QCD factorization and universality of jet cross sections in heavy-ion collisions

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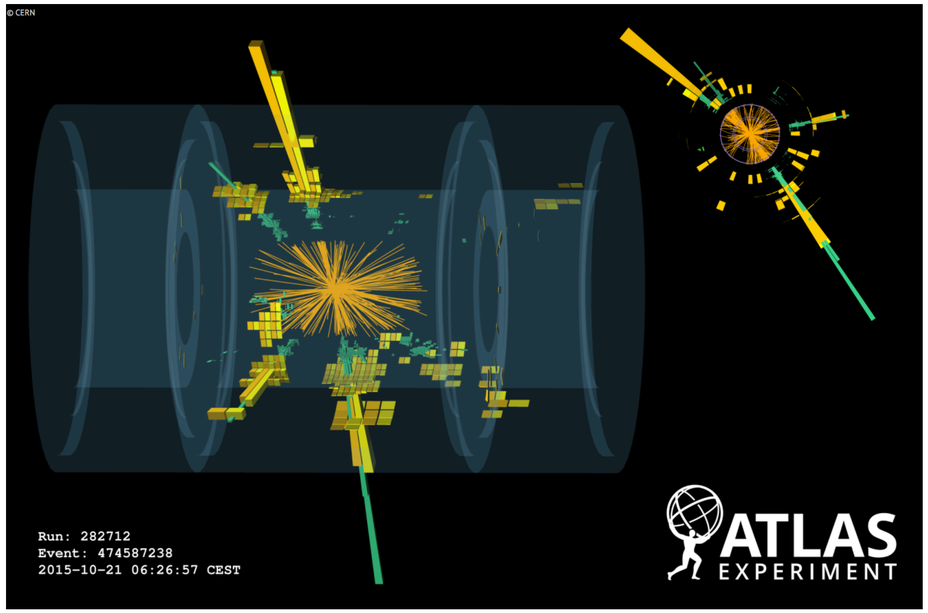
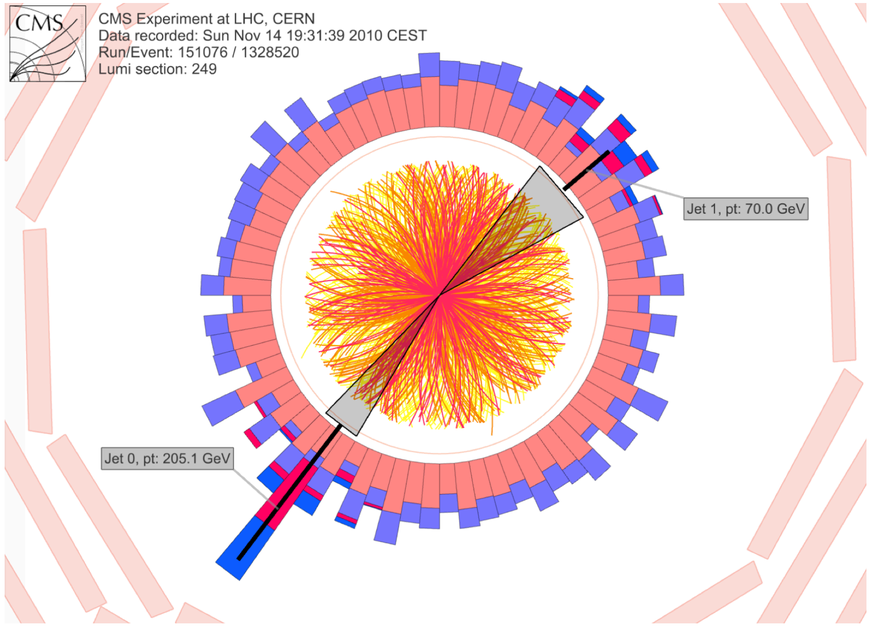
Jets in proton-proton and heavy-ion collisions

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



- Inclusive jet cross section $\dfrac{\mathrm{d}\sigma^{pp\to\ \text{jet}\ +X}}{\mathrm{d}p_T\mathrm{d}\eta}$
- Precision calculations available in perturbative QCD

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



- Nuclear modification factor $R_{\mathrm{AA}}^{\mathrm{jet}} = \dfrac{\mathrm{d}\sigma^{\mathrm{PbPb}\to\mathrm{jet}+X}}{\langle T_{\mathrm{AA}}\rangle\,\mathrm{d}\sigma^{pp\to\mathrm{jet}+X}}$
- QCD Factorization?

Outline

- Introduction
- QCD factorization and universality
- Inclusive jets in heavy-ion collisions
- Conclusions

QCD factorization

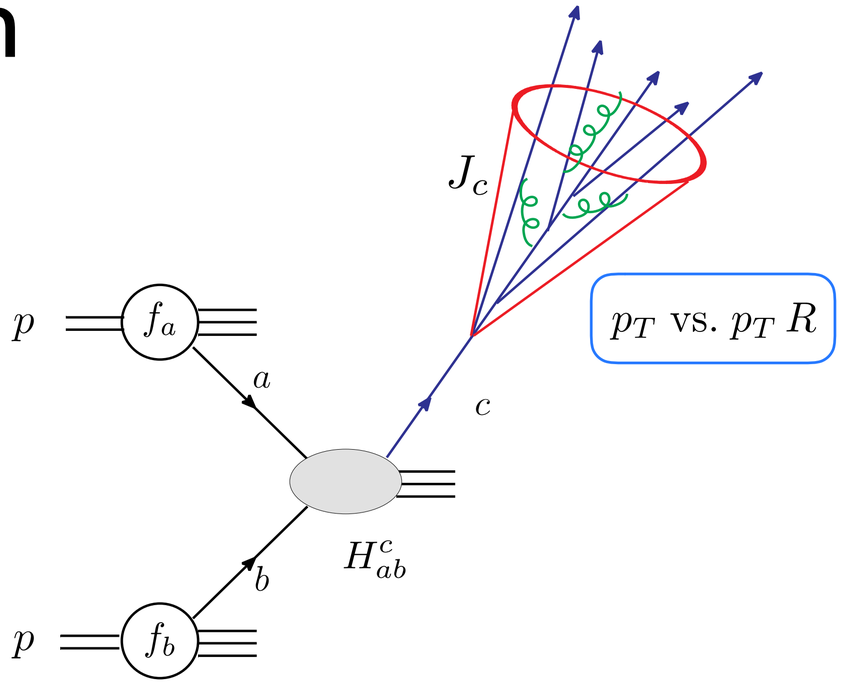
- Inclusive jet production $pp \to \text{jet} + X$

PDFs

$$\frac{\mathrm{d}\sigma^{pp\to\text{jet}+X}}{\mathrm{d}p_T \mathrm{d}\eta} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$

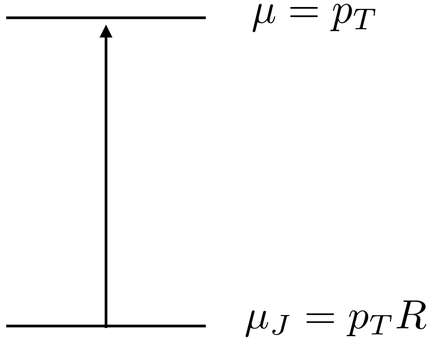
Hard-scattering

Jet functions



- Hard and jet function calculable
- DGLAP evolution equation
- Resummation of $\alpha_s^n \ln^n R^2$

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

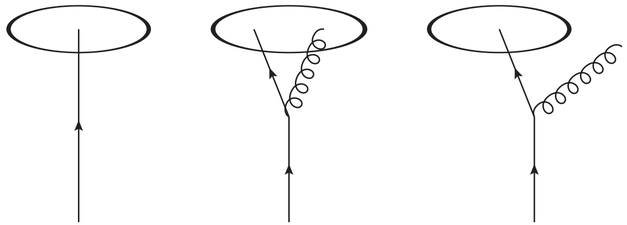


Ellis, Kunszt, Soper `90
Dasgupta, Dreyer, Salam, Soyez `15
Kaufmann, Mukherjee, Vogelsang `15
Kang, FR, Vitev `16
Dai, Kim, Leibovich `16

Jet functions in the vacuum

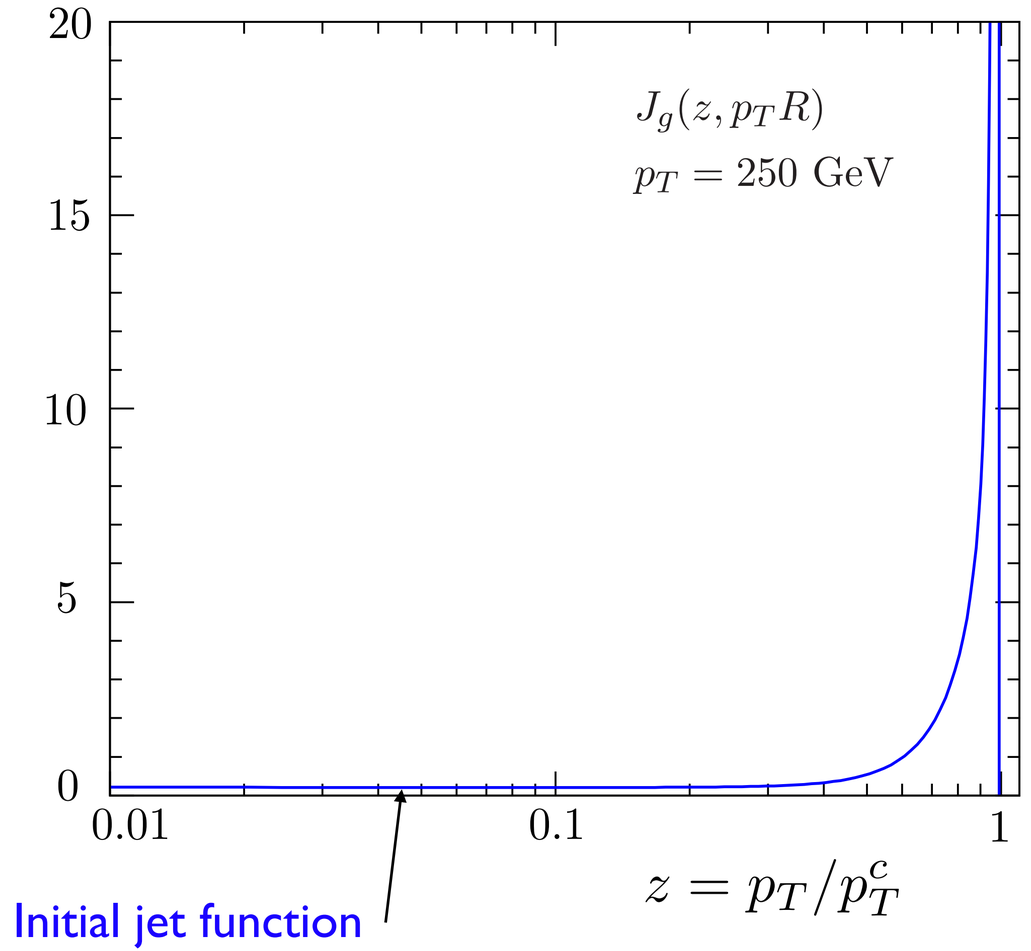
Kang, FR, Vitev `16

- NLO result



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

- Initial condition for the evolution (blue), independent of the jet radius
- DGLAP evolution $p_T R \to p_T$
- Number density similar to fragmentation functions



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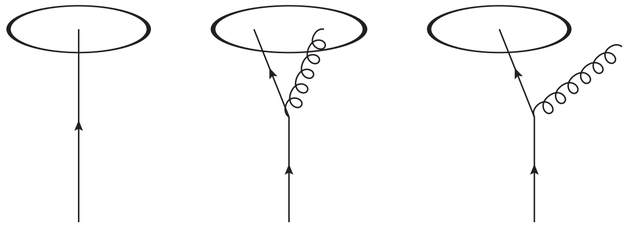

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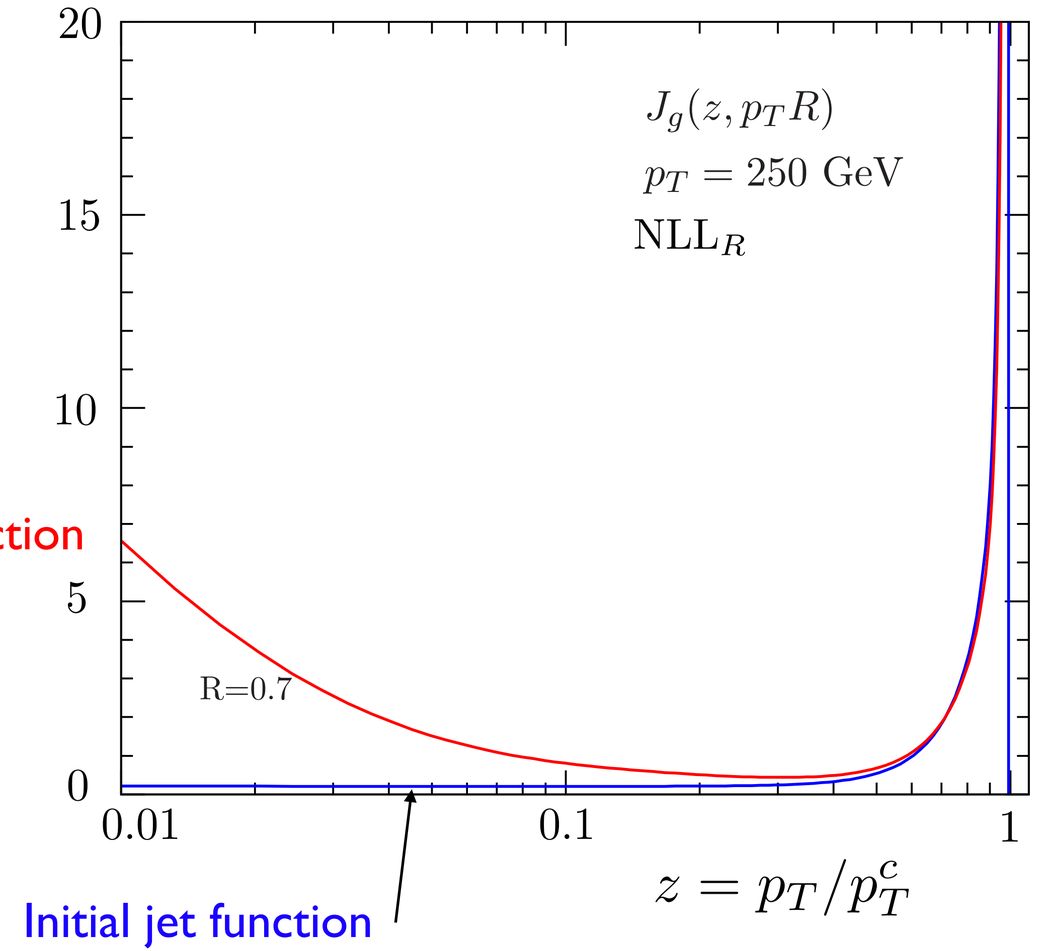

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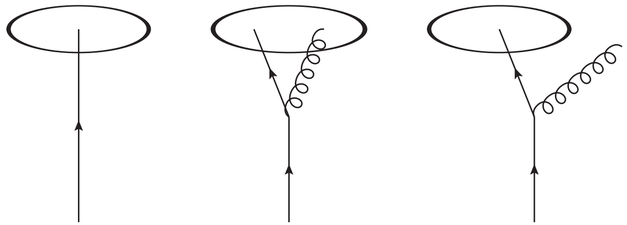

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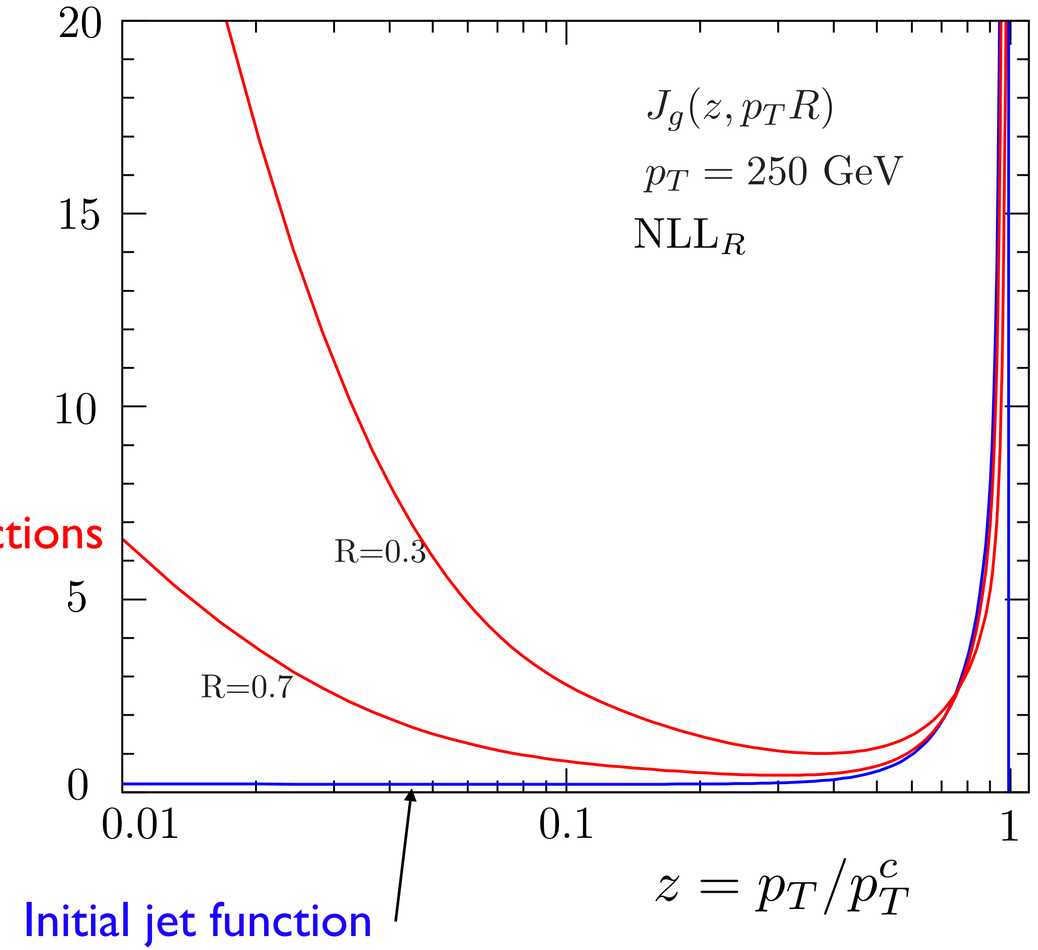
Evolved jet functions



Initial jet function

Jet functions in the vacuum

Kang, FR, Vitev `16

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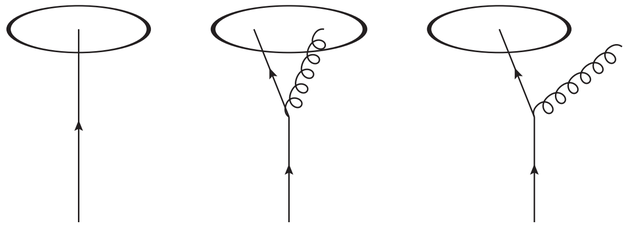

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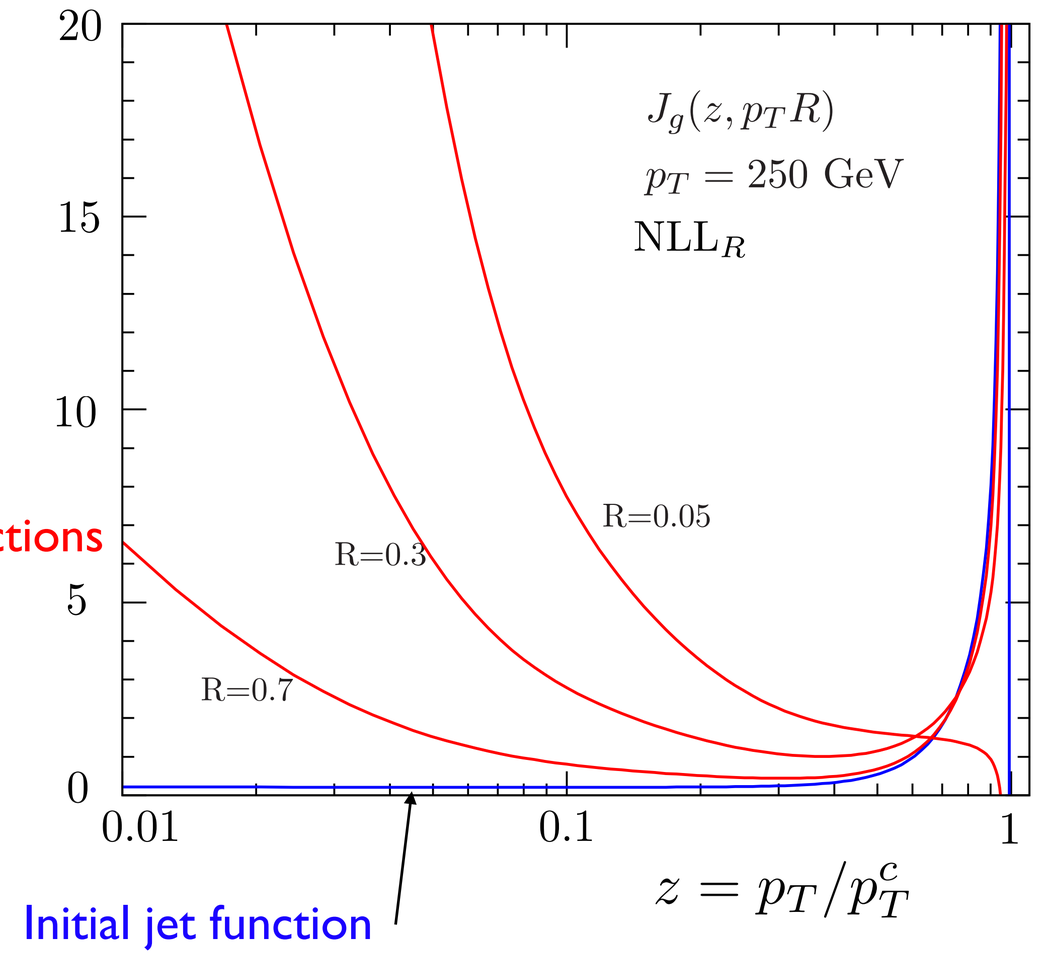


Evolved jet functions

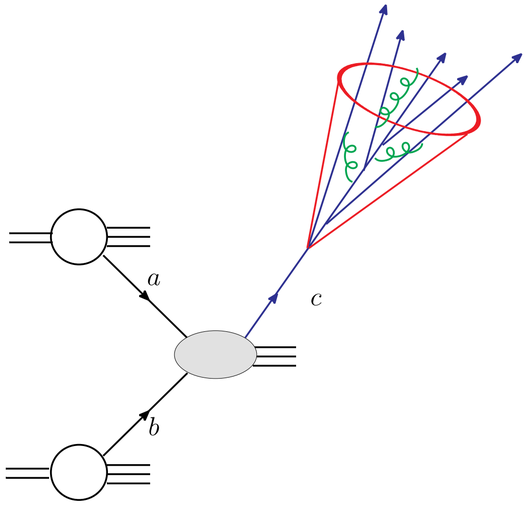
Initial jet function

QCD factorization

- Proton-proton
  - Proof from first principles for the Drell-Yan process *Collins, Soper, Sterman `85, Bodwin `85*
  - Partial proofs: $pp \to h + X$ *Nayak, Qiu, Sterman `05*
  - And phenomenologically well established:

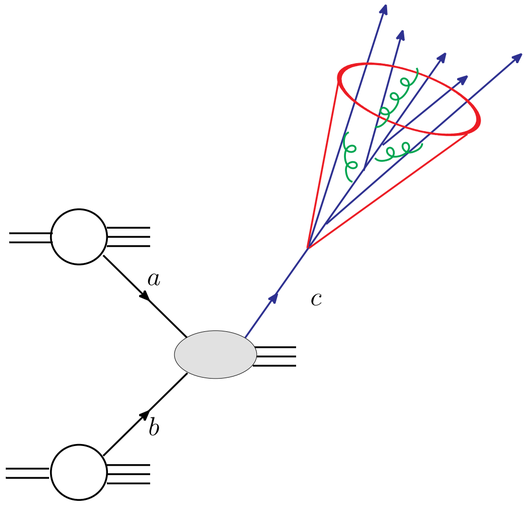
    Global analyses of PDFs give a consistent picture!

    ABMP, CJ, CT, JAM, MMHT, NNPDF …



$$\frac{\mathrm{d}\sigma^{pp\to\mathrm{jet}+X}}{\mathrm{d}p_T\mathrm{d}\eta} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$

QCD factorization



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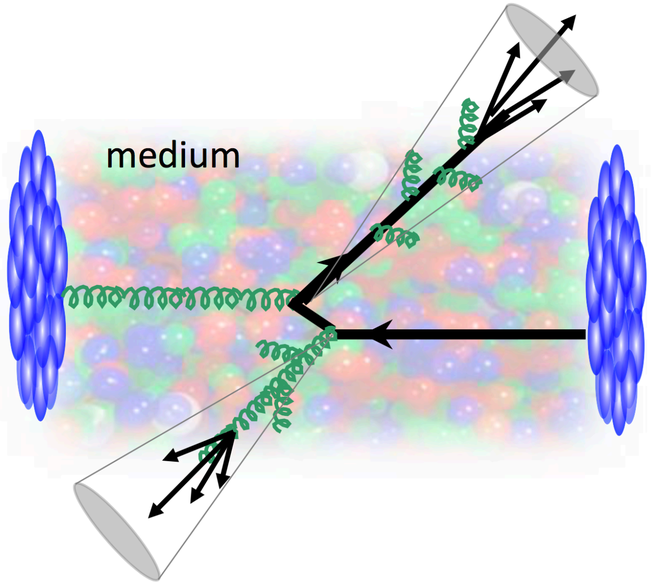


- Heavy-ion
  - Try to establish a phenomenological approach
  - Possibly broken. If so, how large is the effect?

The predictive power of QCD and universality

- Inclusive jet production $pp \to \text{jet} + X$
- Related to hadron production $pp \to h + X$

- The jet fragmentation function
- Inclusive subjets

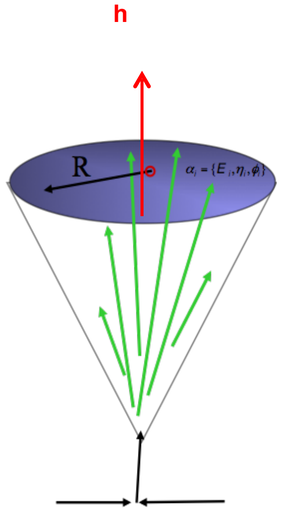
$H_{ab}^{c} \otimes J_c$

$H_{ab}^{c} \otimes D_c^h$

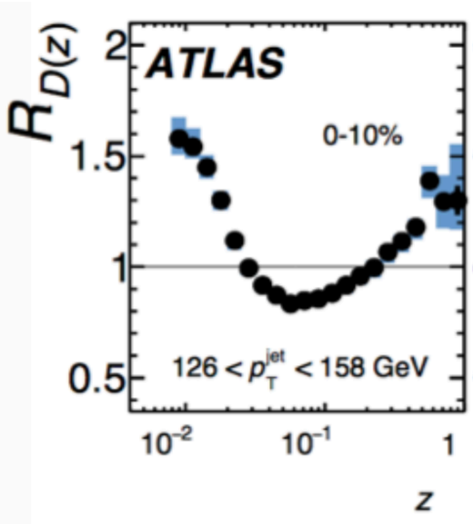
$H_{ab}^{c} \otimes J_c \otimes D_c^h$

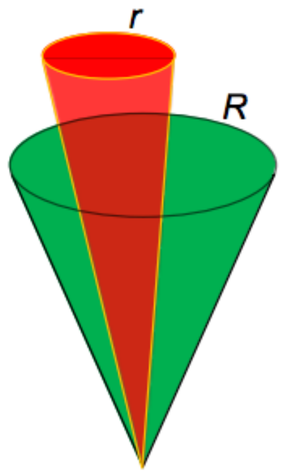
$H_{ab}^{c} \otimes J_c \otimes J_c$

Reuse universal functions in other factorization theorems



ATLAS, PRC 98 (2018) 024908





The predictive power of QCD and universality

- Inclusive jet production $pp \to \text{jet} + X$
- Related to hadron production $pp \to h + X$

- The jet fragmentation function
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- Quark/gluon fractions of any jet substructure observable

$H_{ab}^c \otimes J_c$

$H_{ab}^c \otimes D_c^h$

$H_{ab}^c \otimes J_c \otimes D_c^h$

$H_{ab}^c \otimes J_c \otimes J_c$

$H_{ab}^c \otimes J_c \otimes \mathcal{G}_c(\tau)$

Reuse universal functions in other factorization theorems

For example the soft drop groomed radius

$$\frac{\mathrm{d}\sigma^{pp}}{\mathrm{d}p_T \mathrm{d}\eta \mathrm{d}\theta_g} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes \sum_{i=q,\bar{q},g} \sum_n \mathcal{H}_{c\to i}^n (z, p_T R, \mu) \otimes_\Omega S_{i,n}^{\notin \mathrm{gr}} (z_{\mathrm{cut}} p_T R, \mu; \beta) \times \sum_m C_i^m (\theta_g p_T R, \mu) \otimes_\Omega S_{i,m}^{\in \mathrm{gr}} (z_{\mathrm{cut}} \theta_g^{1+\beta} p_T R, \mu; \beta)$$

Larkoski, Marzani, Soyez, Thaler `14; Kang, Lee, Liu, Neill, FR `19, FR, Xiao, Yuan `19

The predictive power of QCD and universality

- Inclusive jet production $pp \to \text{jet} + X$
- Related to hadron production $pp \to h + X$

$H^c_{ab} \otimes J_c$

$H^c_{ab} \otimes D^h_c$

Reuse universal functions in other factorization theorems

- The jet fragmentation function

$H^c_{ab} \otimes J_c \otimes D^h_c$

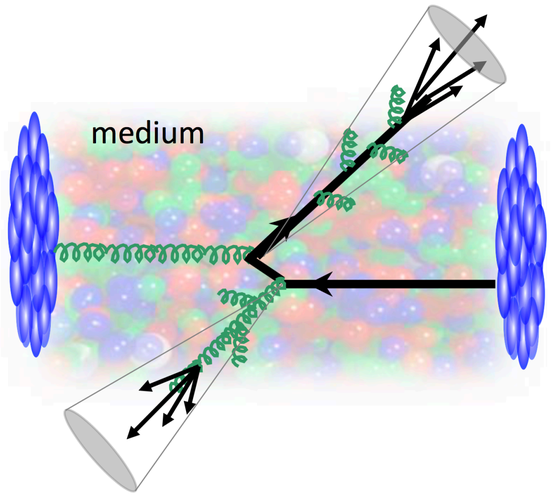
- Inclusive subjets

$H^c_{ab} \otimes J_c \otimes J_c$

- Quark/gluon fractions of any jet substructure observable

$H^c_{ab} \otimes J_c \otimes \mathcal{G}_c(\tau)$

- Can we use similar approach in AA ?
- Minimal theory assumptions
- Factorization breaking effects in AA $\longleftrightarrow$ universality ?
- Can we find medium jet functions for AA ?



Outline

- Introduction
- QCD factorization and universality
- Inclusive jets in heavy-ion collisions
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Factorization for jets in heavy-ion collisions

Qiu, FR, Sato, Zurita `19

- Proton-proton

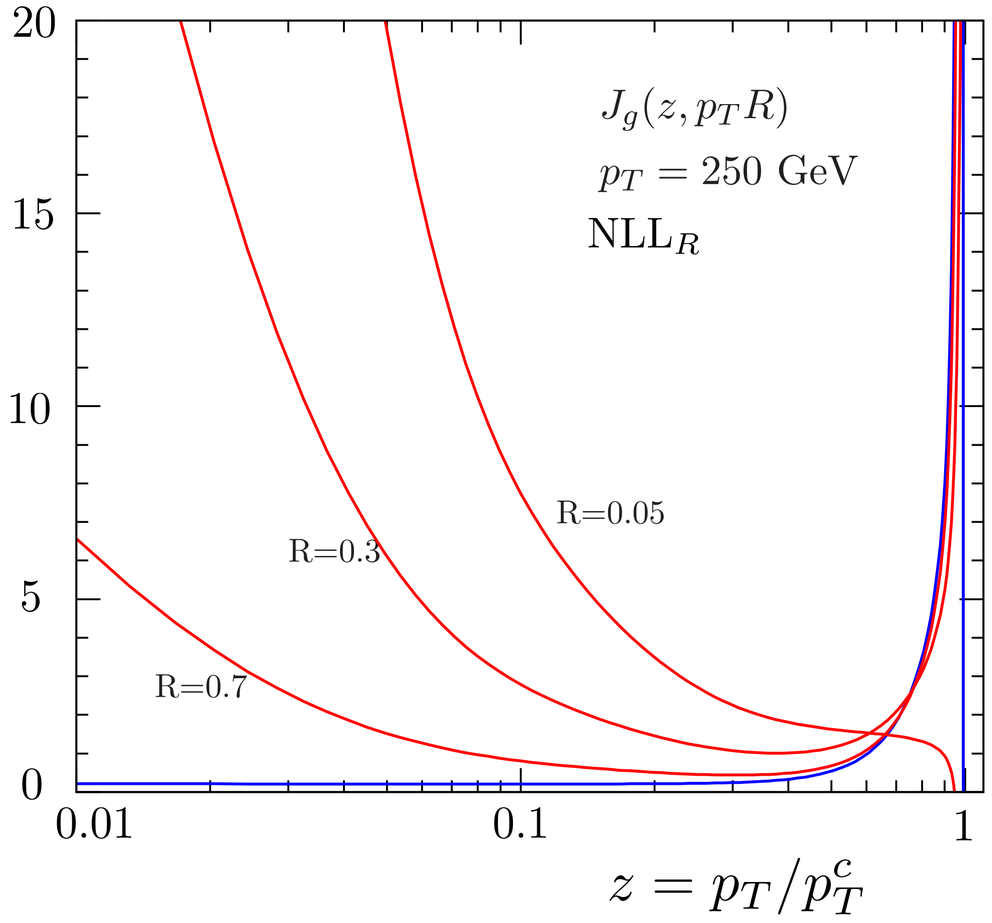
$$\frac{\mathrm{d}\sigma^{pp\to\mathrm{jet}+X}}{\mathrm{d}p_T\mathrm{d}\eta} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$

- Heavy-ion

$$\frac{\mathrm{d}\sigma^{AA\to\mathrm{jet}+X}}{\mathrm{d}p_T\mathrm{d}\eta} = \sum_{abc} f_{a/A} \otimes f_{b/A} \otimes H_{ab}^c \otimes J_c^{\mathrm{med}}$$

Initial state e.g. nPDFs

Medium jet functions



see also: Kang, FR, Vitev `17
He, Pang, Wang `18
Sirimanna, Cao, Majumder `19

Factorization for jets in heavy-ion collisions

Qiu, FR, Sato, Zurita `19

- Introduce a modification at the initial scale $\mu = p_T R$

$$J_c^{\rm med}(z, p_T R, \mu_J) = W_c(z) \otimes J_c(z, p_T R, \mu_J)$$

$$W_c(z) = \epsilon_c \delta(1-z) + N_c\, z^{\alpha_c}(1-z)^{\beta_c}$$

- Momentum sum rule

$$\int_0^1 {\rm d}z\, z J_c\left(z, p_T^c R, \mu\right) = 1$$

- Monte Carlo sampling approach

NNPDF `17, JAM `16

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

nFFs *Sassot, Stratmann, Zurita `10*

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NNPDF `17, JAM `16

- A modification of the evolution?

$$\mu^2 \frac{\rm d}{{\rm d}\mu^2} J_i = \sum_j P_{ji} \otimes J_j$$

$$\mu^2 \frac{\rm d}{{\rm d}\mu^2} J_i = \sum_j P_{ji} \otimes J_j + \frac{1}{\mu^2} \Gamma \otimes T$$

$$\mu^2 \frac{\rm d}{{\rm d}\mu^2} T = \gamma \otimes T$$

Kang, Ma, Qiu, Sterman `14

nPDFs *Eskola, Paakkinen, Paukkunen, Salgado `17, Kovarik et al. `16*
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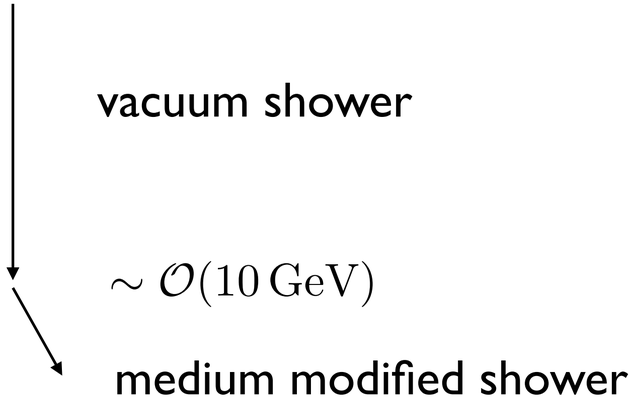
- A modification of the evolution?
- Comparison to medium parton shower



- LBT *Li, Liu, Ma, Wang, Zhu `11*
- MATTER *Majumder `13, Kordell, Majumder `17*

see also Hybrid, JEWEL, Martini, Q-Pythia, JETSCAPE …

Factorization for jets in heavy-ion collisions

Qiu, FR, Sato, Zurita `19

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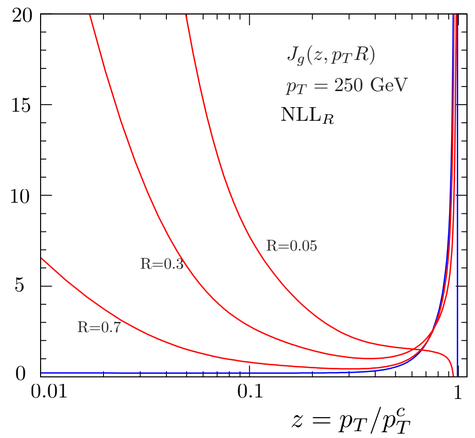
NNPDF `17, JAM `16

- A modification of the evolution?
- Comparison to medium parton shower

vacuum shower

$p_T R$

Fit to data



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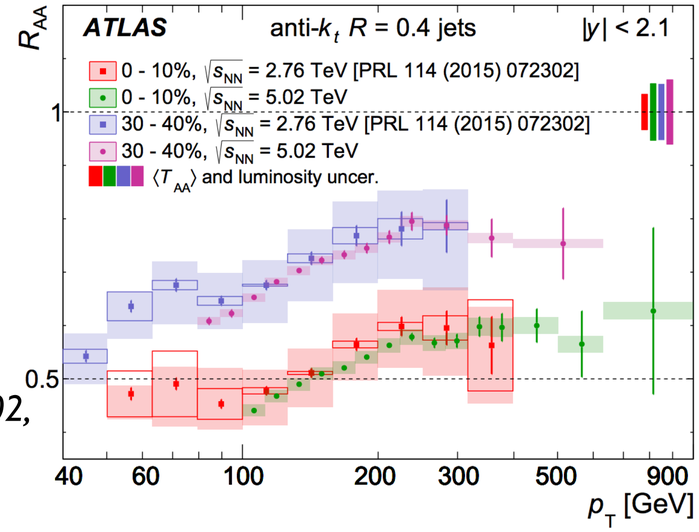
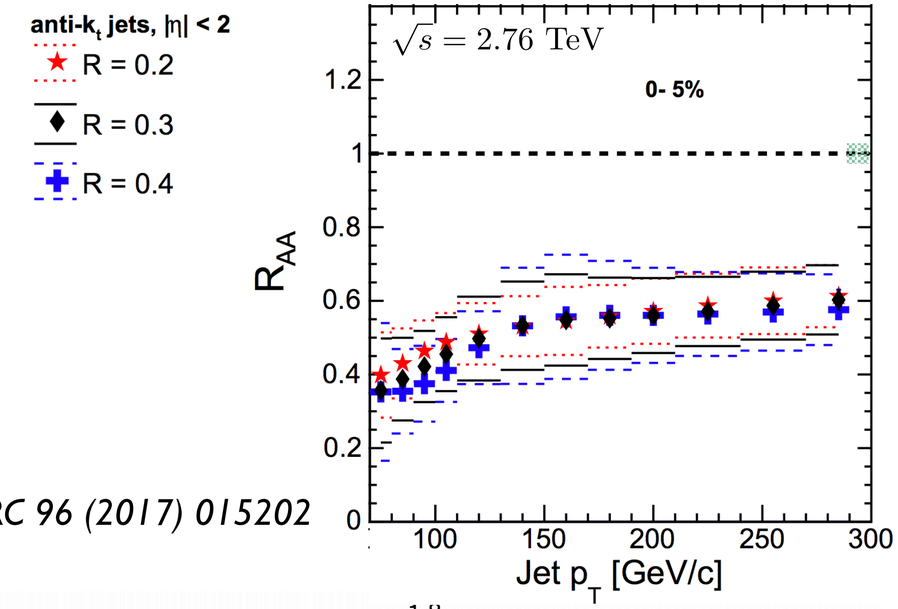
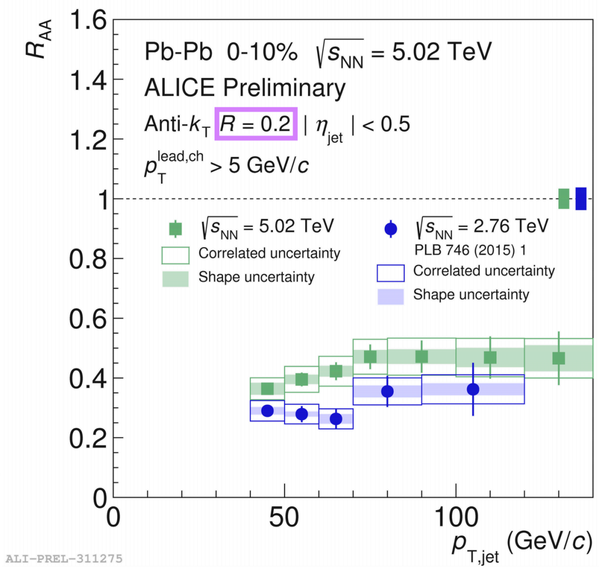
Inclusive jet data included in the analysis



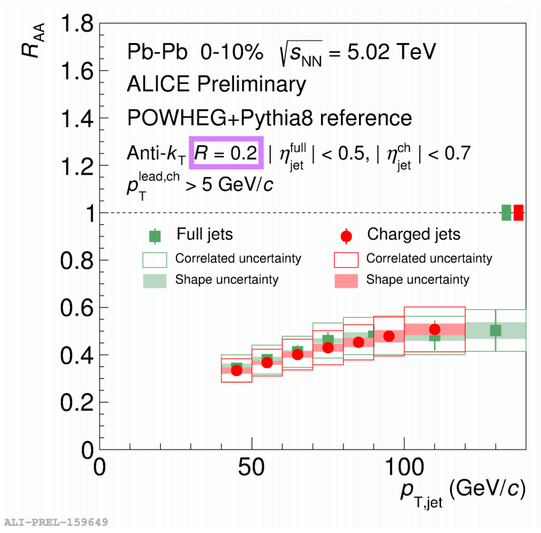
ATLAS, PRL 114 (2015) 072302, PLB 790 (2019) 108

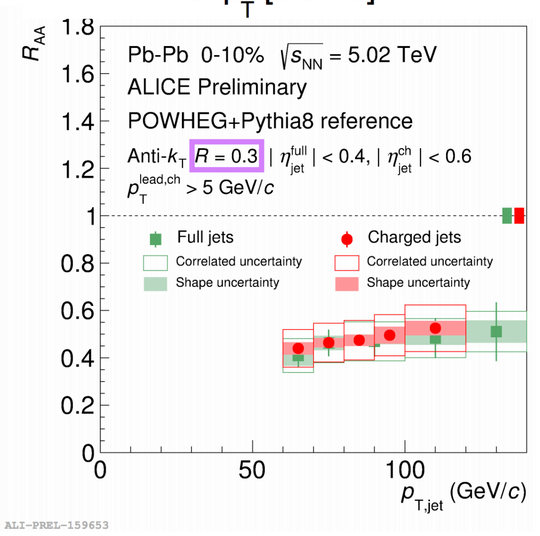


CMS, PRC 96 (2017) 015202



ALICE, PLB 746 (2015)





ALICE preliminary, J. Mulligan, HardProbes18

Inclusive jet production PbPb at the LHC

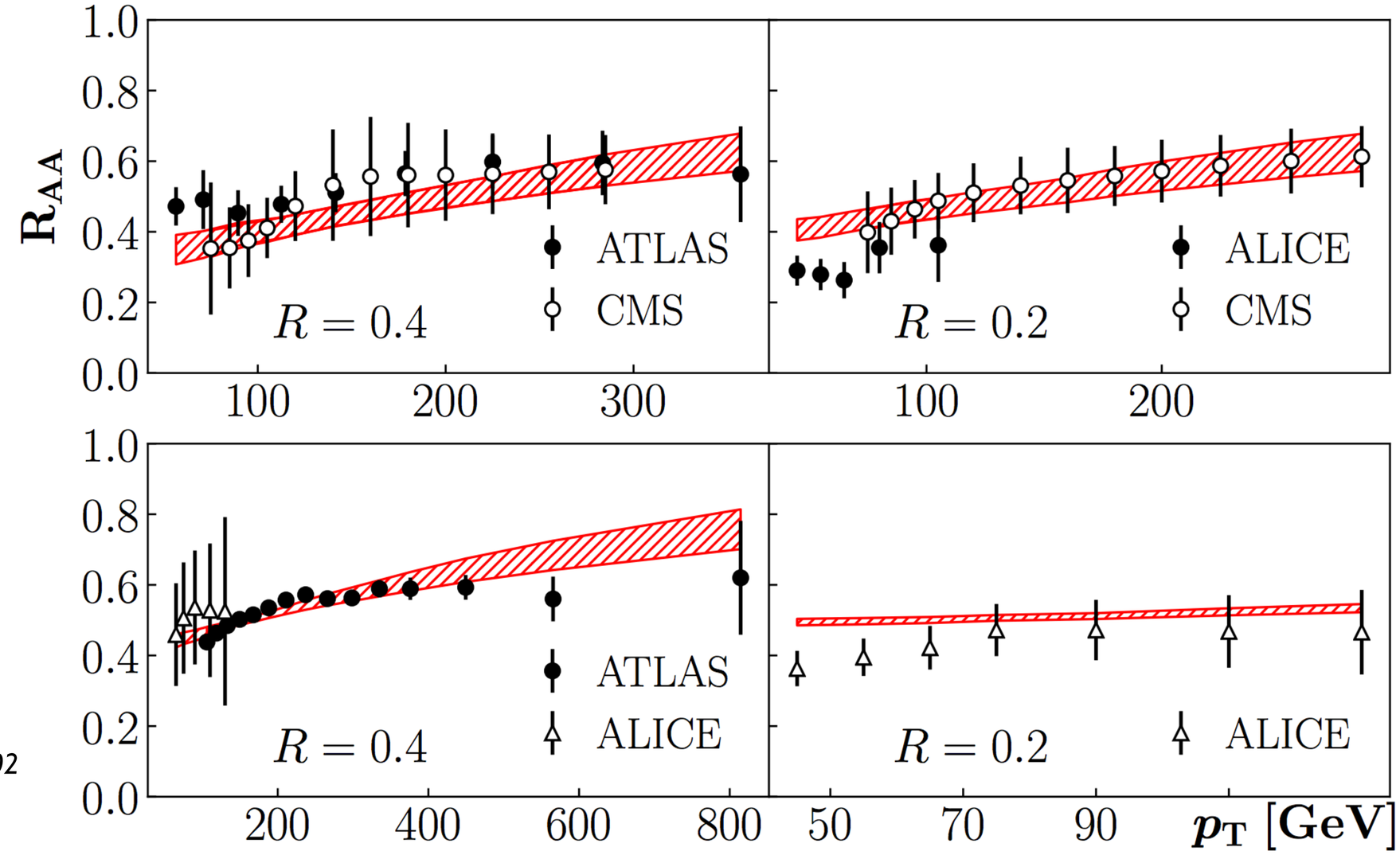
Qiu, FR, Sato, Zurita `19

$\sqrt{s_{\rm NN}} = 2.76$ TeV

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

$\sqrt{s_{\rm NN}} = 5.02$ TeV

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



ALICE, PLB 746 (2015) 1
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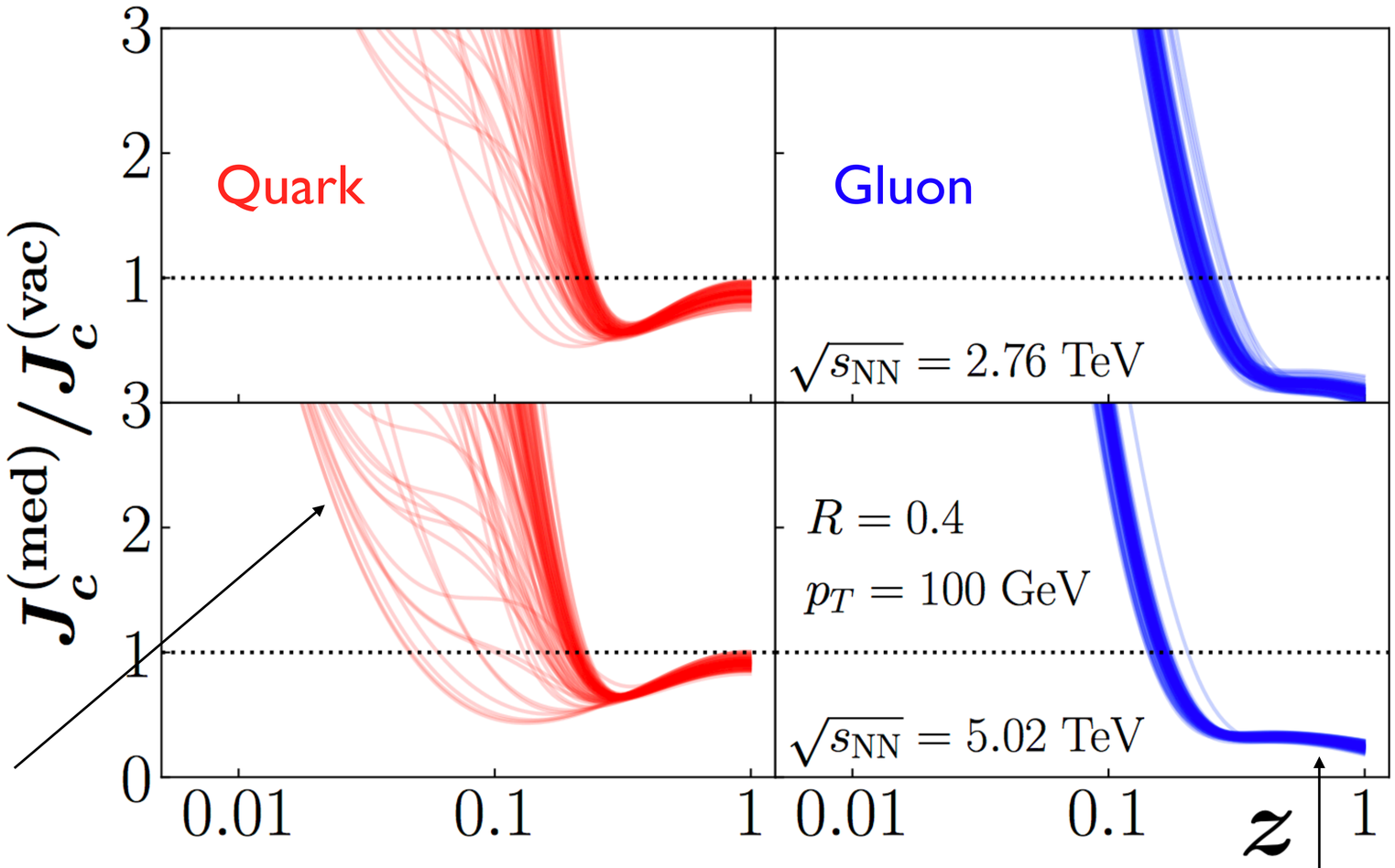
ATLAS, PLB 790 (2019) 108

No initial state effects or nPDFs

The extracted medium jet functions

Qiu, FR, Sato, Zurita `19

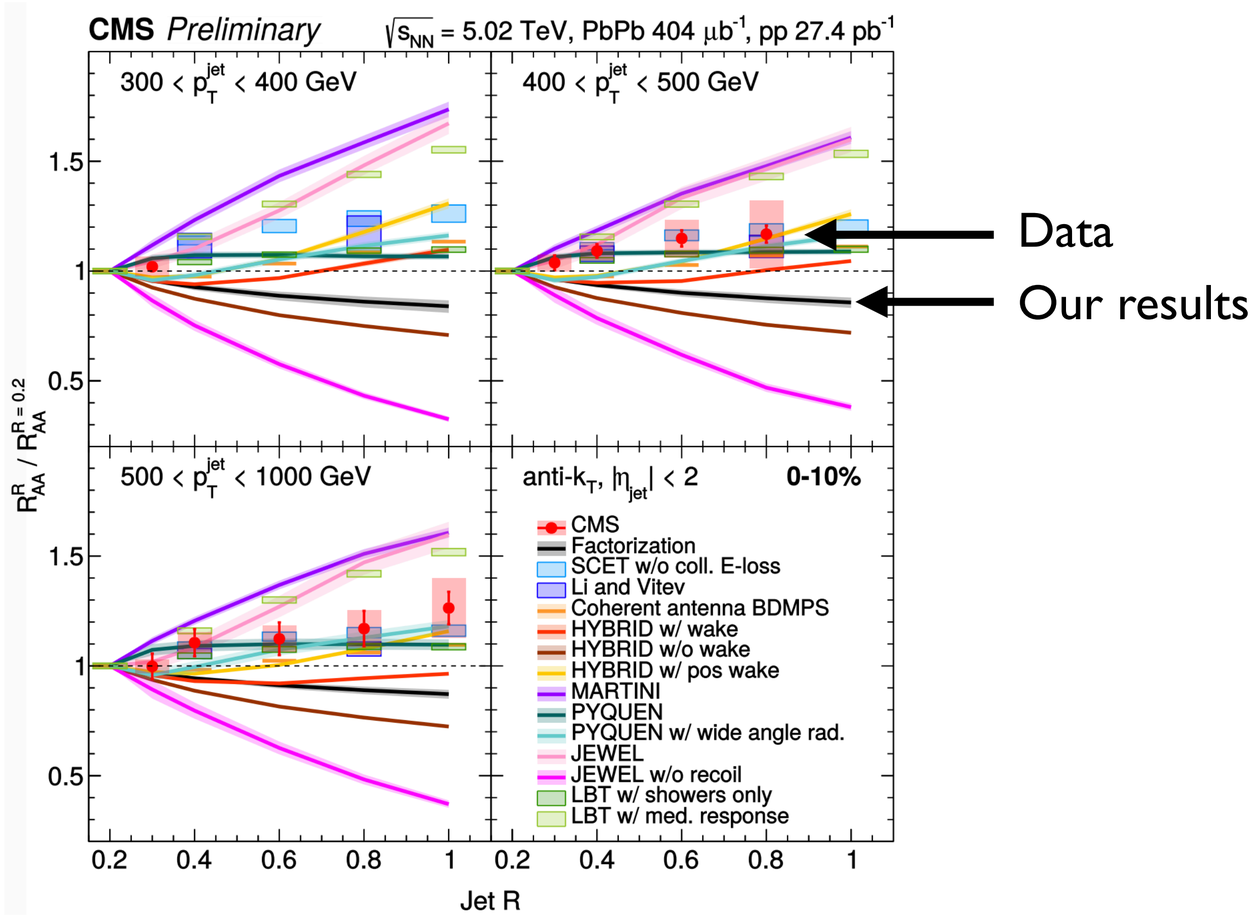


Small-z region less constrained

Significant suppression of gluons

Comparison to QM19 results from ATLAS and CMS

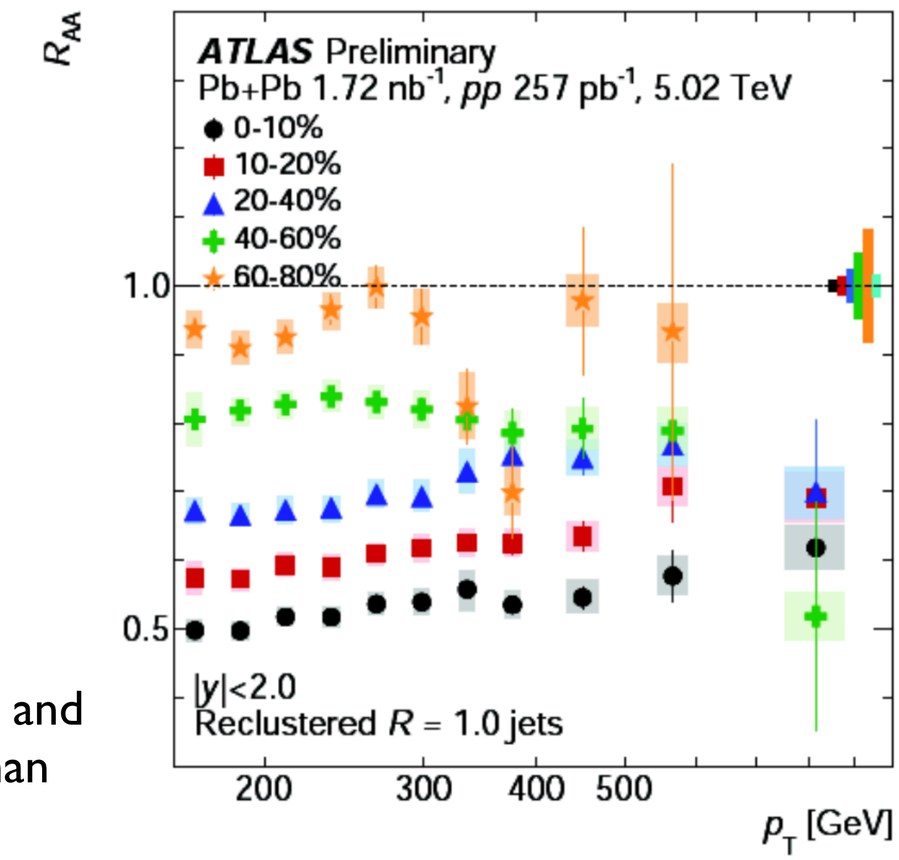
See E. Chapon's talk



Data

Our results

See M. Spousta's talk

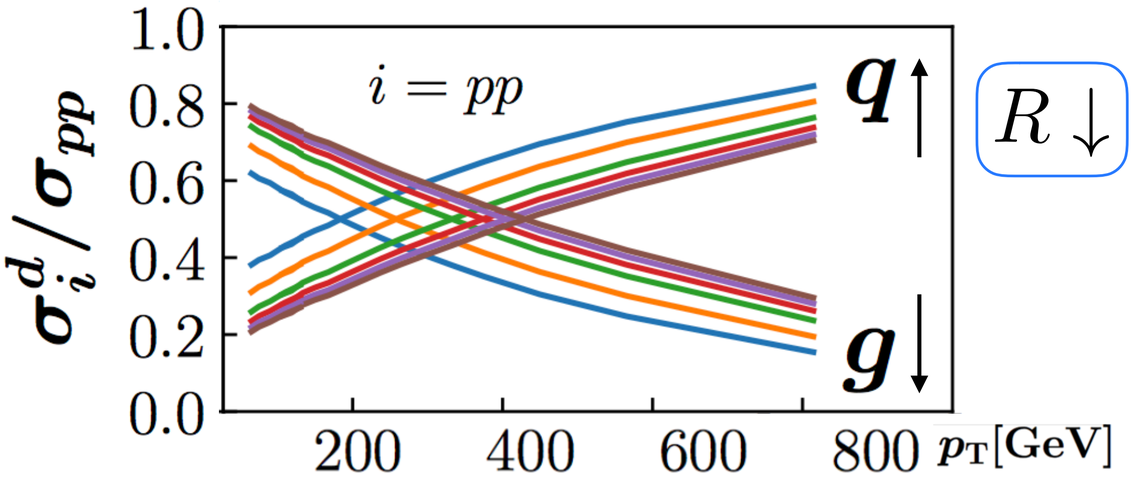


Similar trend and magnitude than R=0.4 jets

Quark/gluon fractions and the jet radius dependence

- Definition of quark/gluon fractions at leading power
- Direct relation to the jet radius dependence

Qiu, FR, Sato, Zurita `19



Quark/gluon fractions and the jet radius dependence

Qiu, FR, Sato, Zurita `19

- Definition of quark/gluon fractions at leading power
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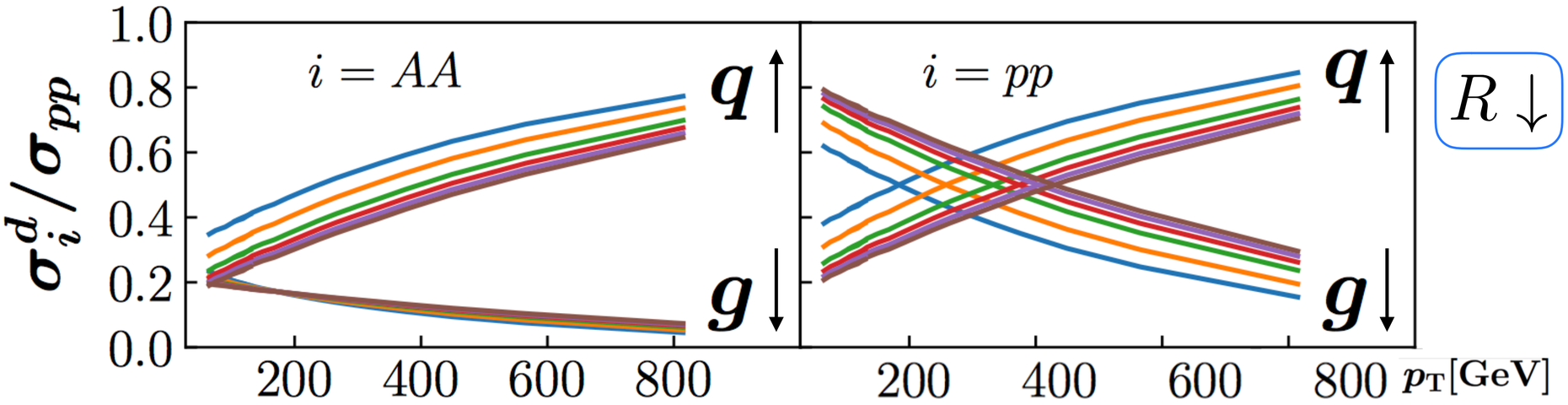

$R = 0.1$ $R = 0.8$
$R = 0.2$ $R = 1.0$
$R = 0.4$ ATLAS
$R = 0.6$ ALICE

$\sqrt{s} = 5.02$ TeV

Quark/gluon fractions and the jet radius dependence

Qiu, FR, Sato, Zurita `19

- Definition of quark/gluon fractions at leading power
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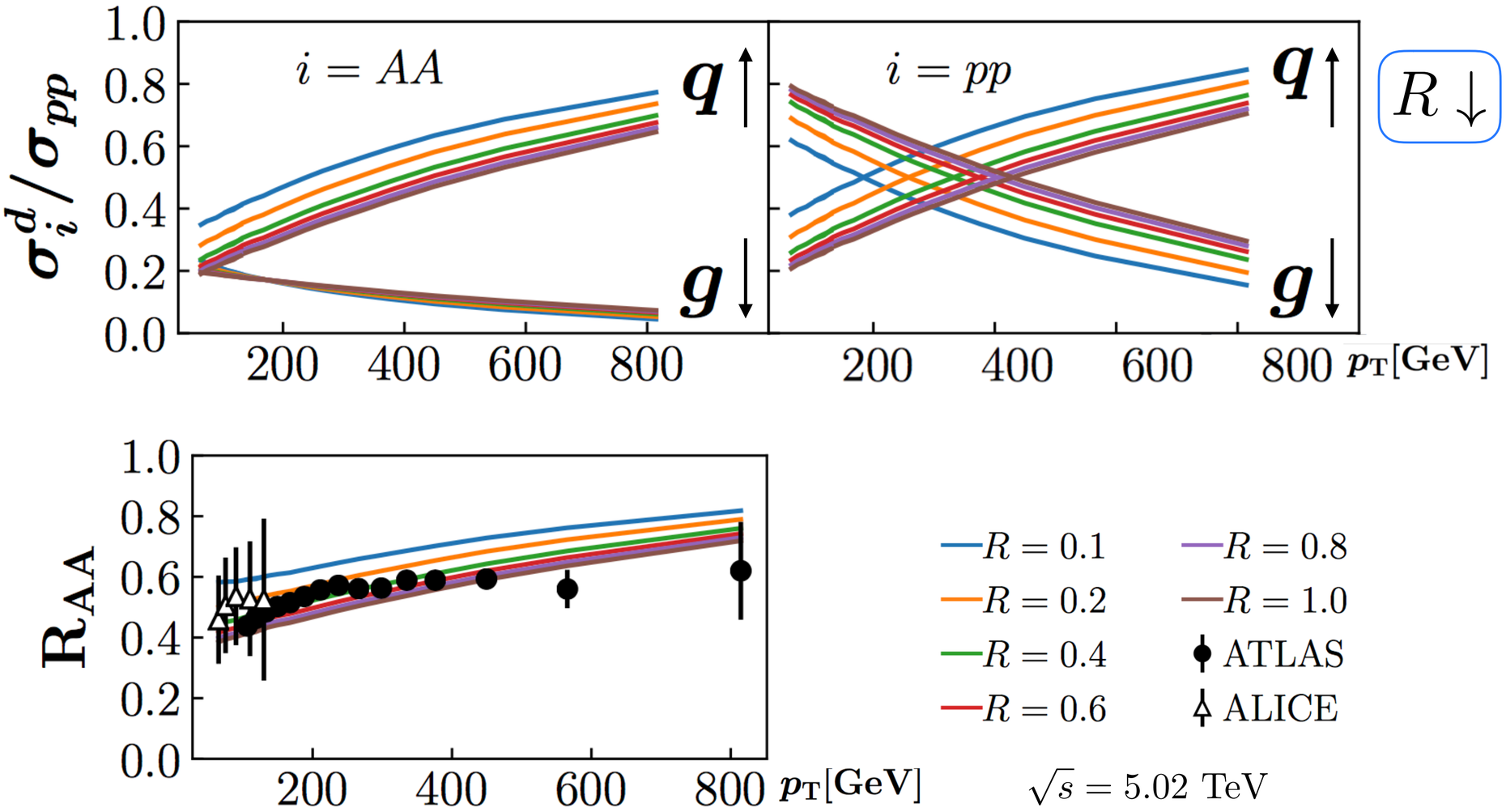
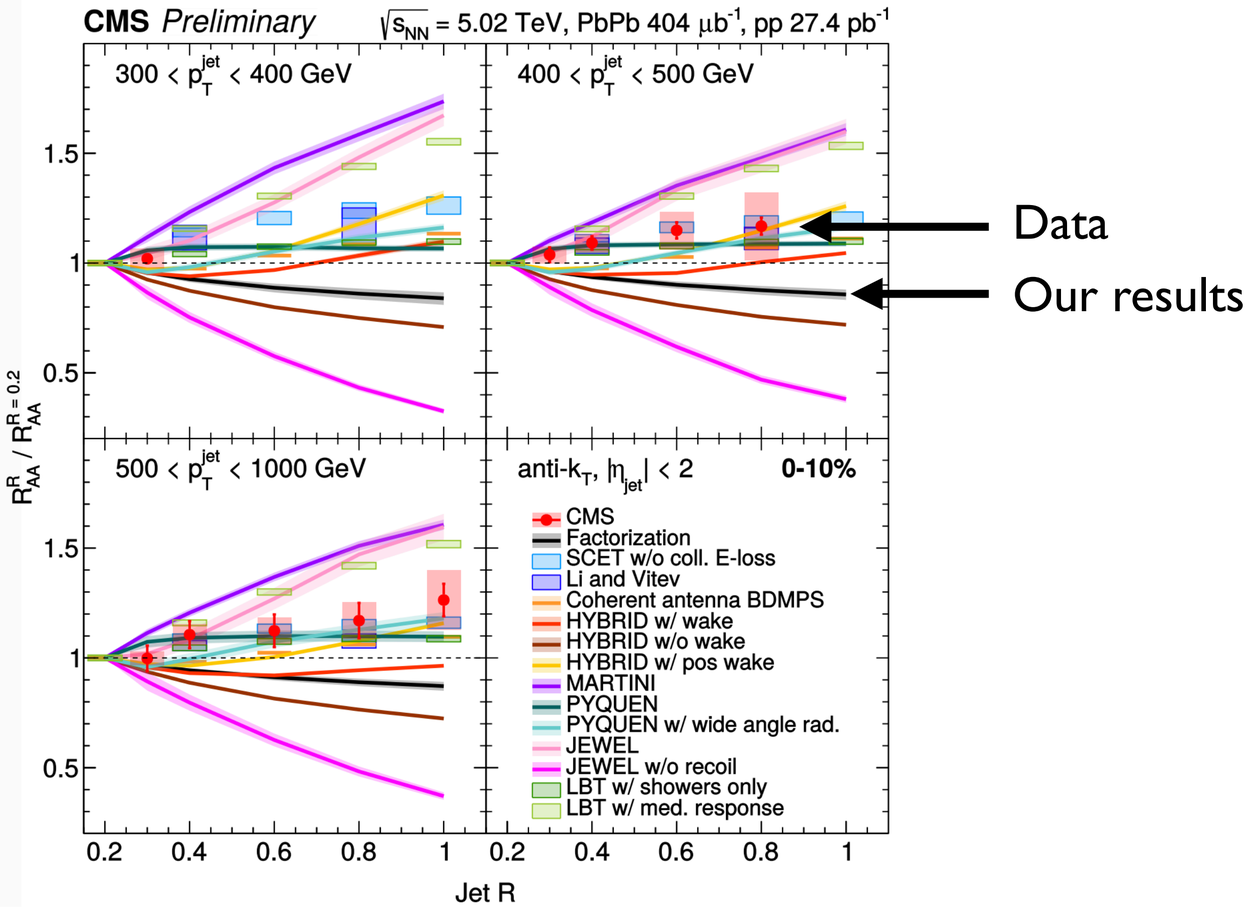


Comparison to QM19 results from ATLAS and CMS

See E. Chapon's talk



Data

Our results

Possible explanations

- Refit?
- Different weight functions?
- Allow for a modified evolution?
- No factorization and universality?
- …

Outline

- Introduction
- QCD factorization and universality
- Inclusive jets in heavy-ion collisions
- Conclusions

Conclusions

- A new framework to explore factorization and universality in heavy-ion collisions
- Minimal theory assumptions
- First global analysis of in-medium jet functions

- Test of universality
- Extracted quark/gluon fractions relevant for jet substructure

- Understand the medium modified parton shower
- Provide guidance for constructing microscopic models