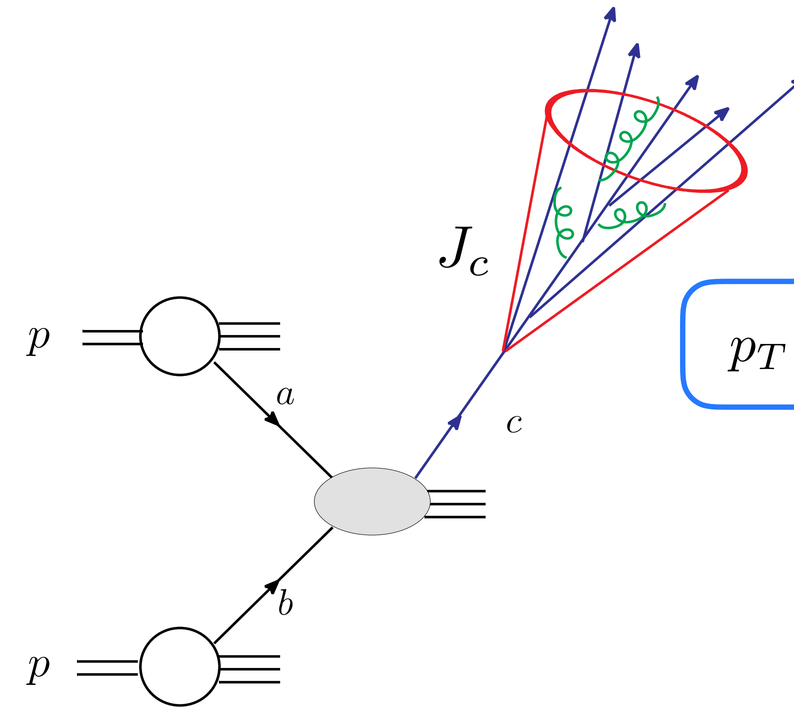
- Introduction
- Inclusive jet production
- Phenomenological results
- Conclusions

QCD factorization

- Inclusive jet production $pp \to \mathrm{jet} + X$

$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes J_c + \mathcal{O}(R^2)$$

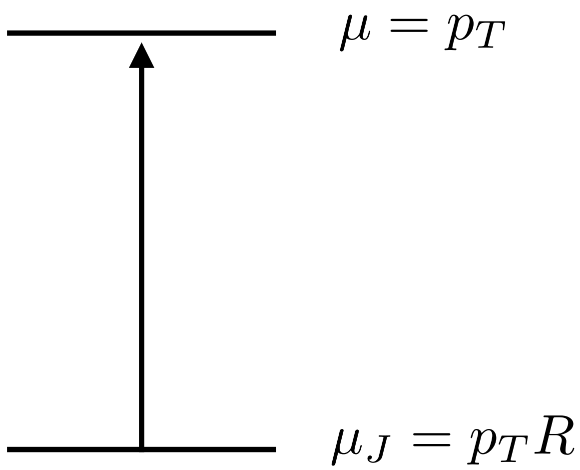
perturbatively calculable



p_T vs. $p_T R$

$$\mu \frac{d}{d\mu} J_i = \sum_j P_{ji} \otimes J_j$$

Similar to fragmentation functions

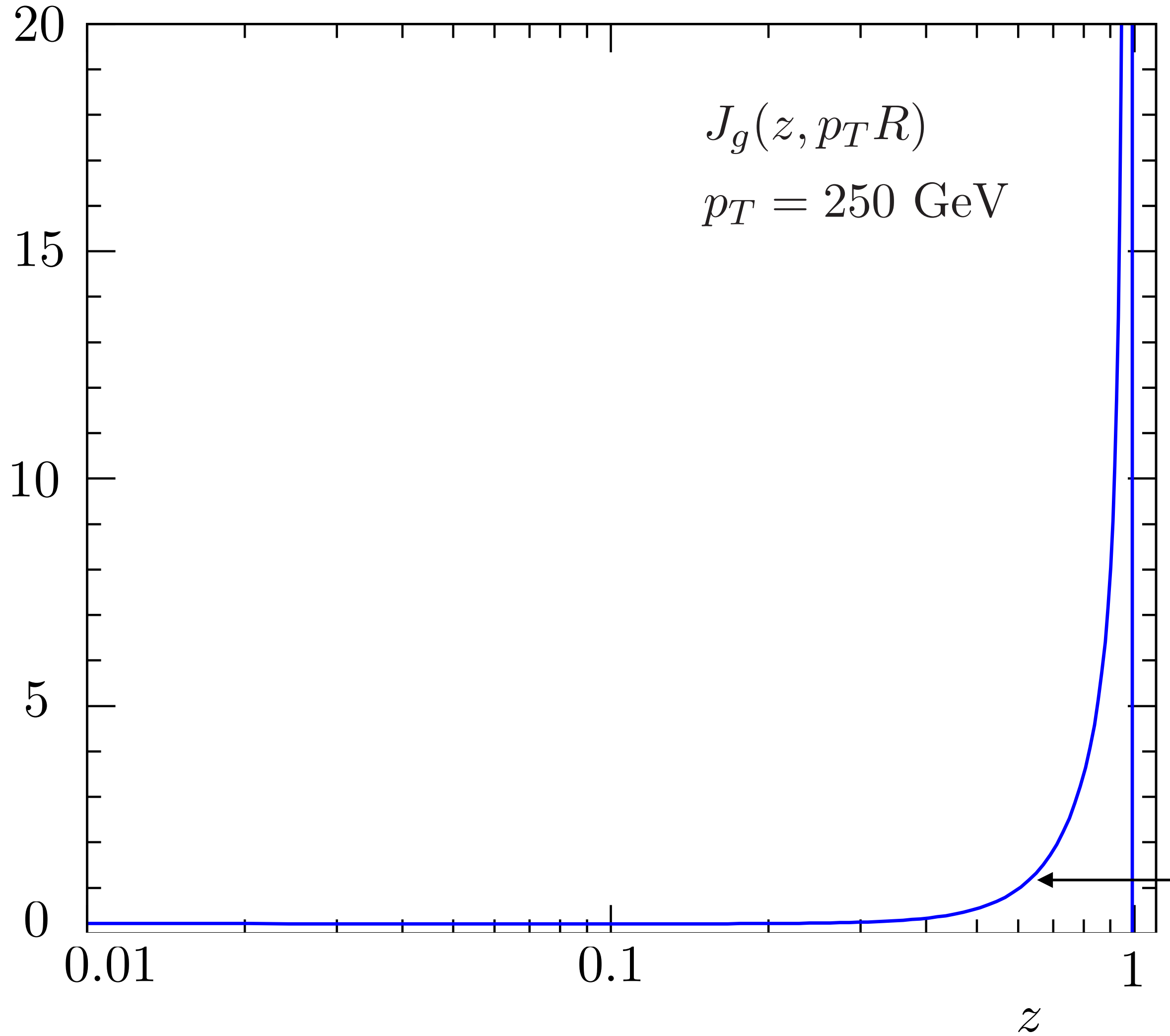


- Separation of scales
- Resummation of $\alpha_s^n \ln^n R$

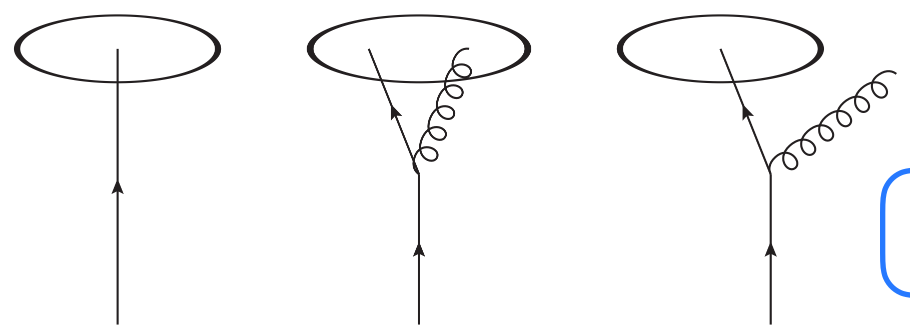
Dasgupta, Dreyer, Salam, Soyez `15
Kaufmann, Mukherjee, Vogelsang `15
Kang, FR, Vitev `16
Dai, Kim, Leibovich `16

Jet functions in the vacuum

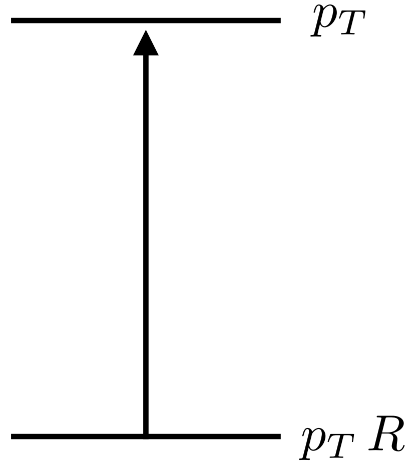
Kang, FR, Vitev `16



initial condition
for the evolution



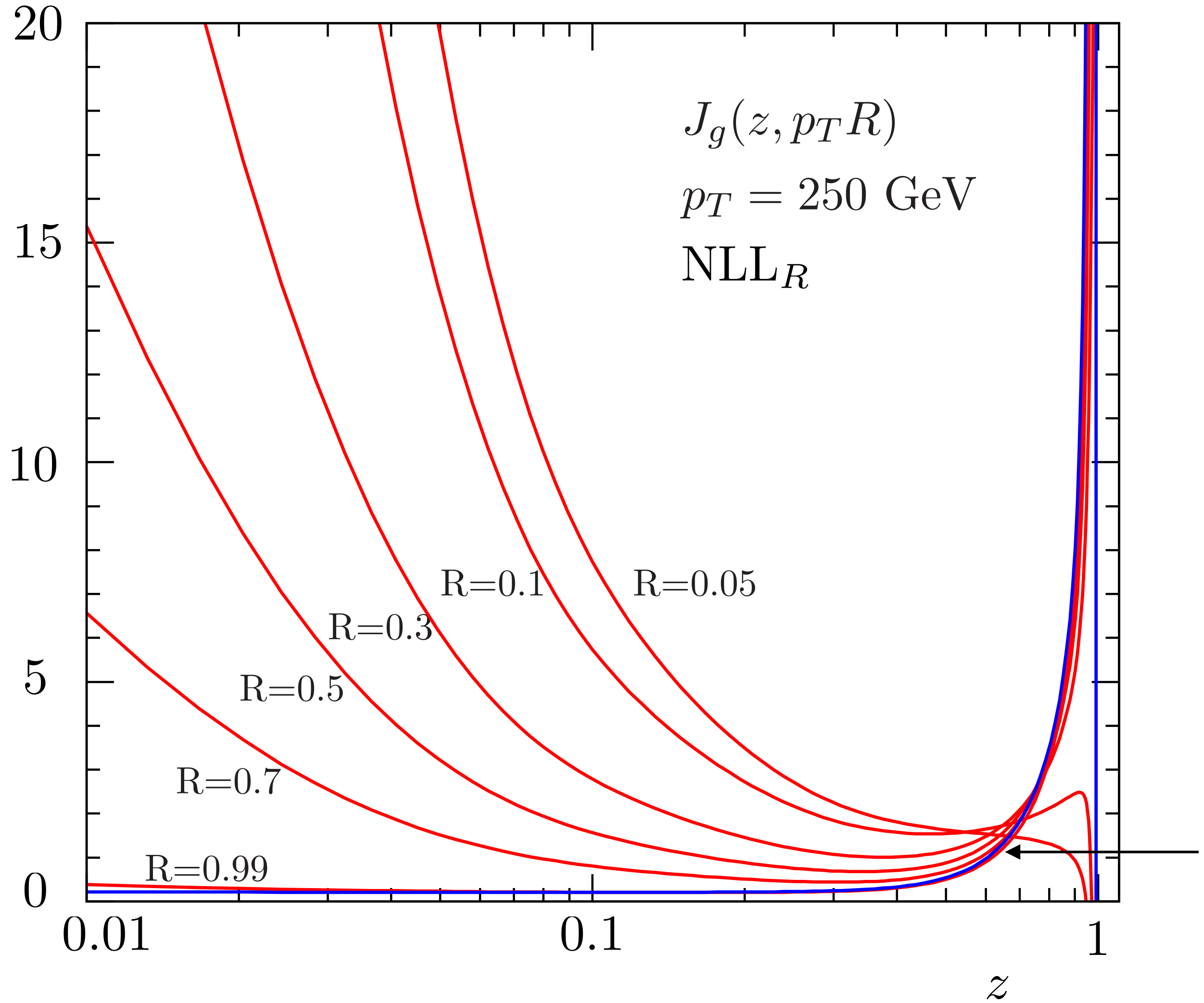
$$z = p_T/p_T^c$$



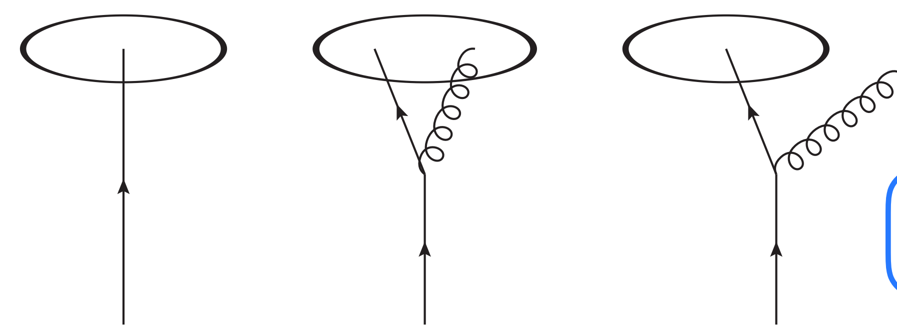
$$J_q(z, p_T R, \mu) = \delta(1-z) + \frac{\alpha_s}{2\pi}\left(\frac{1}{\epsilon} + \ln\left(\frac{\mu^2}{p_T^2 R^2}\right)\right)[P_{qq}(z) + P_{gq}(z)]$$
$$-\frac{\alpha_s}{2\pi}\left\{C_F\left[2\left(1+z^2\right)\left(\frac{\ln(1-z)}{1-z}\right)_+ + (1-z)\right] - \delta(1-z)d_J^{q,\mathrm{alg}}\right.$$
$$\left. + P_{gq}(z) 2\ln(1-z) + C_F z\right\}$$

Jet functions in the vacuum

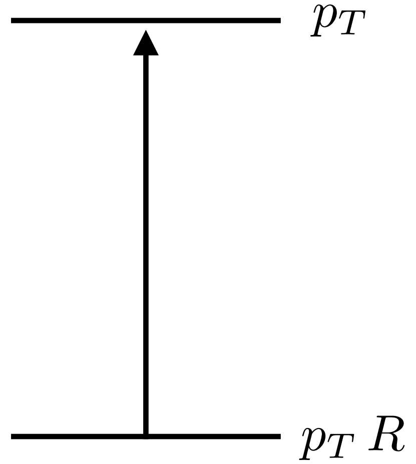
Kang, FR, Vitev `16



initial condition
for the evolution



$z = p_T/p_T^c$



$$
\begin{aligned}
J_q(z, p_T R, \mu) = \delta(1-z) &+ \frac{\alpha_s}{2\pi}\left(\frac{1}{\epsilon} + \ln\left(\frac{\mu^2}{p_T^2 R^2}\right)\right)\left[P_{qq}(z) + P_{gq}(z)\right] \\
&- \frac{\alpha_s}{2\pi}\left\{C_F\left[2\left(1+z^2\right)\left(\frac{\ln(1-z)}{1-z}\right)_+ + (1-z)\right] - \delta(1-z)d_J^{q,\mathrm{alg}}\right. \\
&\left. + P_{gq}(z) 2\ln(1-z) + C_F z\right\}
\end{aligned}
$$

In-medium jet functions

- Starting from factorization in the vacuum *Kang, FR, Vitev `17*

$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes \boxed{J_c} \longrightarrow J_c^{\text{med}}(z, p_T R, \mu)$$

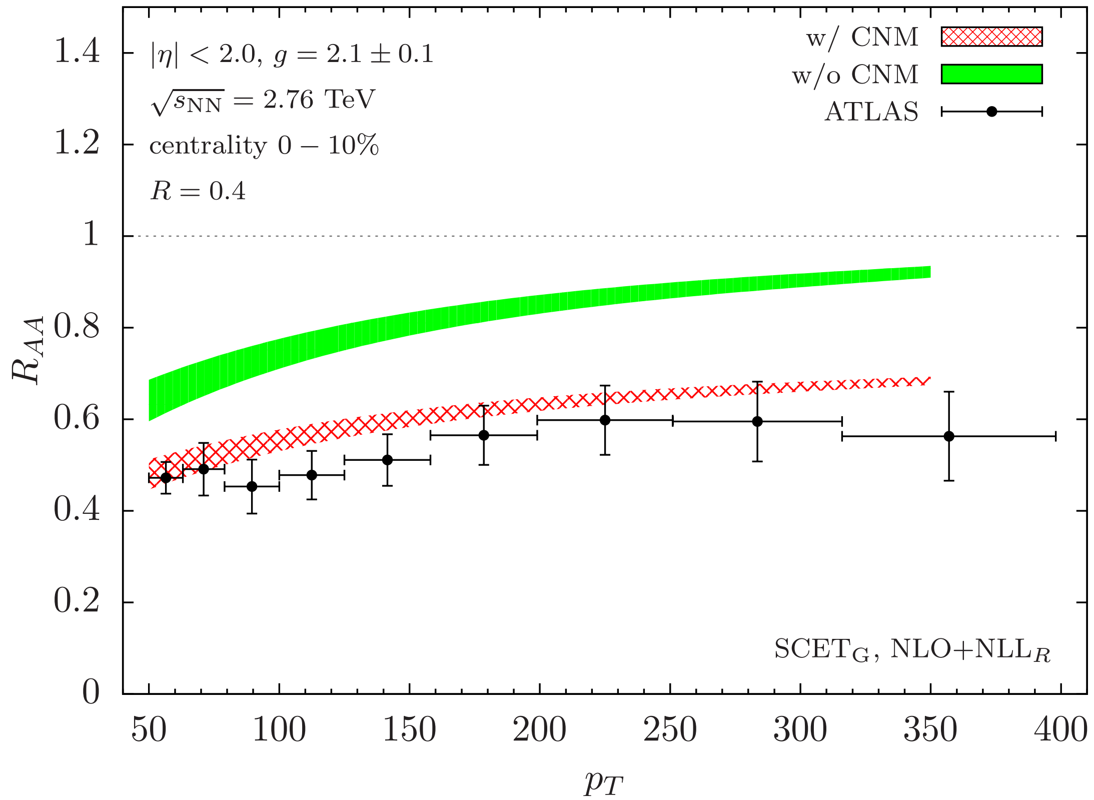
Allows for identifying jet quenching with the final state jet function

- SCET$_G$ *Ovanesyan, Vitev `12*

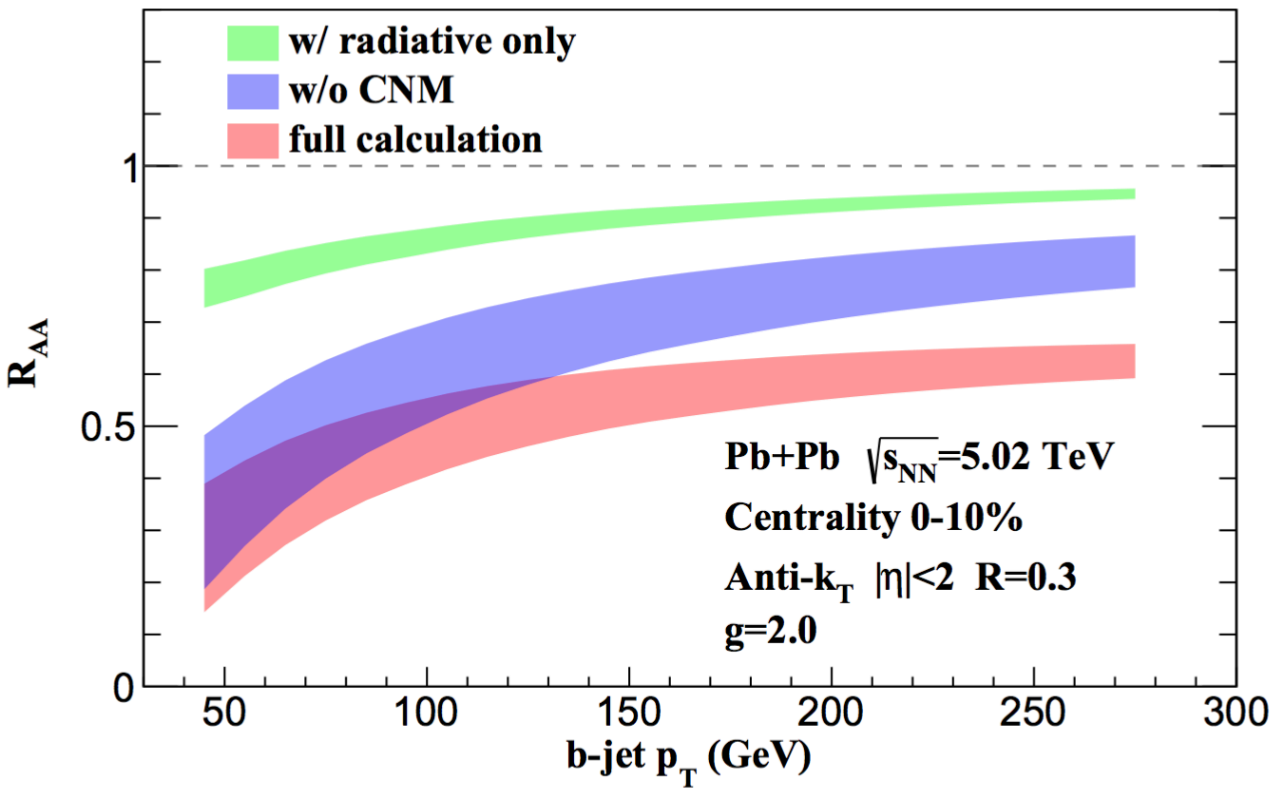
$$J_{qq}(z, p_T R, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P_{qq}(z, q_\perp) \right]_+$$

→ *see Haitao Li's talk*

- Inclusive jets

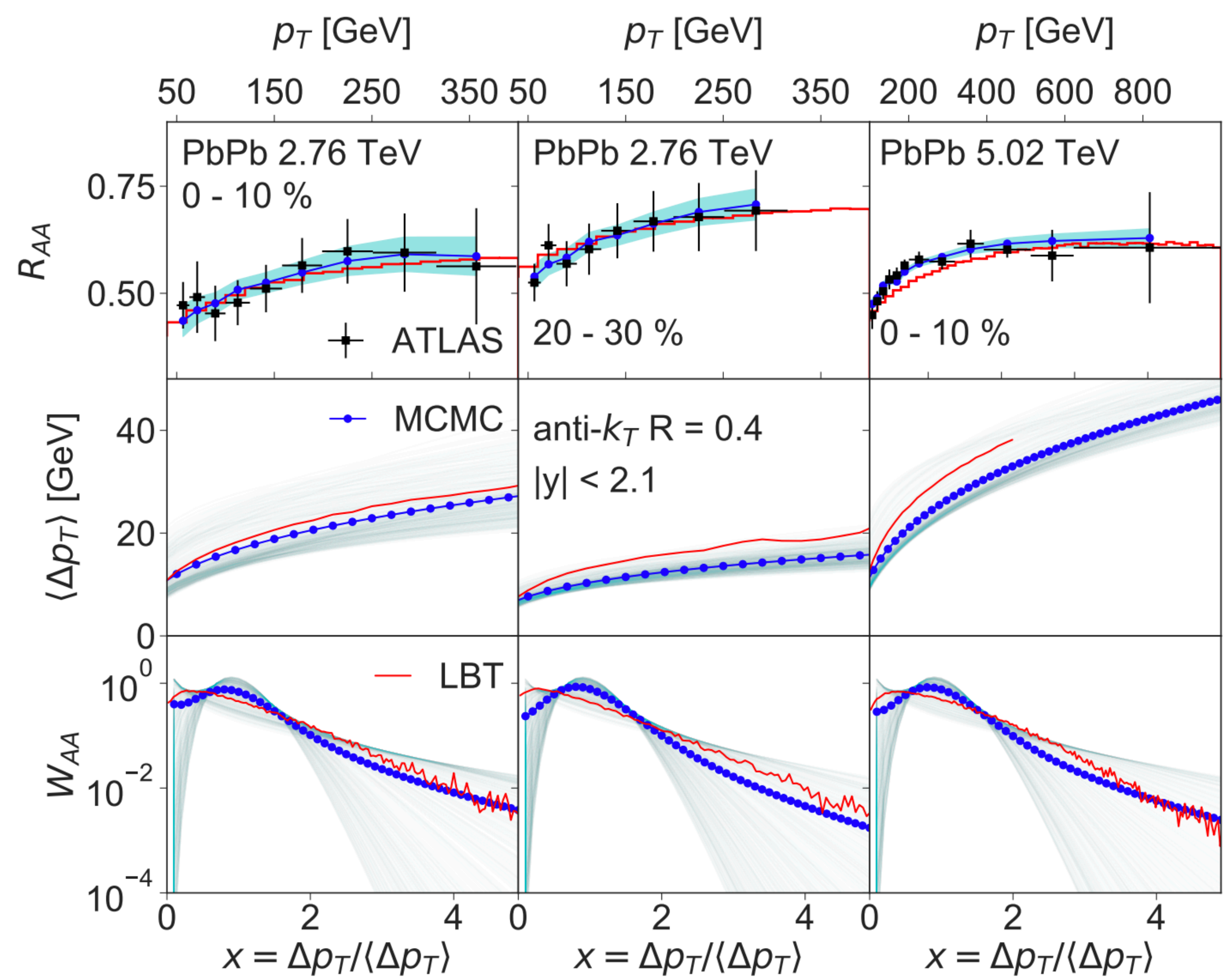


- b-jets *Li, Vitev `18*



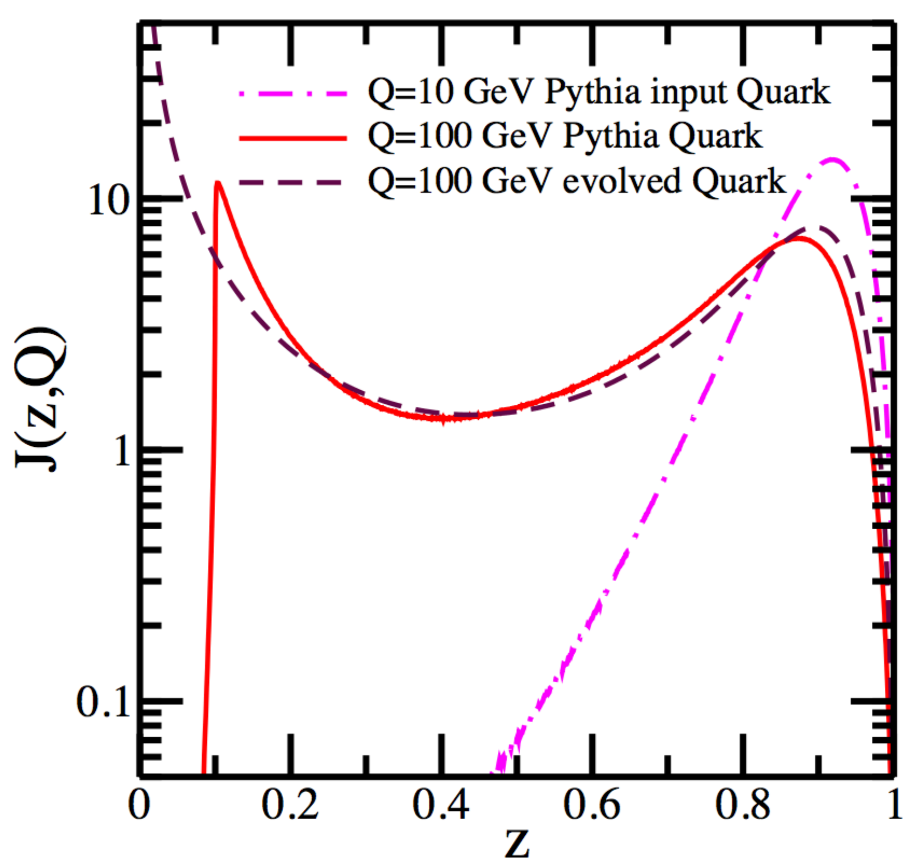
In-medium jet functions

- Jet energy loss and LBT *He, Pang, Wang `18*

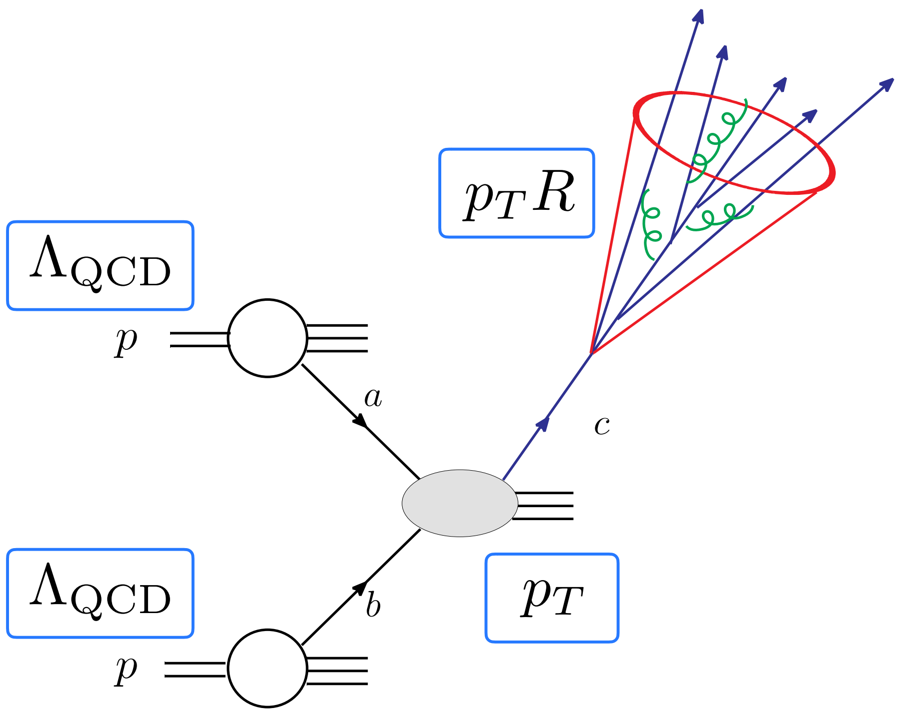


- Jet functions in relation with MATTER

Sirimanna, Cao, Majumder `19



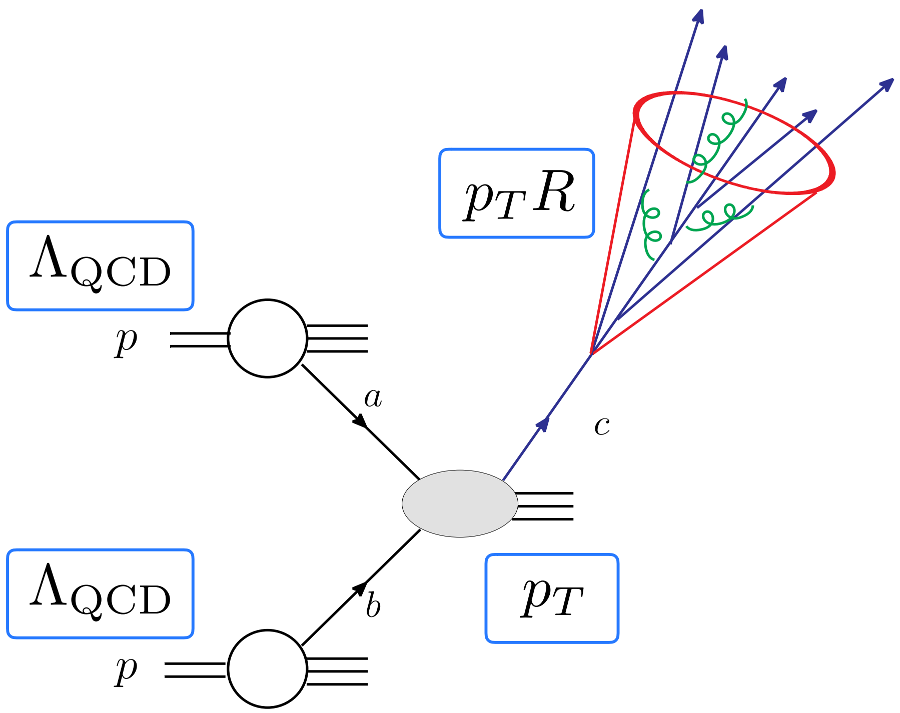
QCD factorization

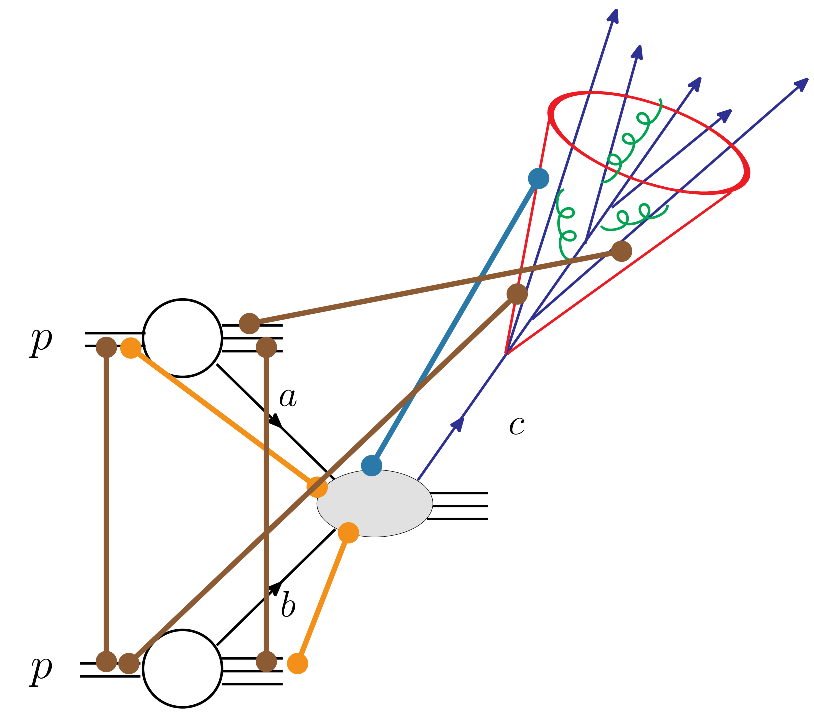


Separation of scales

$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$

QCD factorization





Separation of scales

QCD emissions $\displaystyle\int \frac{d\theta}{\theta}\frac{dz}{z}$

$$\frac{d\sigma^{pp\to {\rm jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$

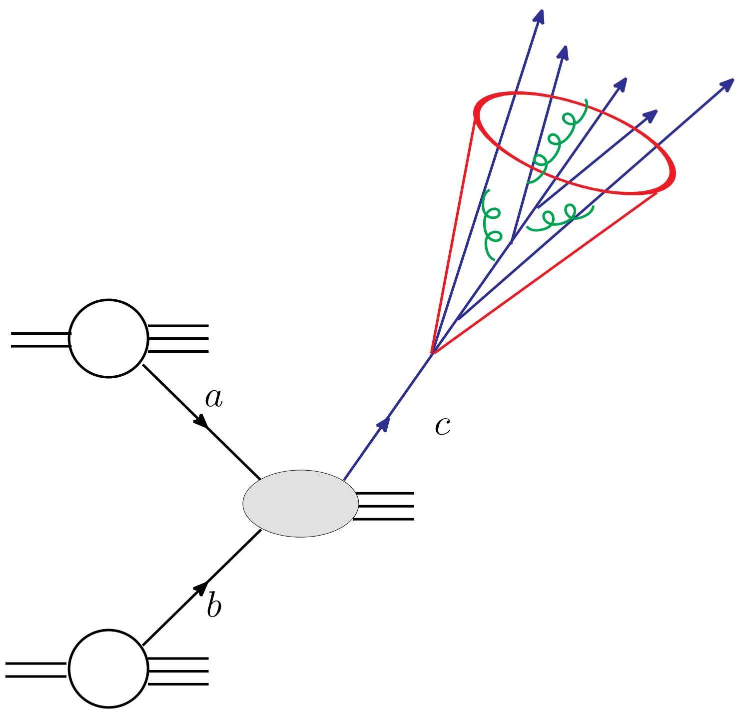
Especially important are interactions with the spectators through Glauber gluons

QCD factorization

- Proton-proton
  - Proofs: Drell-Yan process *Collins, Soper, Sterman `85, Bodwin `85*
  - Partial proofs: $pp \to h + X$ *Nayak, Qiu, Sterman `05*
  - Phenomenologically established:

    Global analyses of PDFs gives a consistent picture!

    ABMP, CJ, CT, MMHT, NNPDF ...

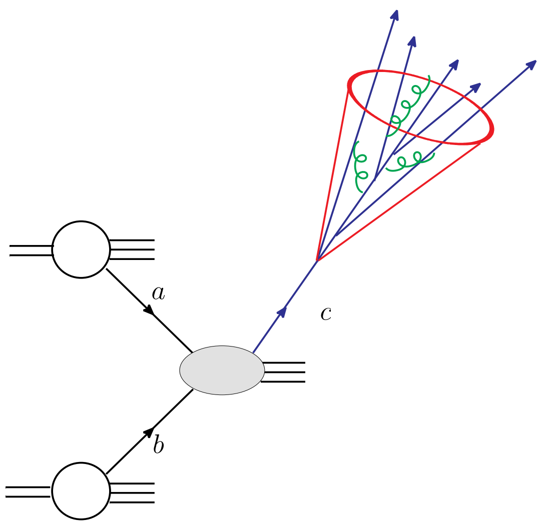


- Heavy-ion
  - Possibly broken. If so, how large is the effect?

$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$

A first global analysis

FR, Sato, Zurita - in preparation



- RG evolution as in the vacuum

$$\frac{d}{d\mu} J_i(z, p_T R, \mu) = \sum_j P_{ji}(z) \otimes J_j(z, p_T R, \mu)$$

- Introduce medium modified jet function at the jet scale

$$J_i^{\mathrm{med}}(z, p_T R, \mu_J) = W_i^m(z) \otimes J_i^{\mathrm{vac}}(z, p_T R, \mu_J)$$

$$W_i(z) = \epsilon_i \delta(1-z) + \frac{N_i z^{\alpha_i}(1-z)^{\beta_i}}{B[\alpha_i + 2, \beta_i + 1]}$$

$$\int_0^1 dz\, z\, J_i^{\mathrm{med}}(z, \hat{p}_T R, \mu_J) = 1$$

$\longrightarrow$ 6 independent parameters

nPDFs *Eskola, Paakkinen, Paukkunen, Salgado `17, Kovarik et al. `16*
de Florian, Sassot, Zurita, Stratmann `12

nFFs *Sassot, Stratmann, Zurita `10*

Relation to a parton shower picture

For example:

- LBT
  Li, Liu, Ma, Wang, Zhu `11

vacuum shower

shower cutoff

Linearized Boltzmann Transport

- MATTER
  Majumder `13, Kordell, Majumder `17

vacuum shower

$\sim \mathcal{O}(10\,\mathrm{GeV})$

medium modified shower

- Medium jet functions

vacuum shower

$p_T R$

Fit to data

$$\boldsymbol{J}(N, p_T) = \left(\frac{\alpha_s(p_T)}{\alpha_s(p_T R)}\right)^{-\boldsymbol{P}^{(0)}(N)/\beta_0} \boldsymbol{J}(N, p_T R)$$

see also JEWEL, Martini, Q-Pythia, JETSCAPE

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  ?

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see also JEWEL, Martini, Q-Pythia, JETSCAPE

Outline

- Introduction
- Inclusive jet production
- Phenomenological results
- Conclusions

Implementation

- Earlier implementations not practical to perform fits *Bodwin, Chao, Chung, Kim, Lee, Ma `15, Kang, FR, Vitev `16*

- Purely Mellin space implementation

$$\sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c = \sum_c H'_c \otimes J_c$$

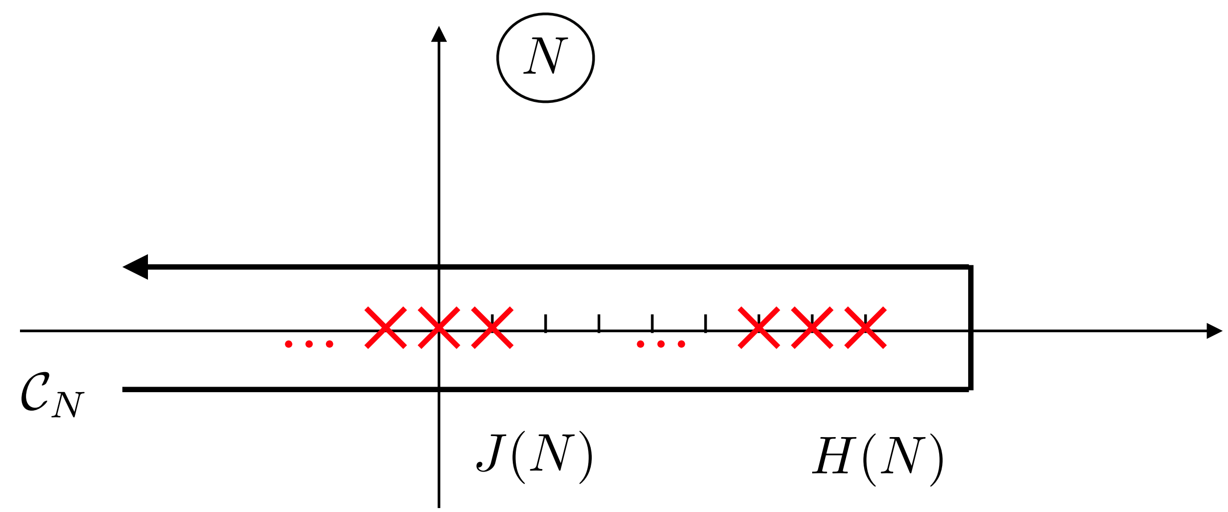
Actual convolution

Fit of numerical result $\sim z^\alpha (1-z)^\beta$

- Singular distributions
- Evolution
- Medium modification
- Fast numerical evaluation

$$\longrightarrow \quad \boxed{\frac{d\sigma}{dp_T d\eta} = \sum_c \int \frac{dN}{2\pi i} z_0^{-N} H'_c(N)\, J_c(N)}$$

$$z_0 = 2p_T/\sqrt{s}\cosh\eta$$

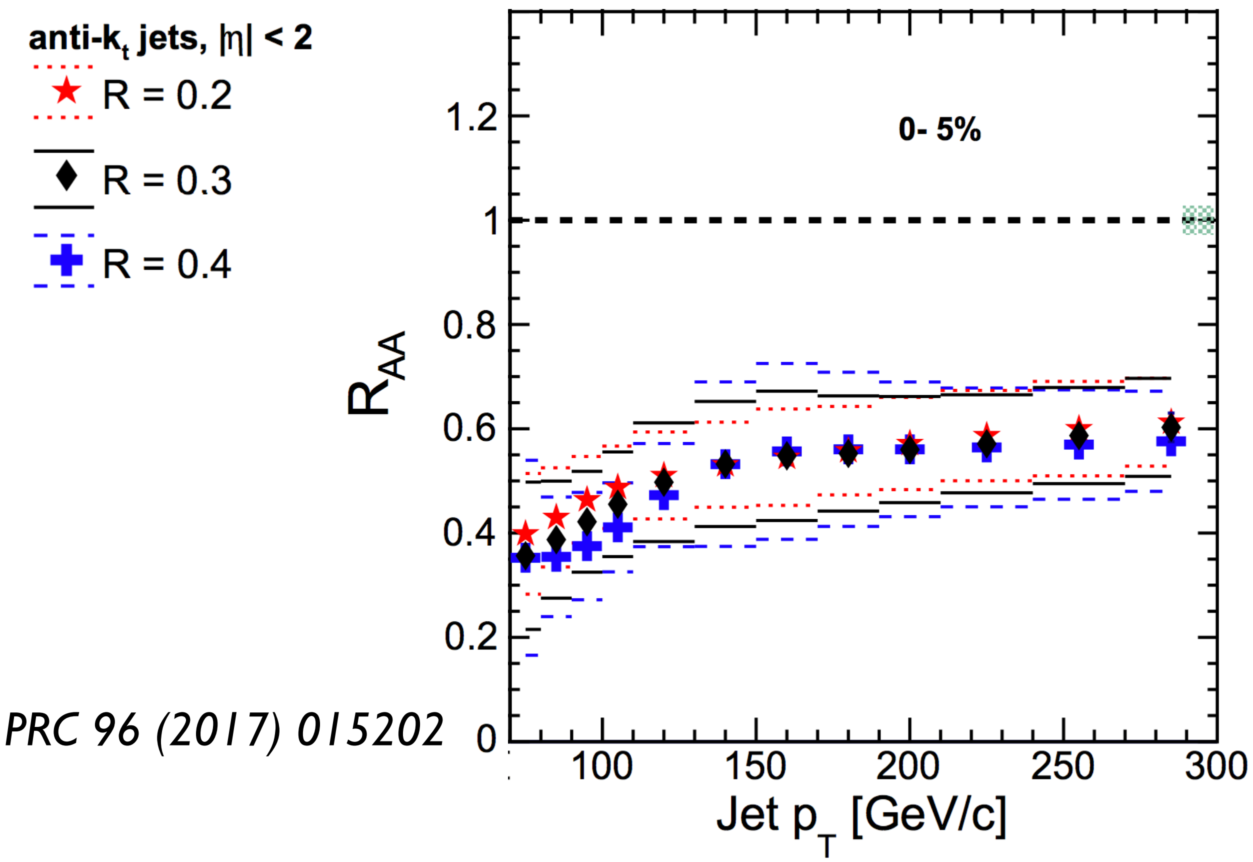


- Error analysis based on the technique from NNPDF

Ball et al. `17

A first global analysis

- Non-trivial χ^2 profile
- Require physical solutions
- It is not possible to fit the data with $W_q(z) = W_g(z)$ while requiring a "physical solution"
- Require that $\sigma^{\rm med}_{q,g} < \sigma^{\rm vac}_{q,g}$

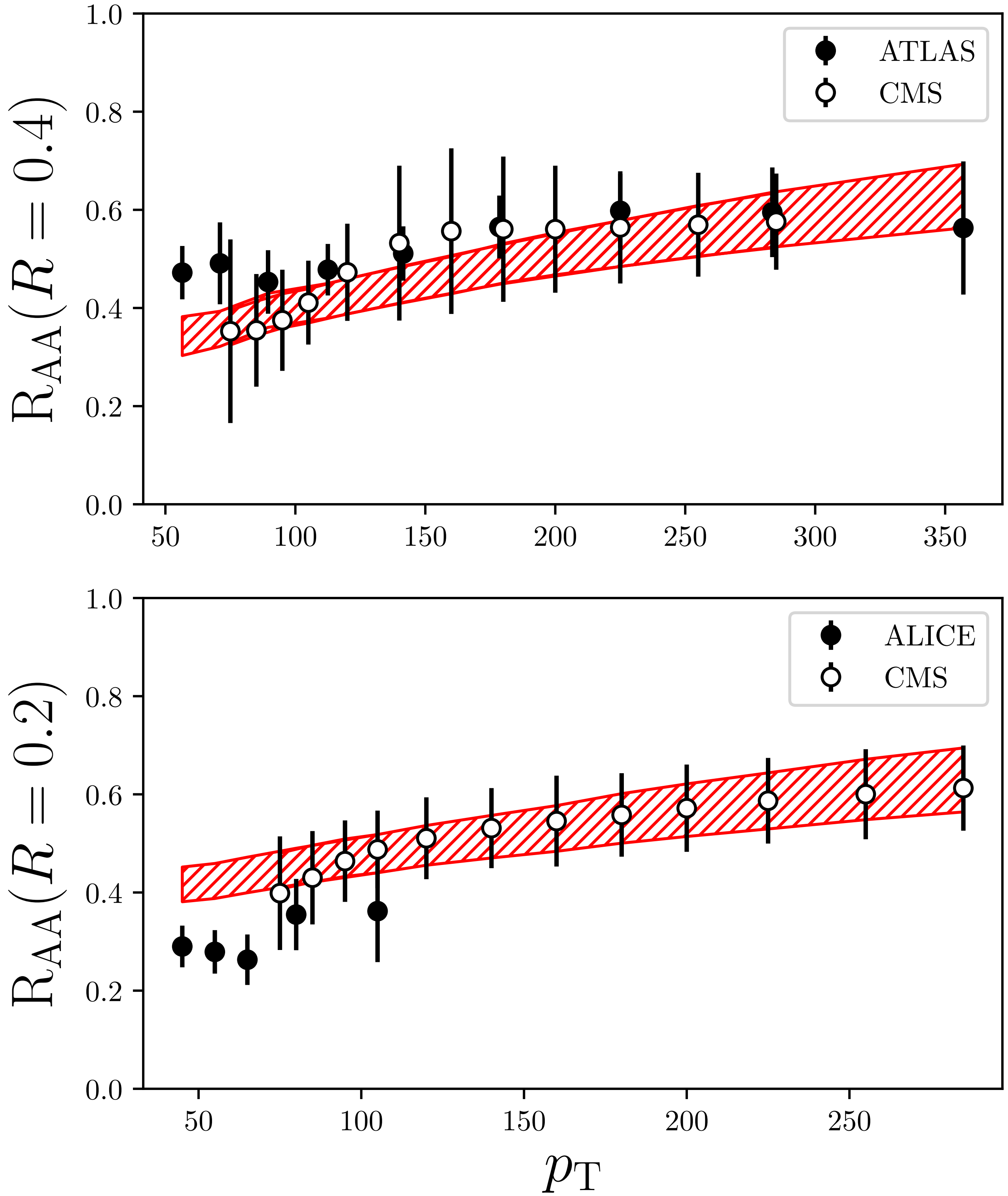


CMS, PRC 96 (2017) 015202

Inclusive jet production in AA

$\sqrt{s} = 2.76$ TeV

Fit with $\chi^2/\text{d.o.f.} = 1.1$



CMS also $R = 0.3$

No initial state effects or nPDFs

ALICE, PLB 746 (2015) 1
ATLAS, PRL 114 (2015) 072302
CMS, PRC 96 (2017) 015202

Inclusive jet production in AA

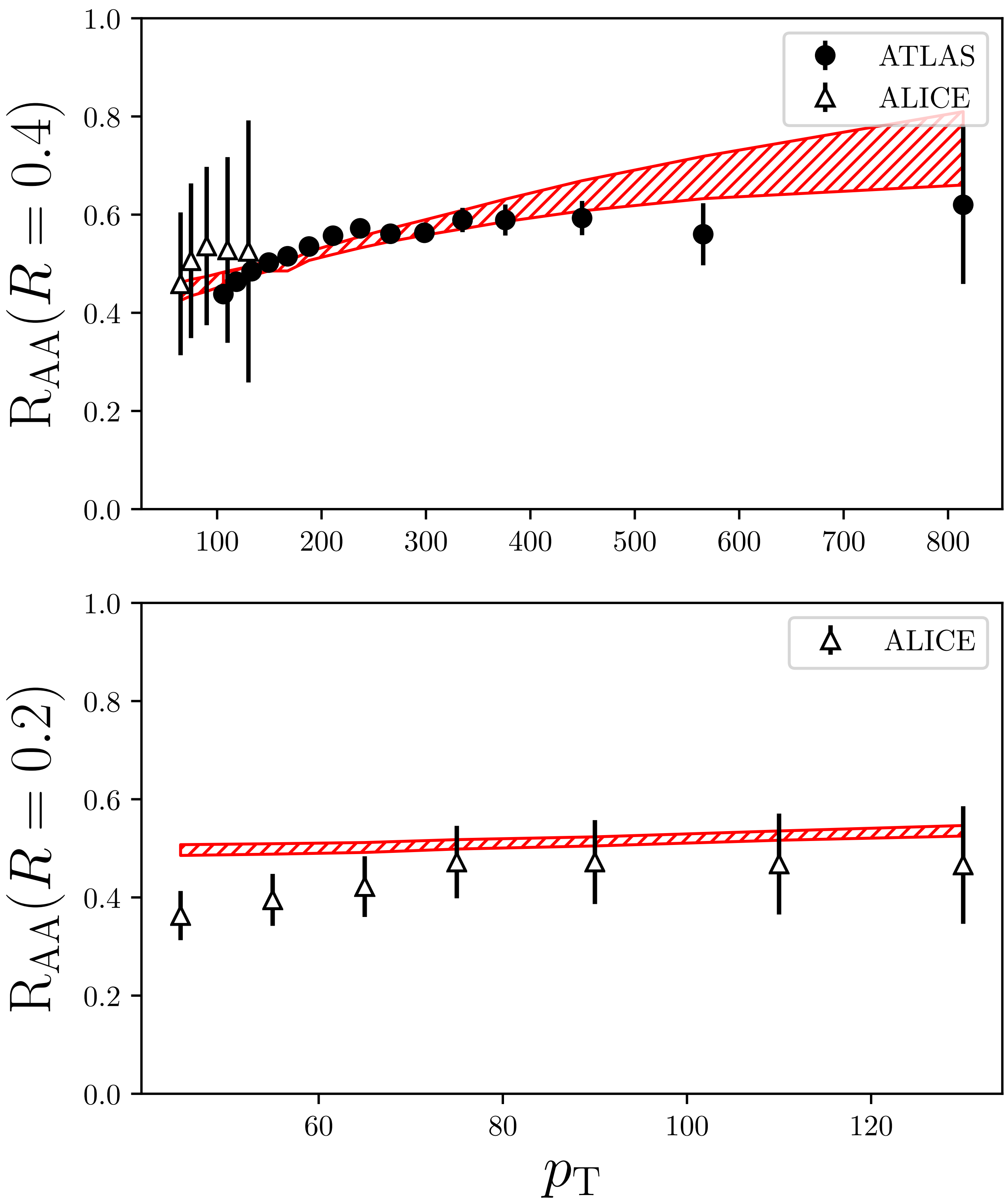
$\sqrt{s} = 5.02$ TeV

Fit with $\chi^2/\text{d.o.f.} = 1.7$

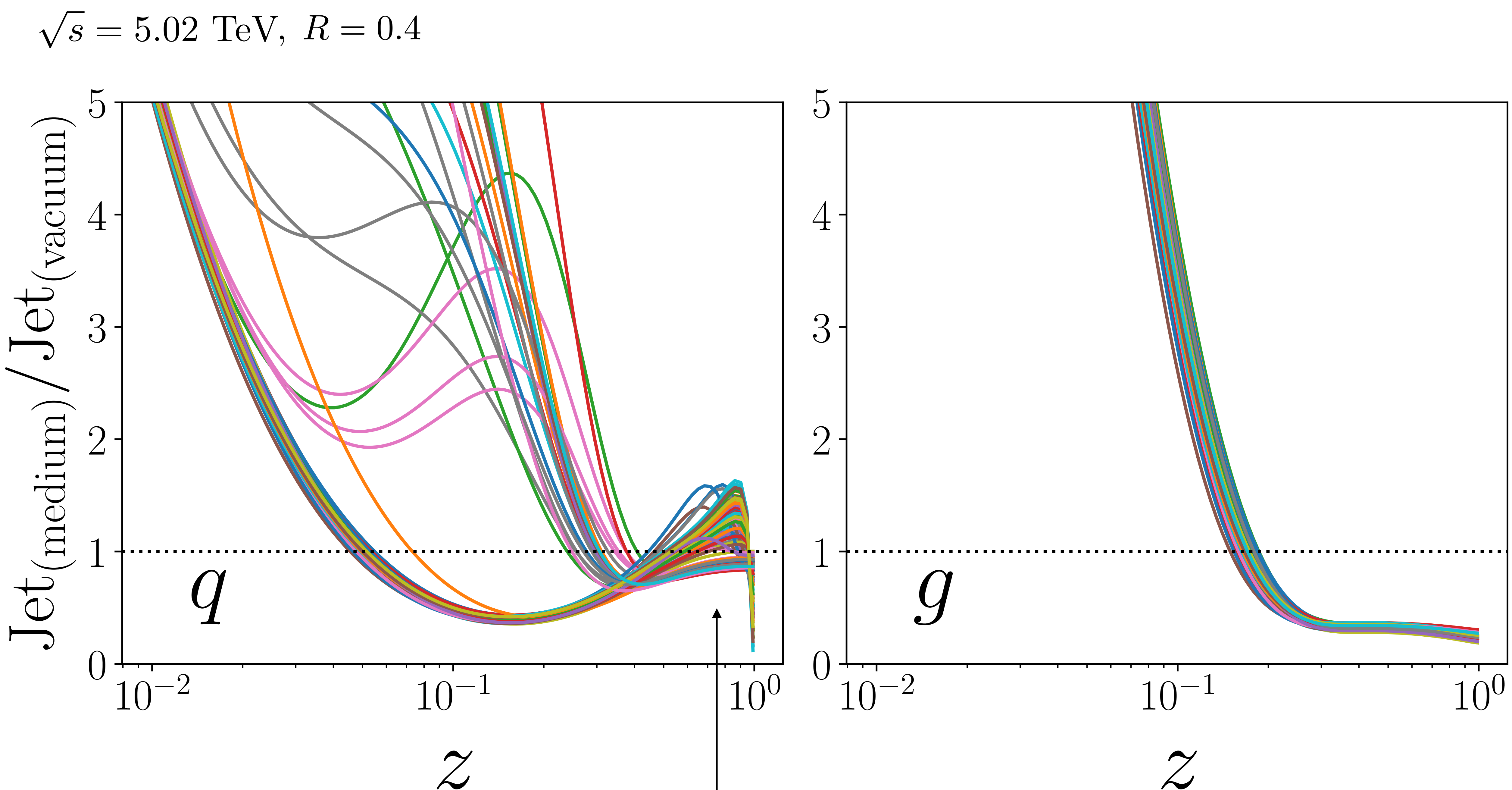
- High p_T easy to fit
- low p_T more difficult

No initial state effects or nPDFs

ALICE preliminary, J. Mulligan, HardProbes18
ATLAS, PLB 790 (2019) 108



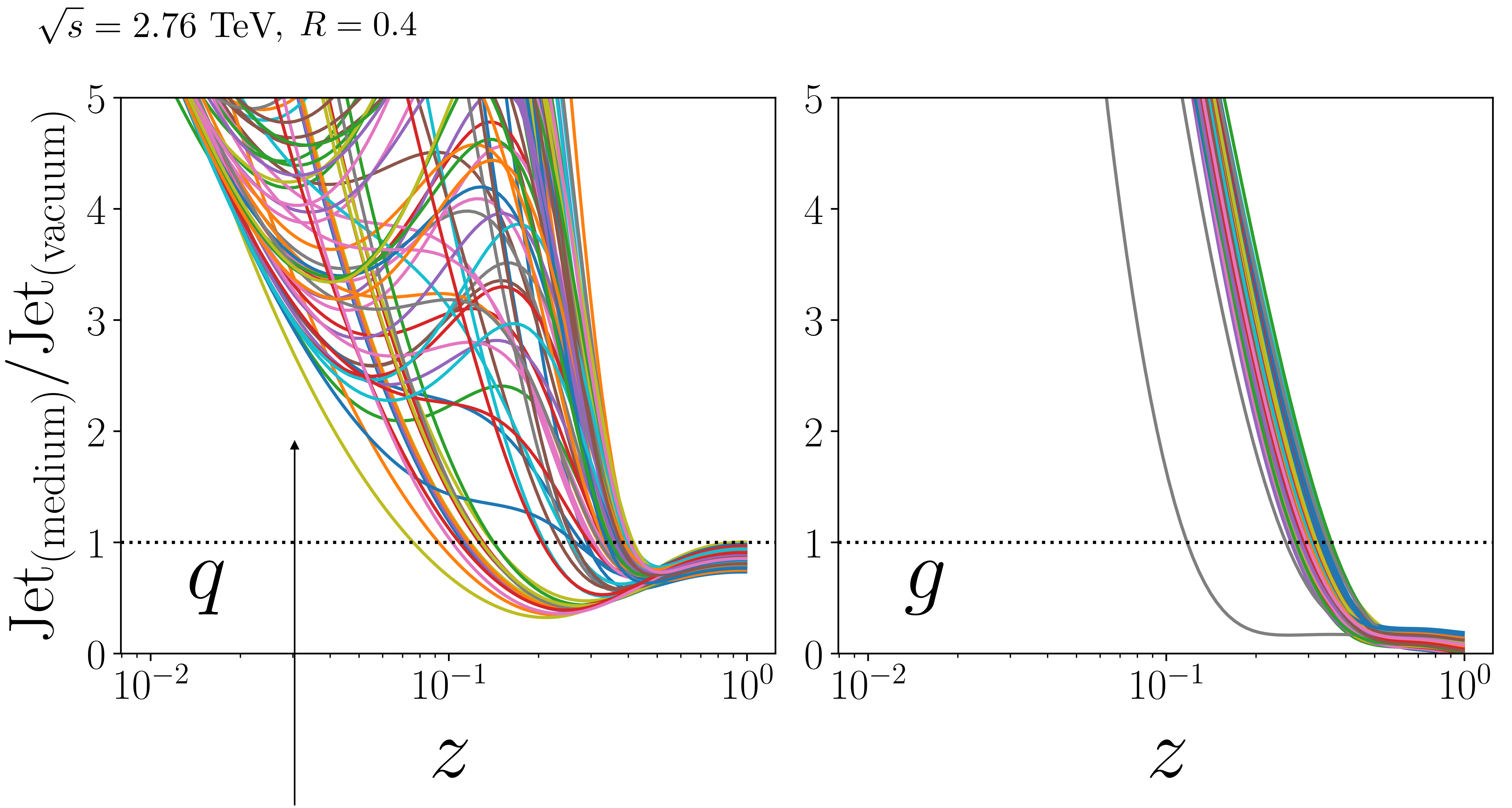
The medium modified jet functions



Requires threshold resummation for $z \to 1$

Dai, Kim, Leibovich `17
Liu, Moch, FR `17

The medium modified jet functions



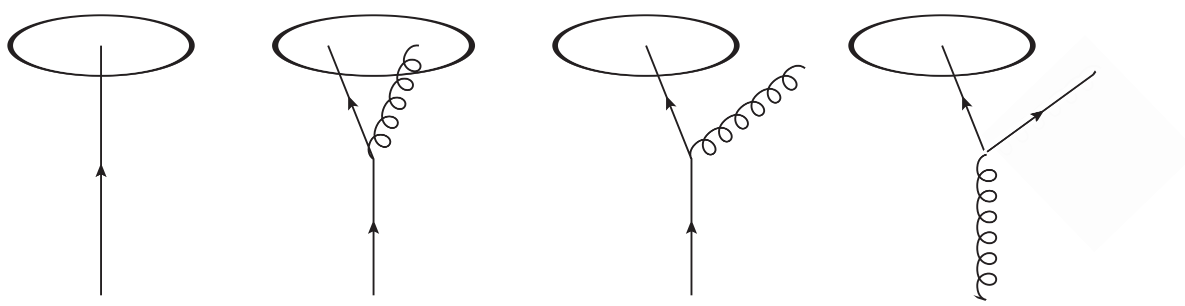
Small-z region generally less constrained

Quark/gluon jets

Keeping track of the flavor d of the jet

$$\frac{d\sigma_d^{pp\to \mathrm{jet}+X}}{dp_T d\eta} = \sum_{abc} f_a \otimes f_b \otimes f_b \otimes H_{ab}^c \otimes J_{cd}$$

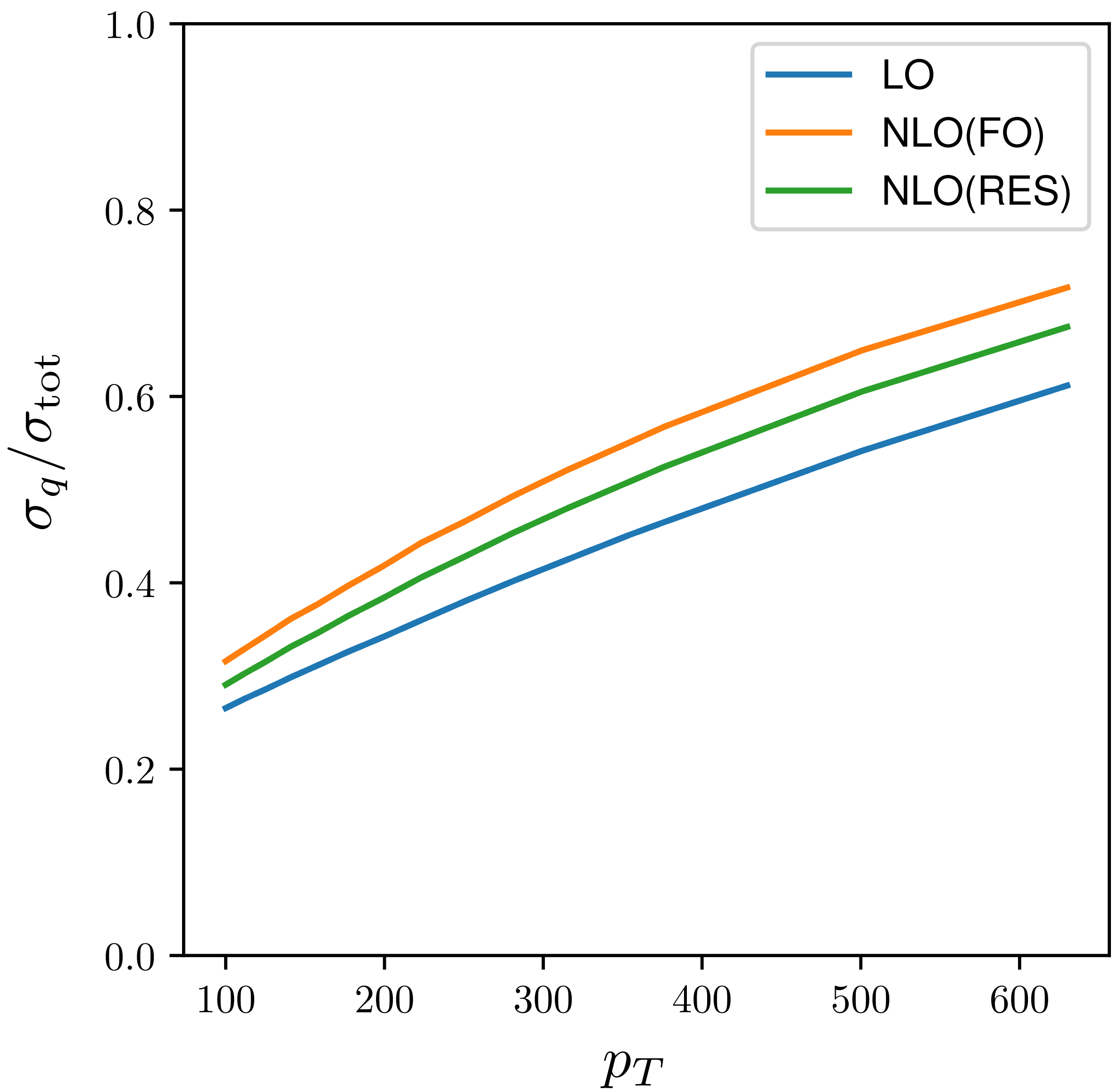
where $$\sum_d J_{cd}(z) = J_c(z)$$



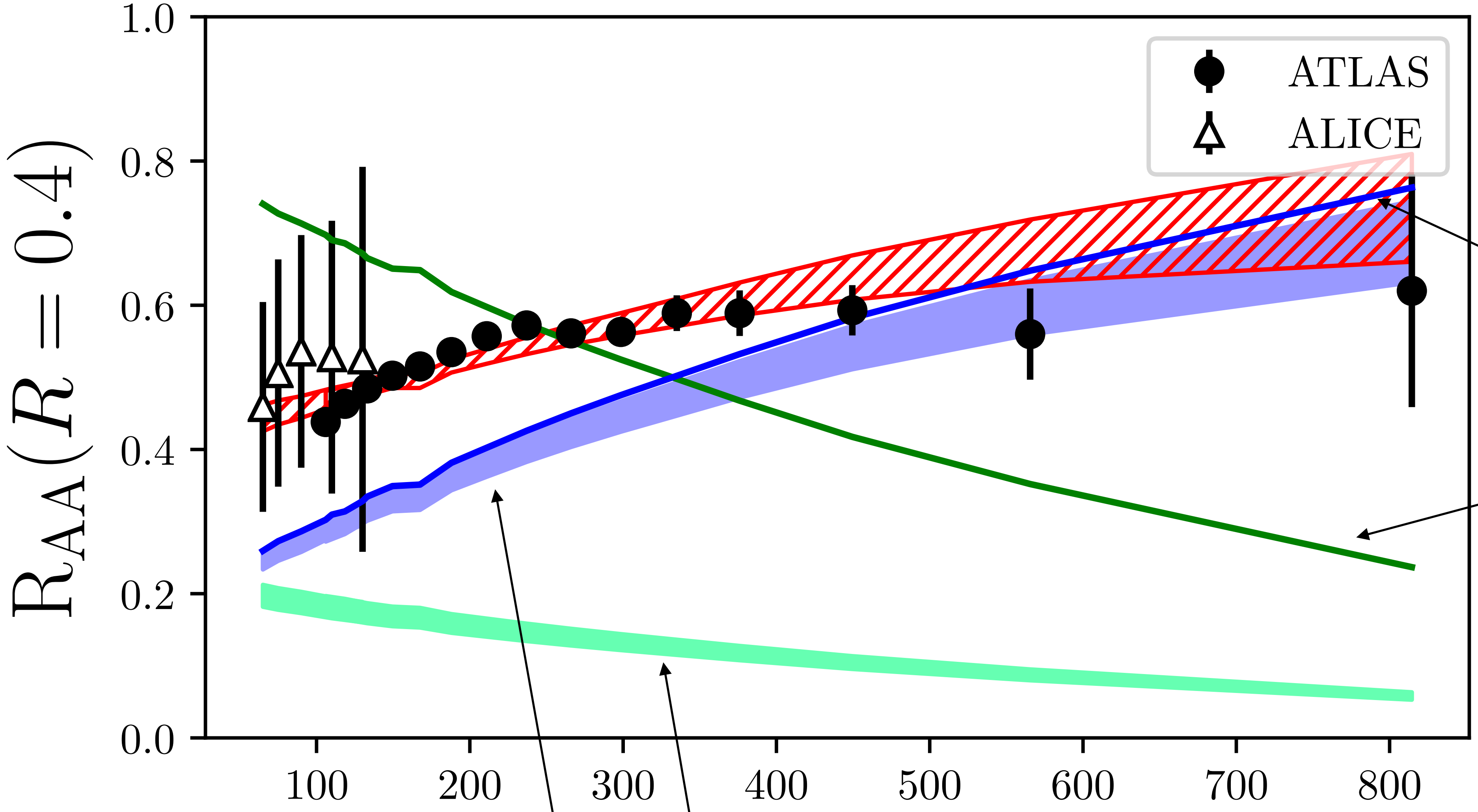
- R_{AA} is sensitive to q/g jets
- Dependence on the perturbative accuracy

see also Marzani, Schunk, Soyez `17
Cal, FR, Waalewijn `19 ⟶ *Kyle Lee and Pedro Cal's talk*

$\sqrt{s} = 5.02$ TeV, $R = 0.4, |\eta| < 1$



Quark/gluon jets



vacuum $\sigma_q/\sigma_{\text{tot,vac}}$

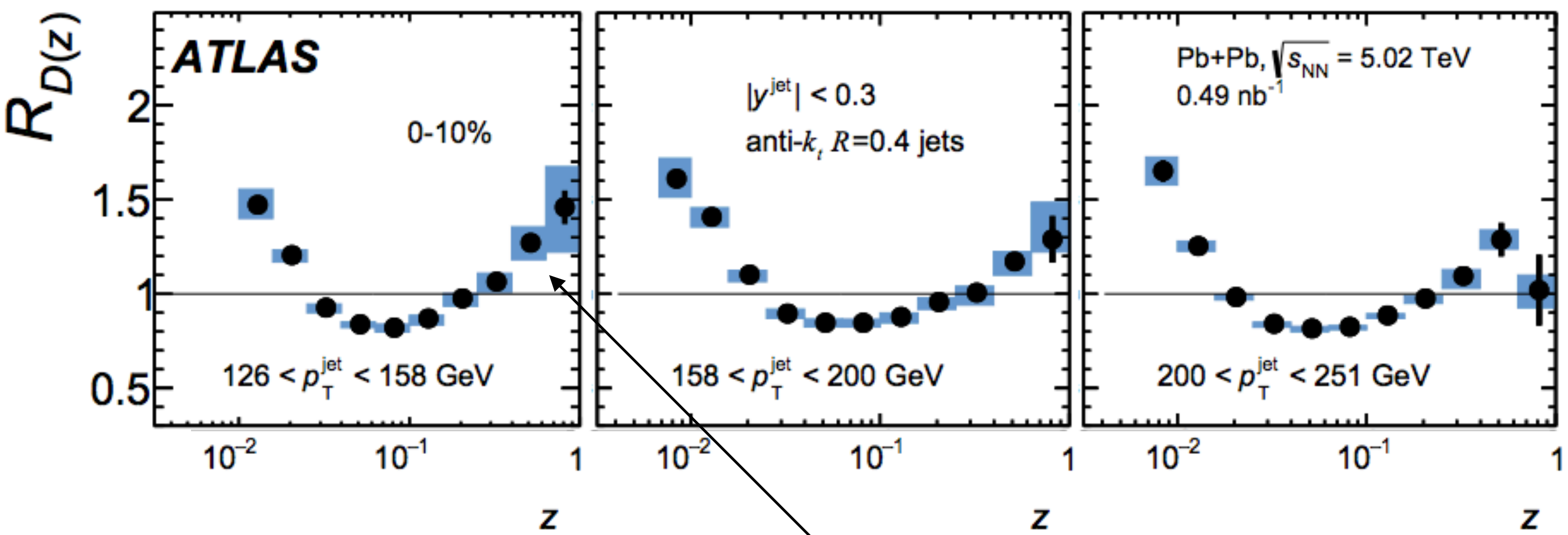
vacuum $\sigma_g/\sigma_{\text{tot,vac}}$

medium $\sigma_q^{\text{med}}/\sigma_{\text{tot,vac}}$

medium $\sigma_g^{\text{med}}/\sigma_{\text{tot,vac}}$

- Sensitivity to q/g
- Need additional handle from $\gamma + \text{jet}$

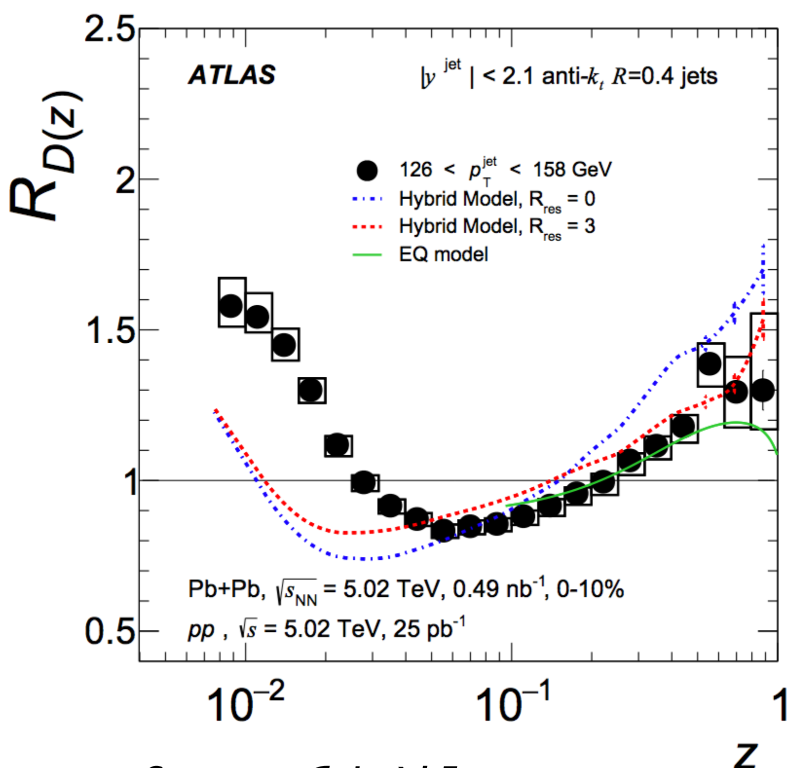
Results from jet substructure



ATLAS, PRC 98 (2018) 024908

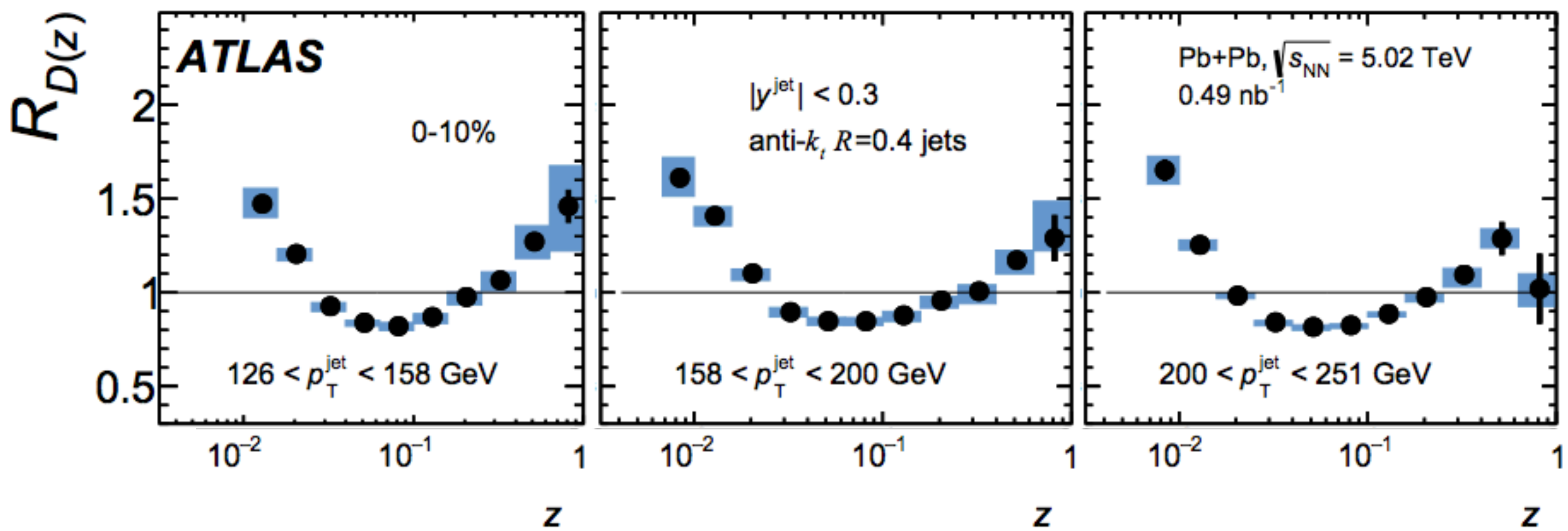
The jet fragmentation function

Quark-like fragmentation at large-z



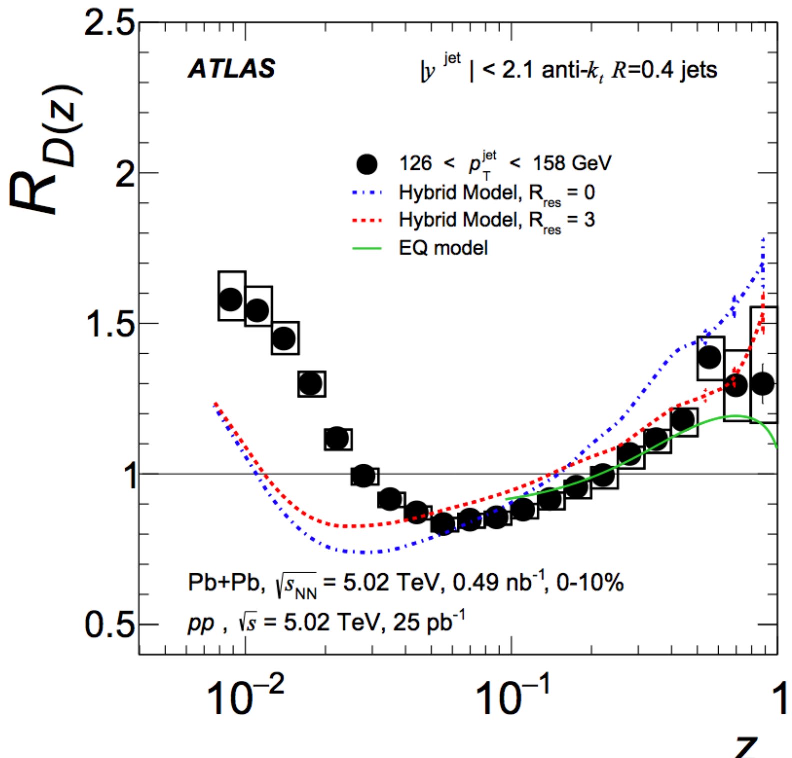
Spousta, Cole `15

Results from jet substructure

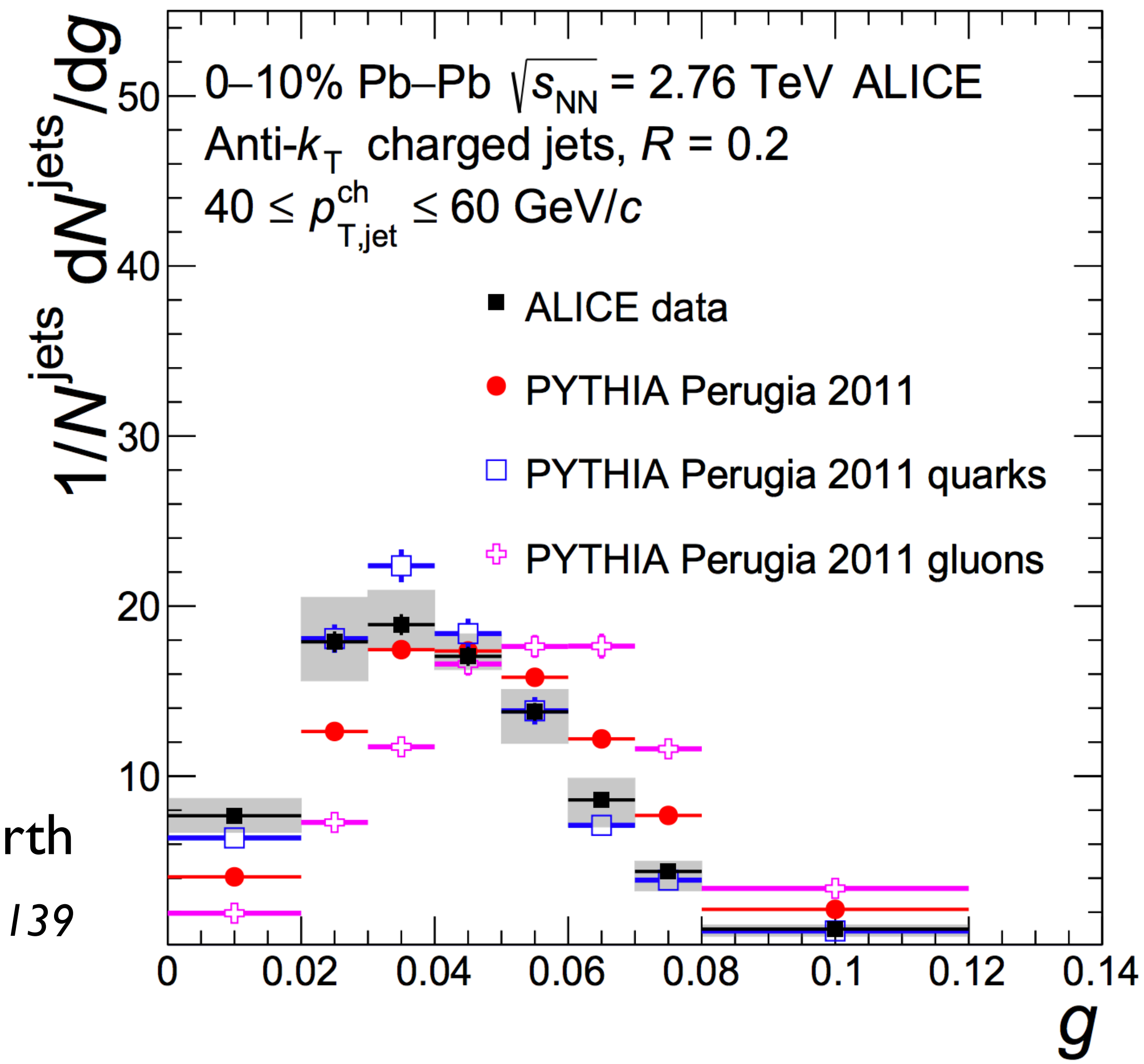


ATLAS, PRC 98 (2018) 024908

The jet fragmentation function



Spousta, Cole `15



Jet girth

ALICE, JHEP 1810 (2018) 139

The jet radius dependence

- Large-R - Parton energy loss recovered in larger jet $R_{AA} \uparrow$
- Small-R
  - Jet sample with harder fragmentation spectrum for fixed p_T $R_{AA} \uparrow$
  - Formally for $R \to 0$ the hadron R_{AA} should be obtained $R_{AA} \uparrow$

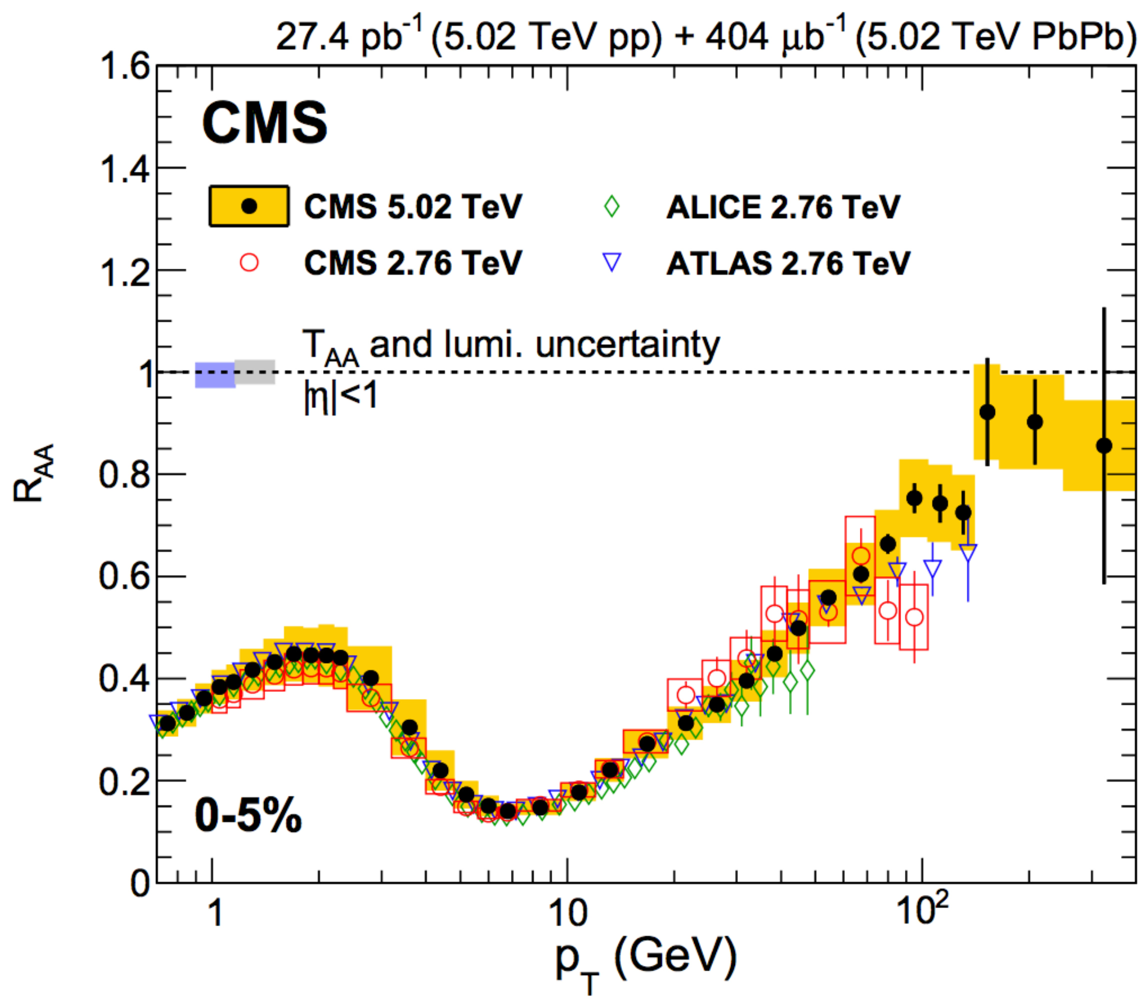
Factorization

$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$

$$\Big\downarrow R \to 0$$

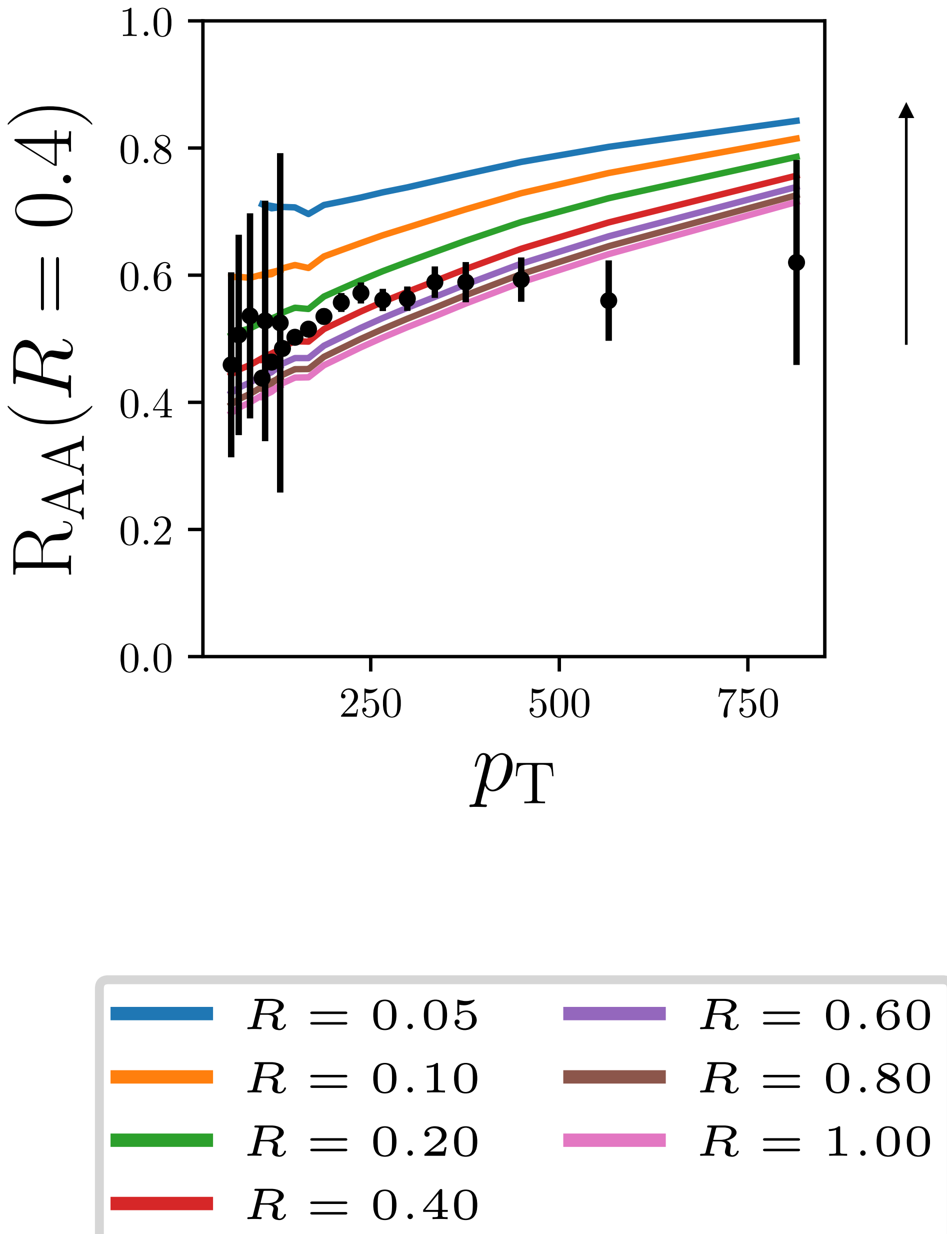
Non-perturbative fragmentation functions D_c^h

see also: Sirimanna, Cao, Majumder `19



CMS, JHEP 1704 (2017) 039

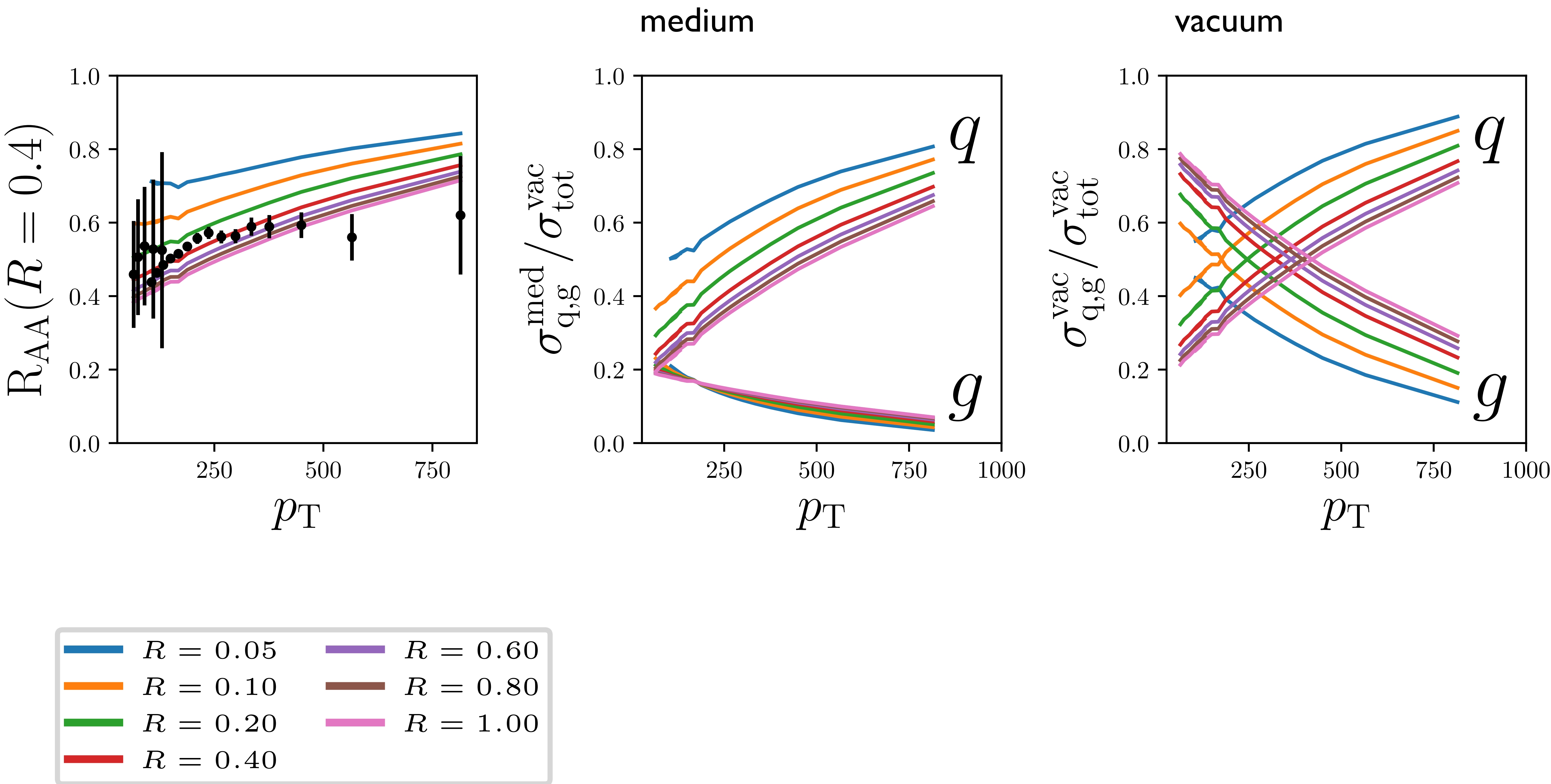
The jet radius dependence



$R \to 0$

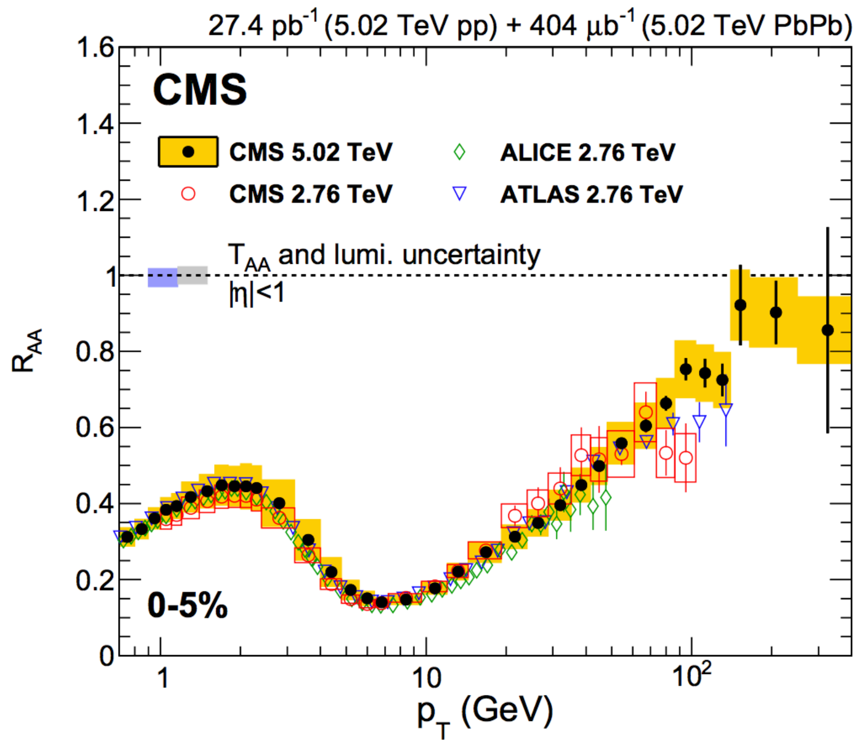
approaching the hadron R_{AA}

The jet radius dependence



Factorization and universality

- Test framework by analyzing inclusive hadron cross sections
- Sensitivity to much smaller scales
- Modification of DGLAP necessary?



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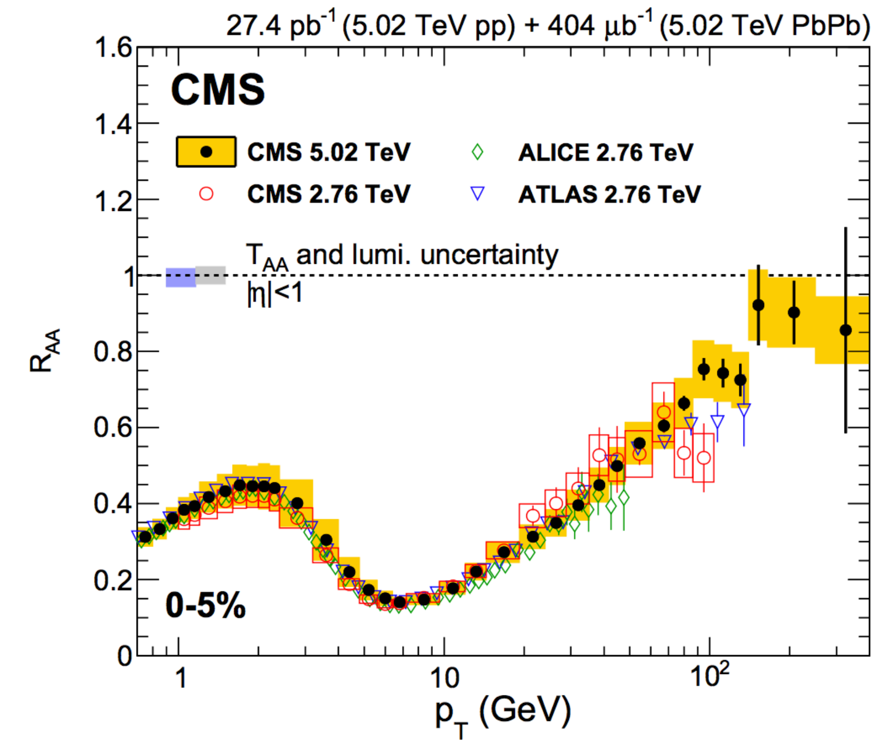
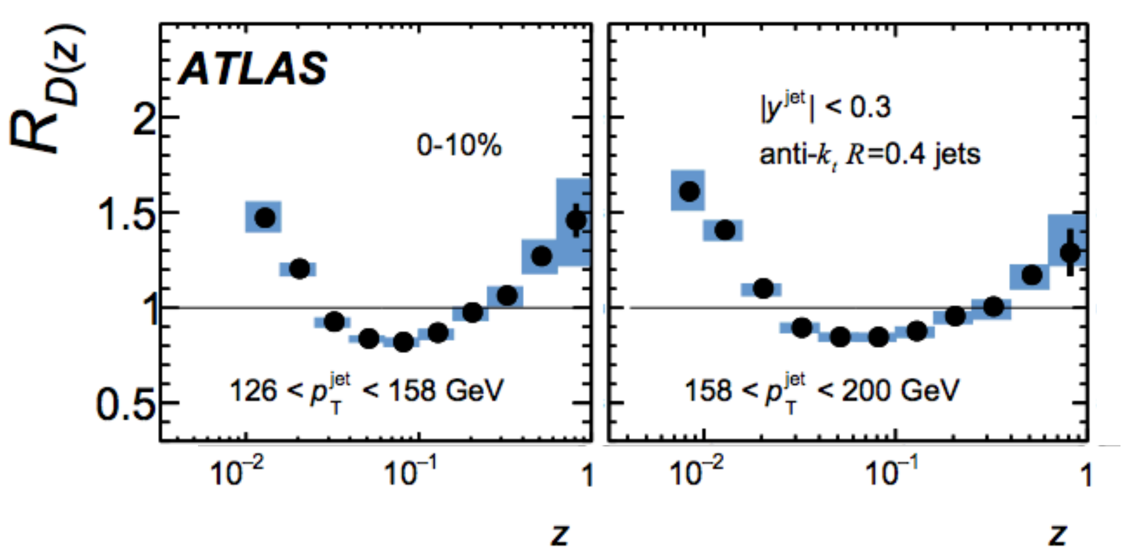


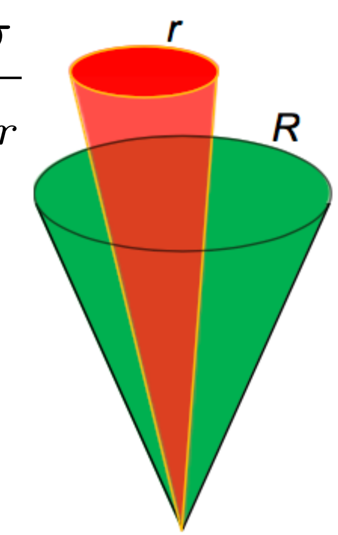
- Test universality using jet substructure observables
- Similar collinear factorization theorems

Hadrons and subjets inside jets

$$f_a \otimes f_b \otimes H_{ab}^c \otimes \mathcal{G}_{cd} \otimes D_d^h$$



$$\frac{d\sigma}{dz_r}$$



Direct probe of in-medium jet functions

Outline

- Introduction
- Inclusive jet production
- Phenomenological results
- Conclusions

Conclusions

- First global analysis of in-medium jet functions
- Support for the notion of QCD factorization in heavy-ion collisions
- Quark/gluon jets modified differently

- Include more data and other processes such as $\gamma + \mathrm{jet}$
- Test of universality by using jet substructure data
- Insights into the modification of parton showers
- Comparison to models