Factorization of jet cross sections in heavy-ion collisions

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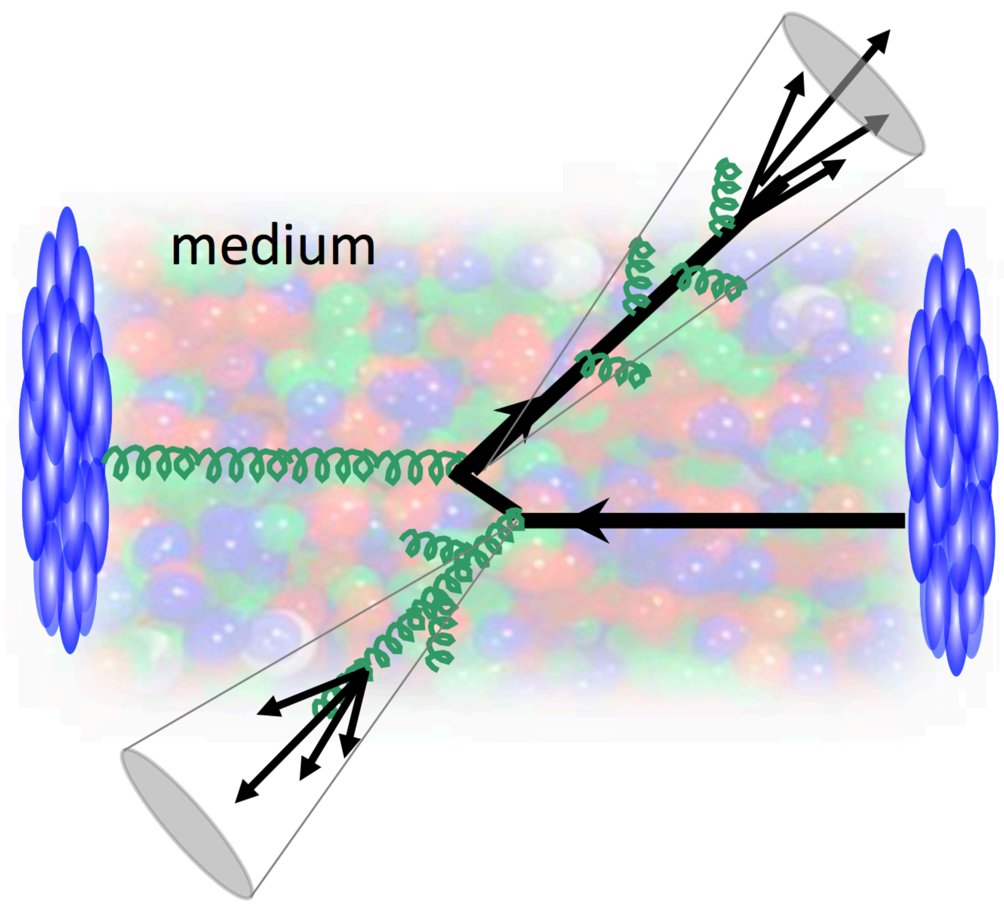
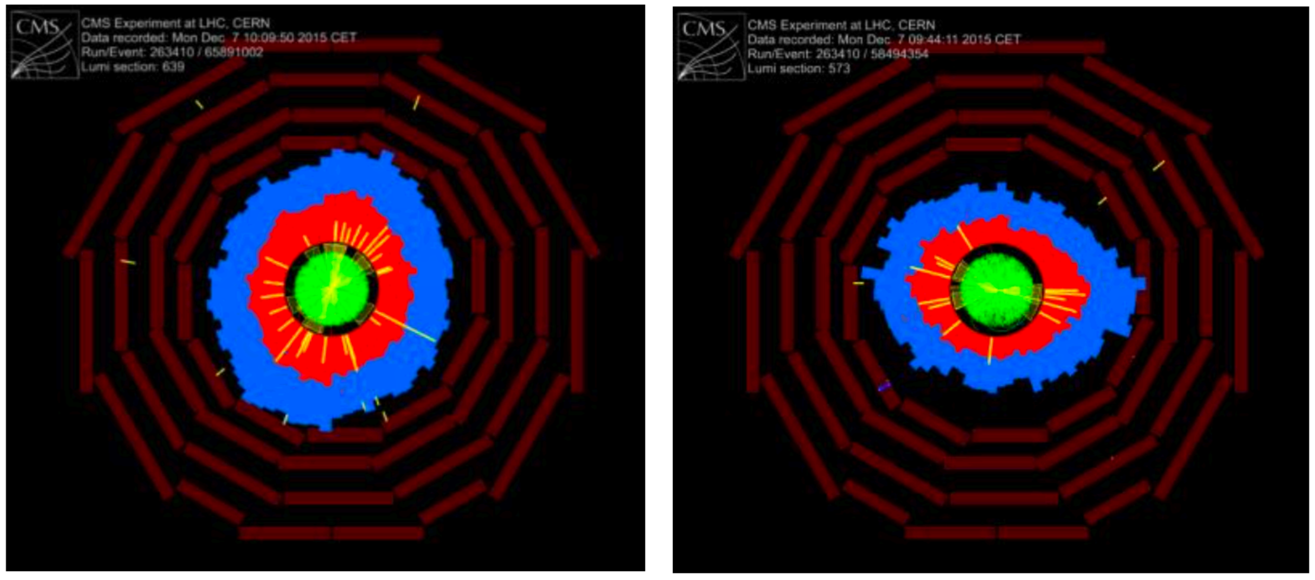
SCET 19 - UCSD, 03/28/19

BERKELEY LAB

Hard and soft probes in heavy-ion collisions





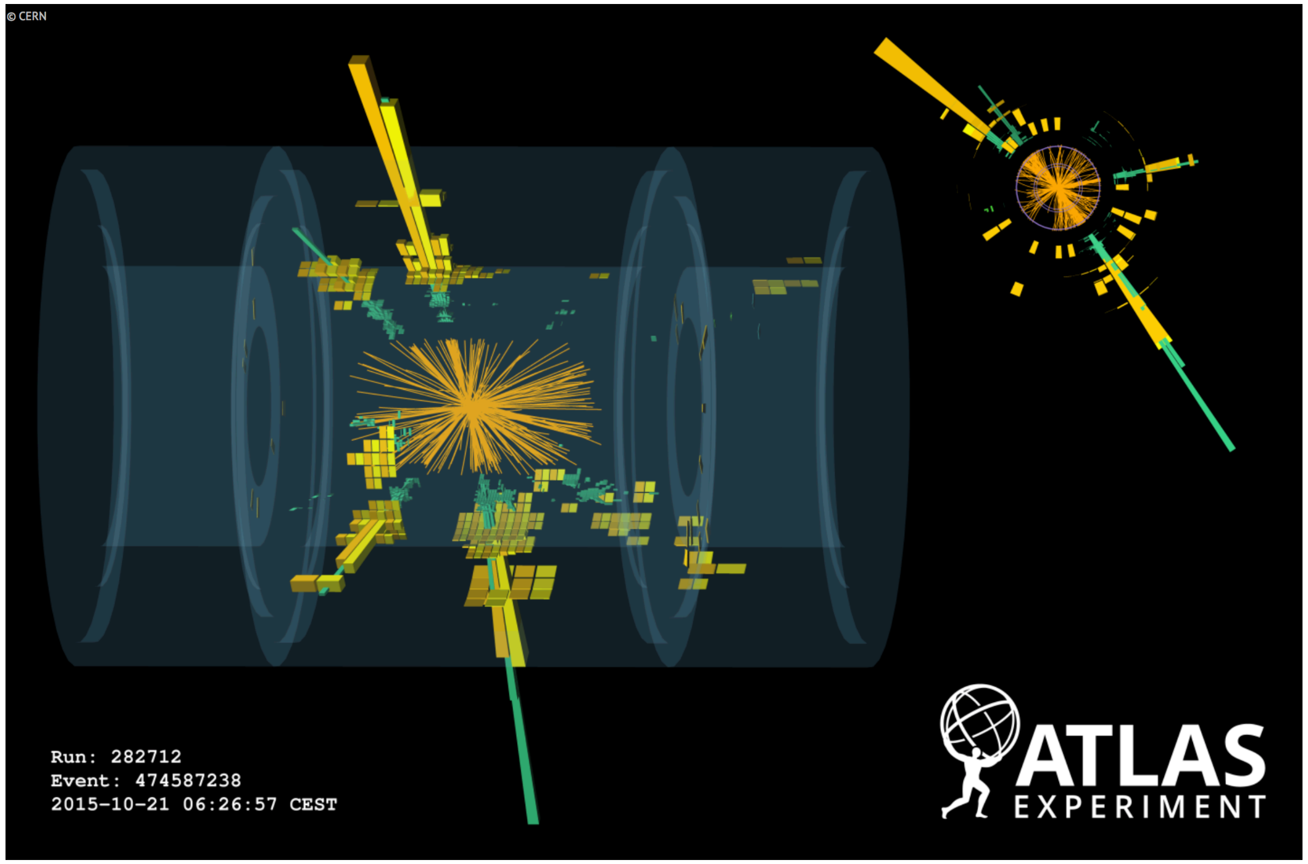
- Highly energetic particles and jets
- QCD factorization and universality?

- Charged particle counting
- Elliptic flow/collectivity

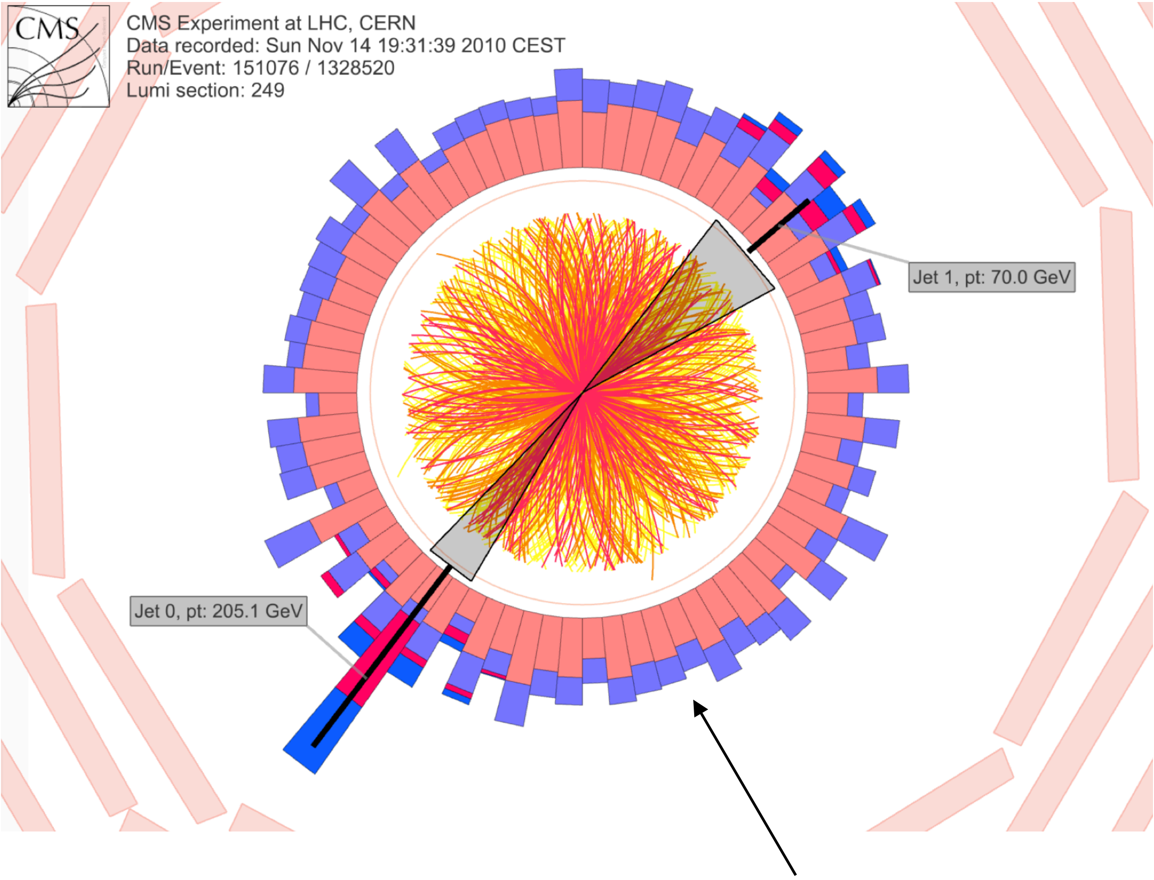
→ Extract properties of the medium

Jets in heavy-ion collisions

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



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



Subtract background

Inclusive jet cross section

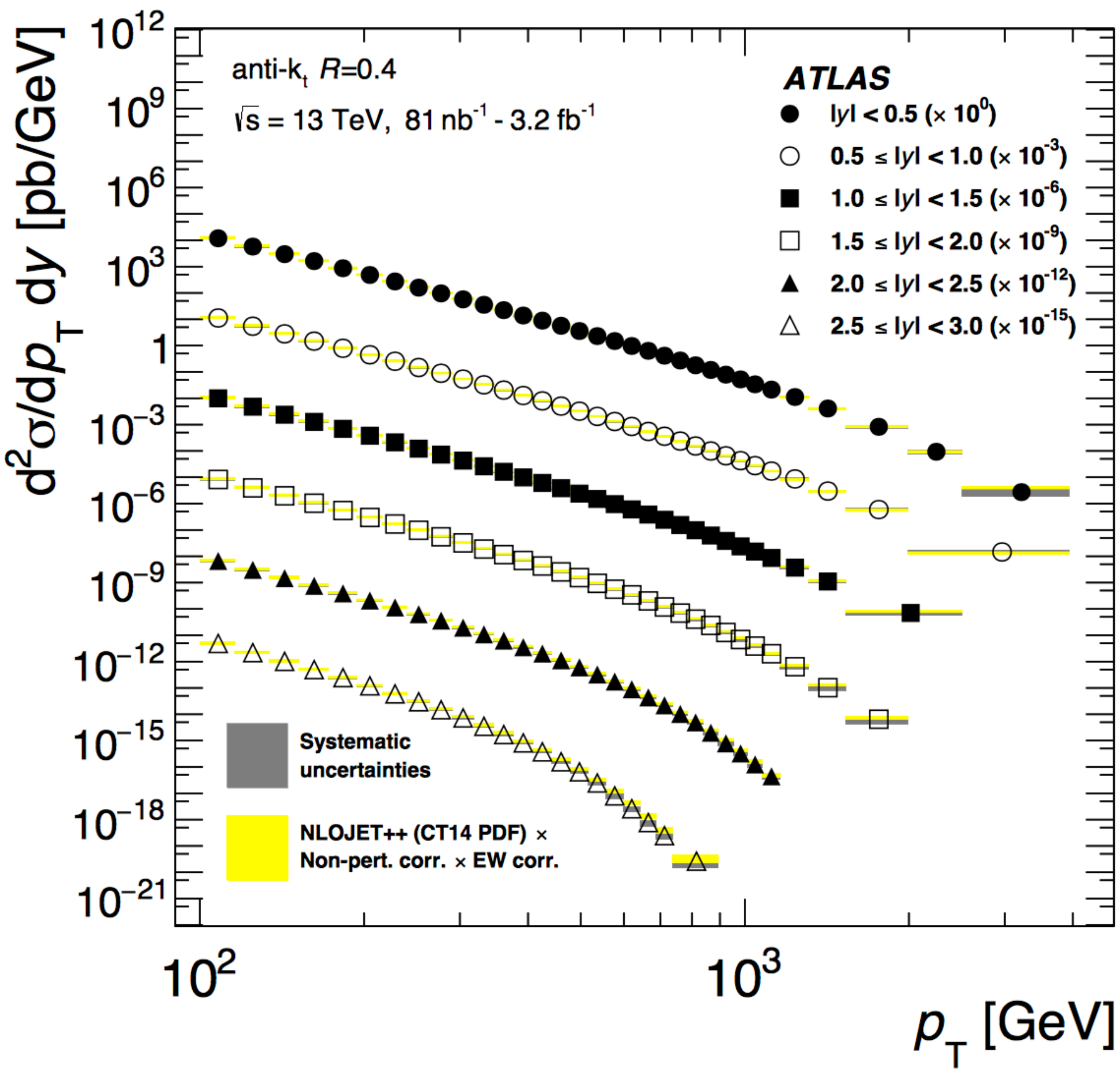
$$\frac{d\sigma^{pp\to \text{jet}+X}}{dp_T d\eta}$$

Nuclear modification factor

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

Inclusive jet production at the LHC

- Proton-proton



- Fixed order - NNLO

  Currie, Glover, Pires `16

- All order resummation

  Threshold and jet radius

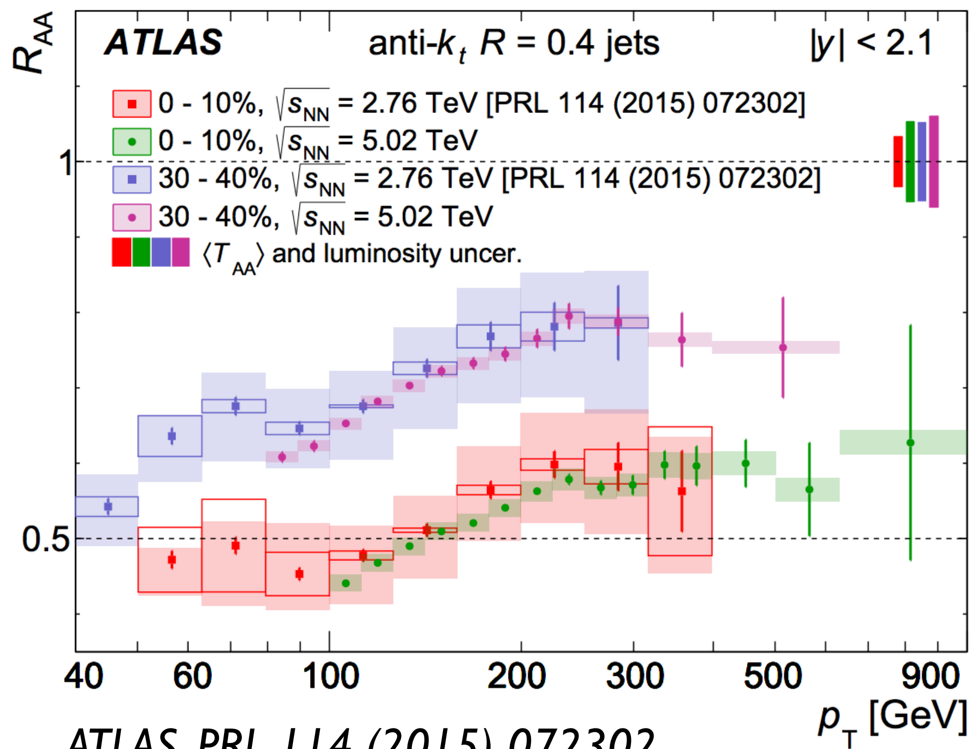
  Dasgupta, Dreyer, Salam, Soyez `14
  Liu, Moch, FR `17

→ Precision physics

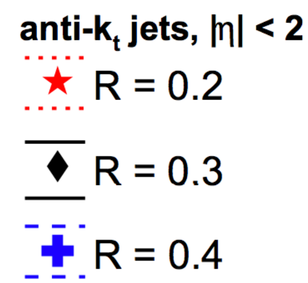
see talk by Bernhard Mistlberger

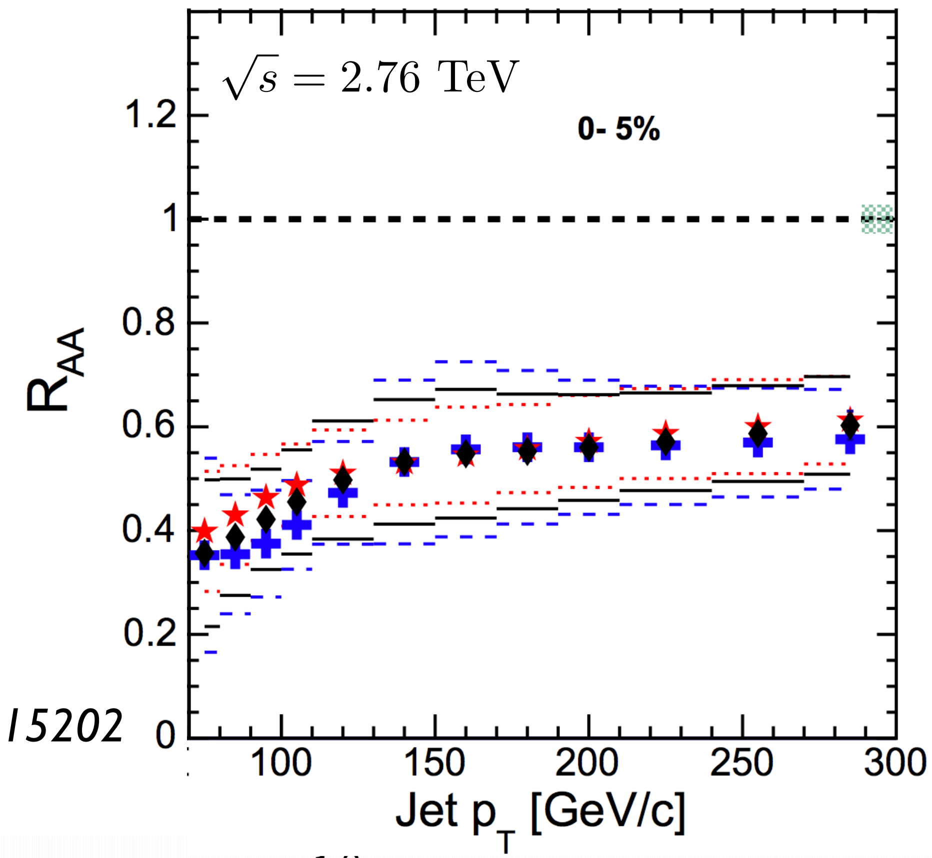
ATLAS, JHEP 1805 (2018) 195

Inclusive jet production at the LHC

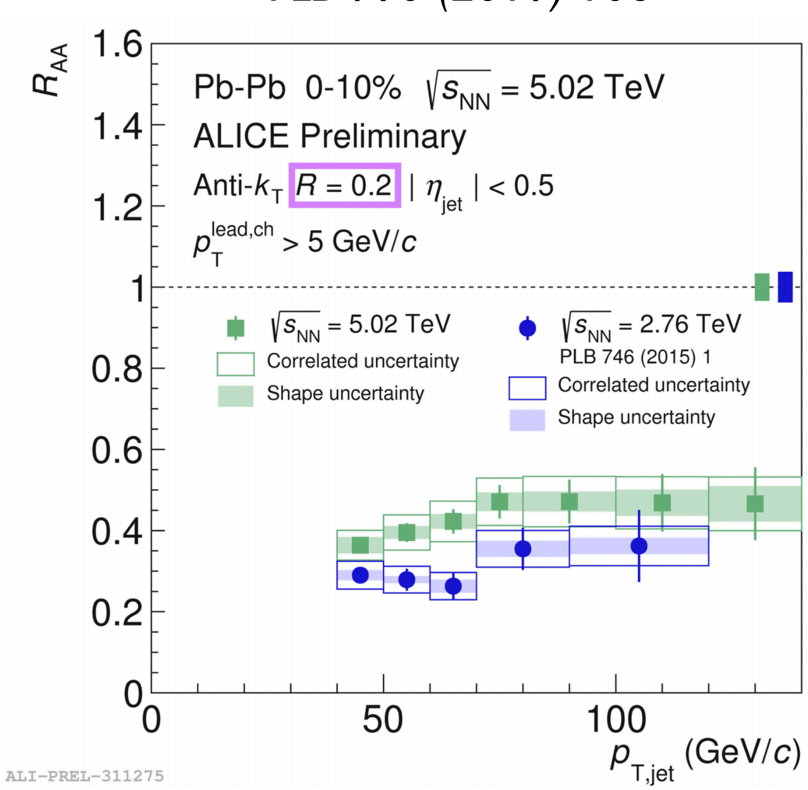


ATLAS, PRL 114 (2015) 072302, PLB 790 (2019) 108

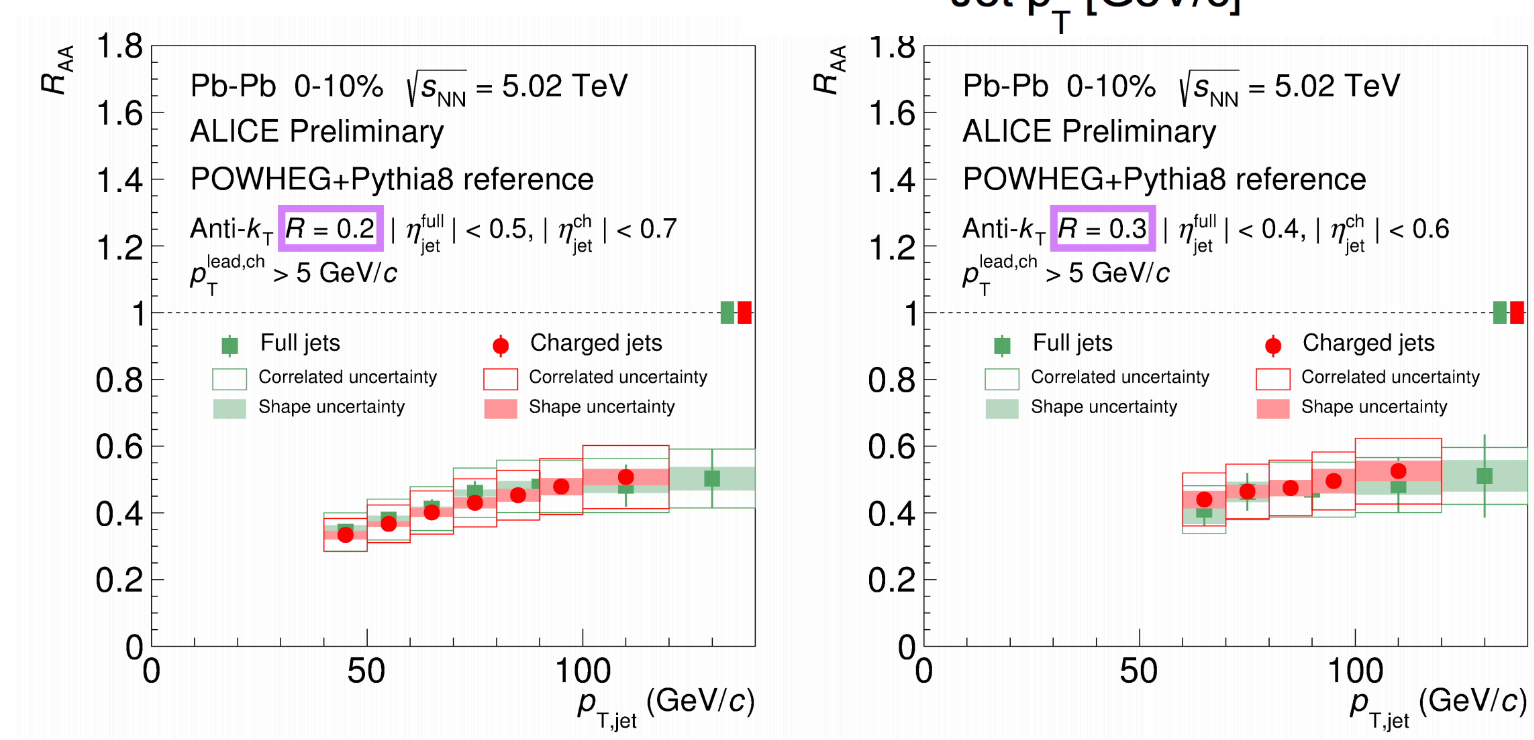




CMS, PRC 96 (2017) 015202

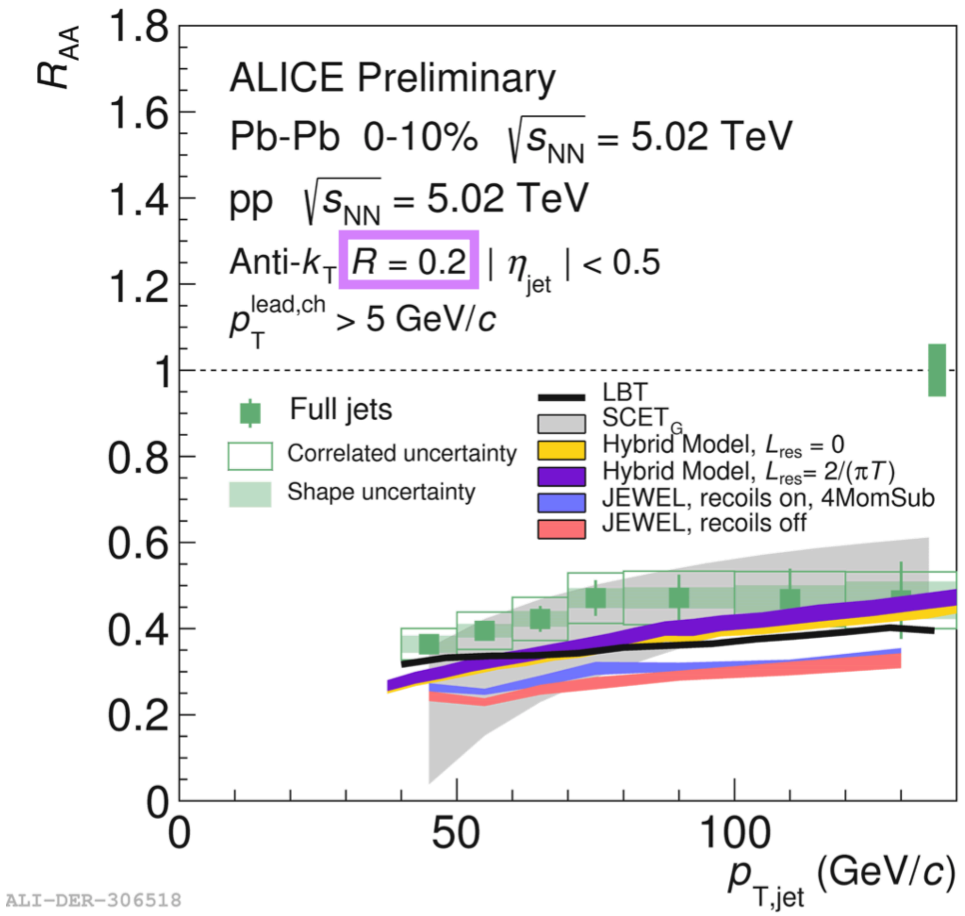


ALICE, PLB 746 (2015) 1

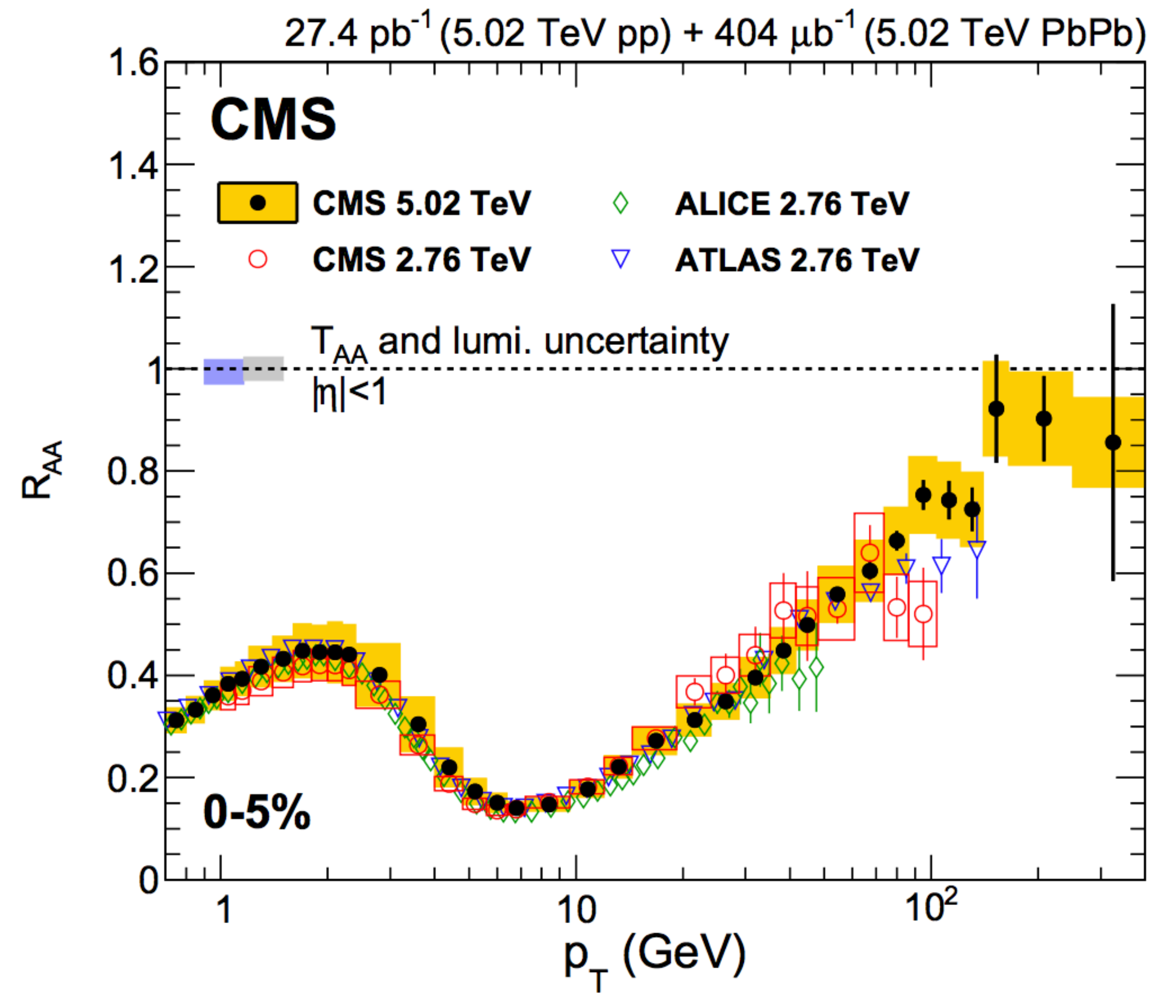


ALICE preliminary, J. Mulligan, HardProbes18

Inclusive jet production at the LHC



ALICE preliminary, J. Mulligan, HardProbes18



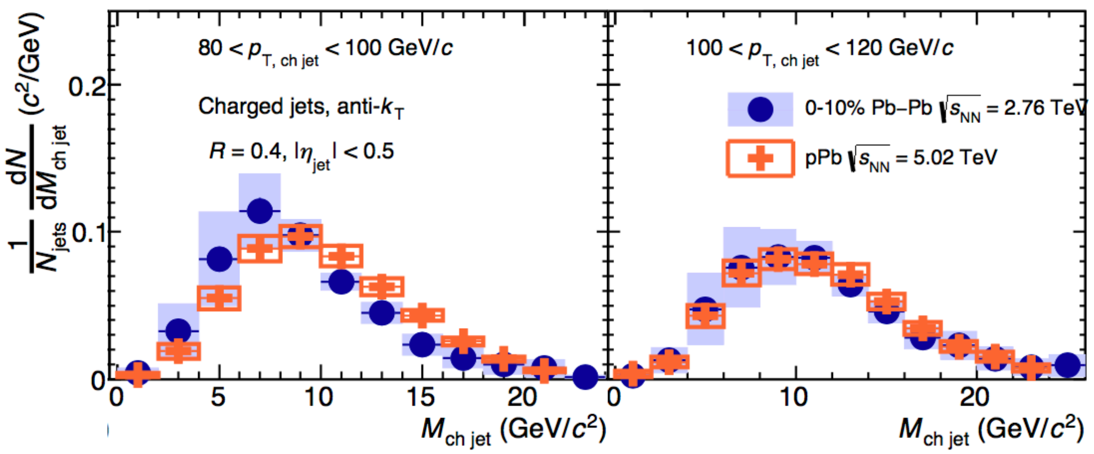
Hadron R_{AA}

This talk …

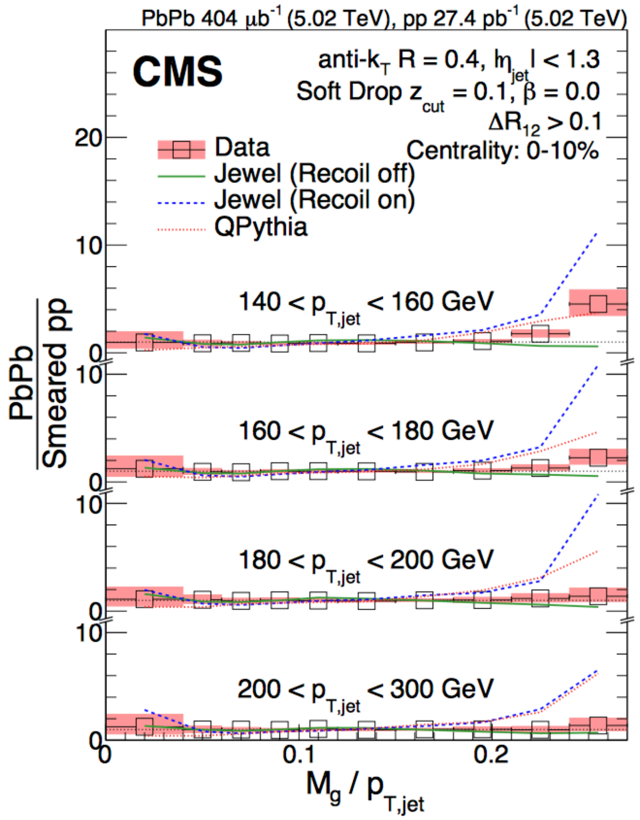
- Phenomenological approach
- Minimal theory input/approximations
- QCD factorization?
- Universality?

Jet substructure

Jet mass



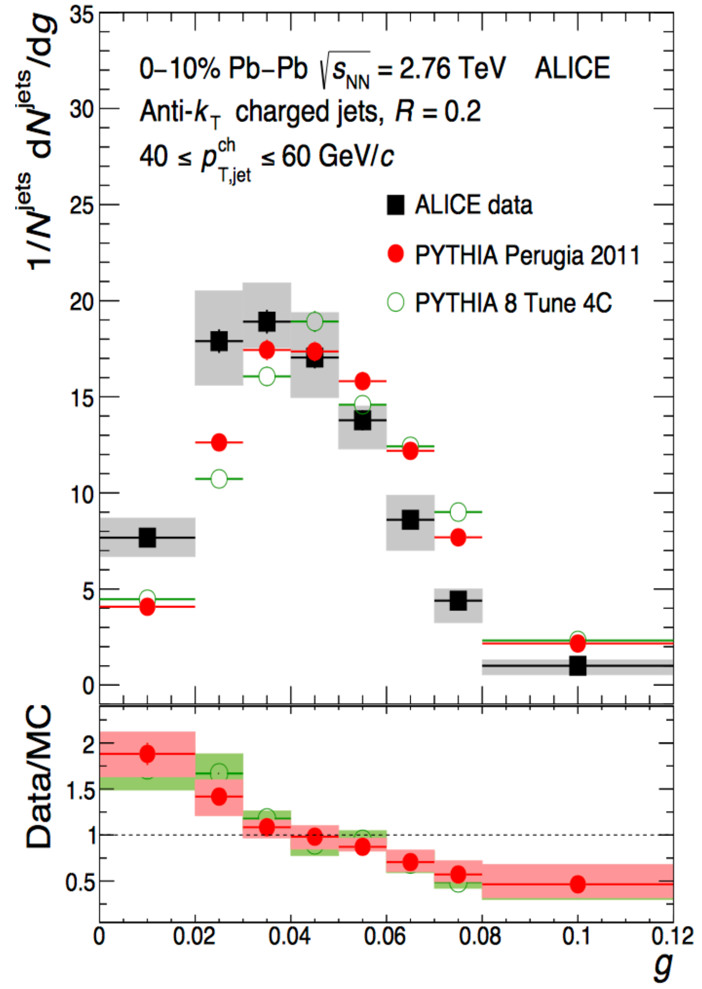
ALICE, PLB 776 (2018) 249



CMS, arXiv 1805.05145

Jet broadening, …

$$g = \frac{1}{p_T} \sum_{i \in J} p_{Ti} \Delta R_{iJ}$$



ALICE, arXiv 1807.06854

→ *see Yang-Ting Chien's talk*

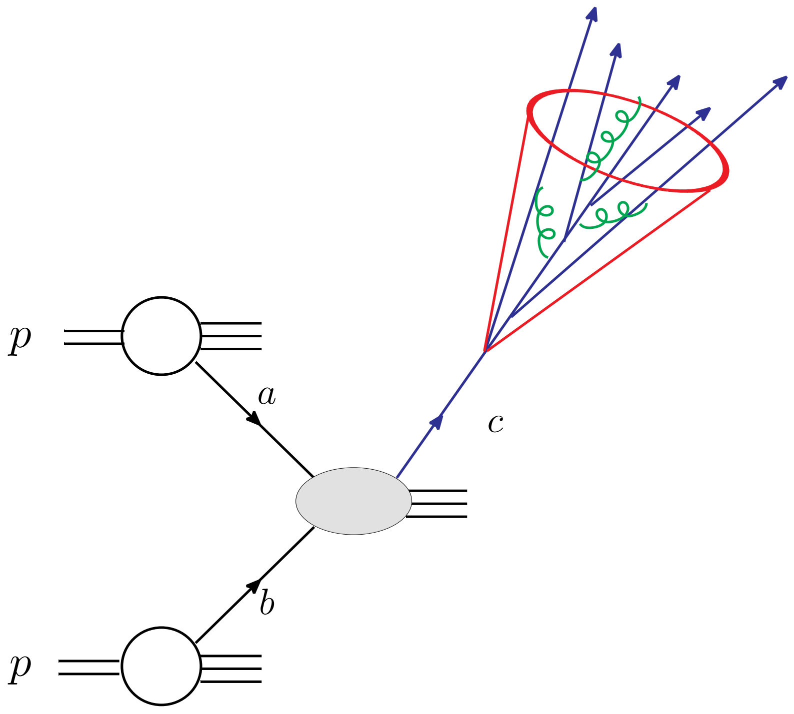
Outline

- Introduction
- Inclusive jet production
- Phenomenological results
- Conclusions

QCD factorization

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

$$\frac{d\sigma^{pp\to\text{jet}+X}}{dp_T d\eta} = \sum_{ab} f_{a/p} \otimes f_{b/p} \otimes \mathcal{H}_{ab}^{\text{jet}}$$ ⟵ Perturbatively calculable



Ellis, Kunszt, Soper `90
Currie, Glover, Pires `16

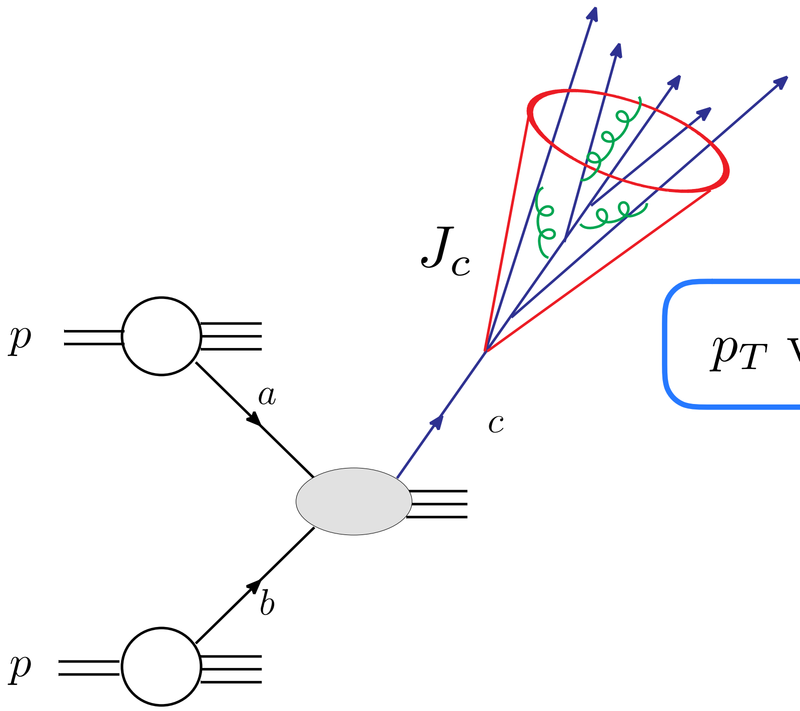
QCD factorization

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

$$\frac{d\sigma^{pp\to\text{jet}+X}}{dp_T d\eta} = \sum_{ab} f_{a/p} \otimes f_{b/p} \otimes \mathcal{H}_{ab}^{\text{jet}}$$

$$= \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c + \mathcal{O}(R^2)$$

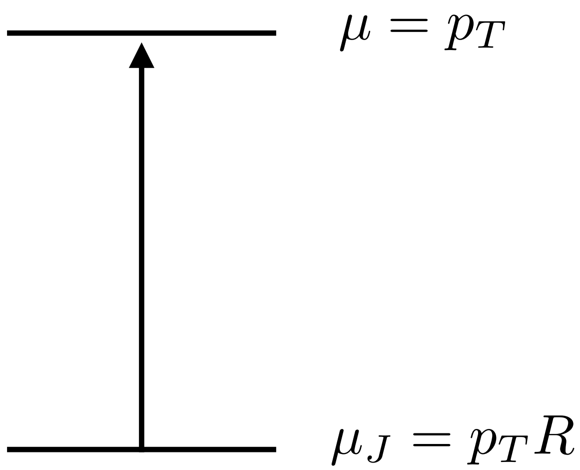
Perturbatively calculable



p_T vs. $p_T R$

- DGLAP

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

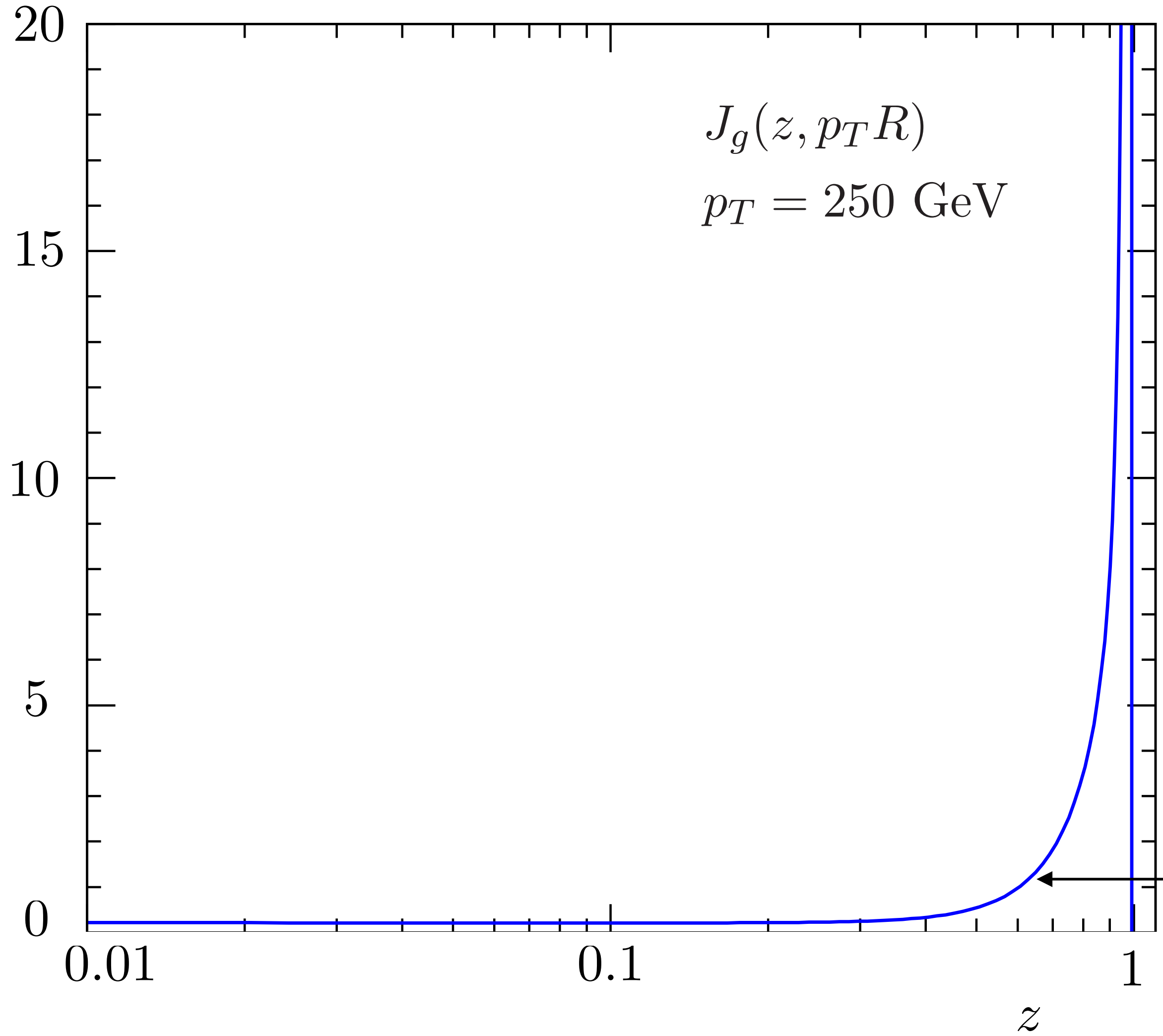


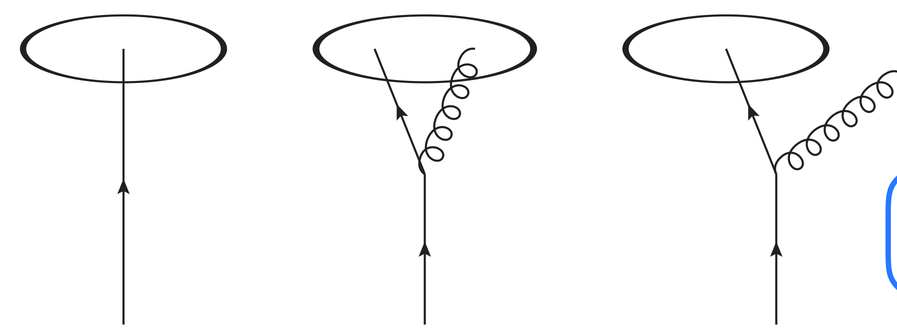
- Separation of scales
- Resummation of $\alpha_s^n \ln^n R$

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

Jet functions in the vacuum

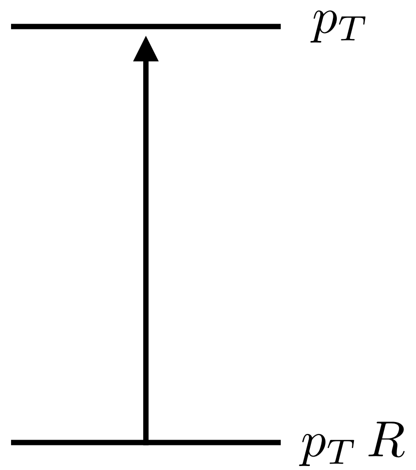
Kang, FR, Vitev `16





$$z = p_T / p_T^c$$

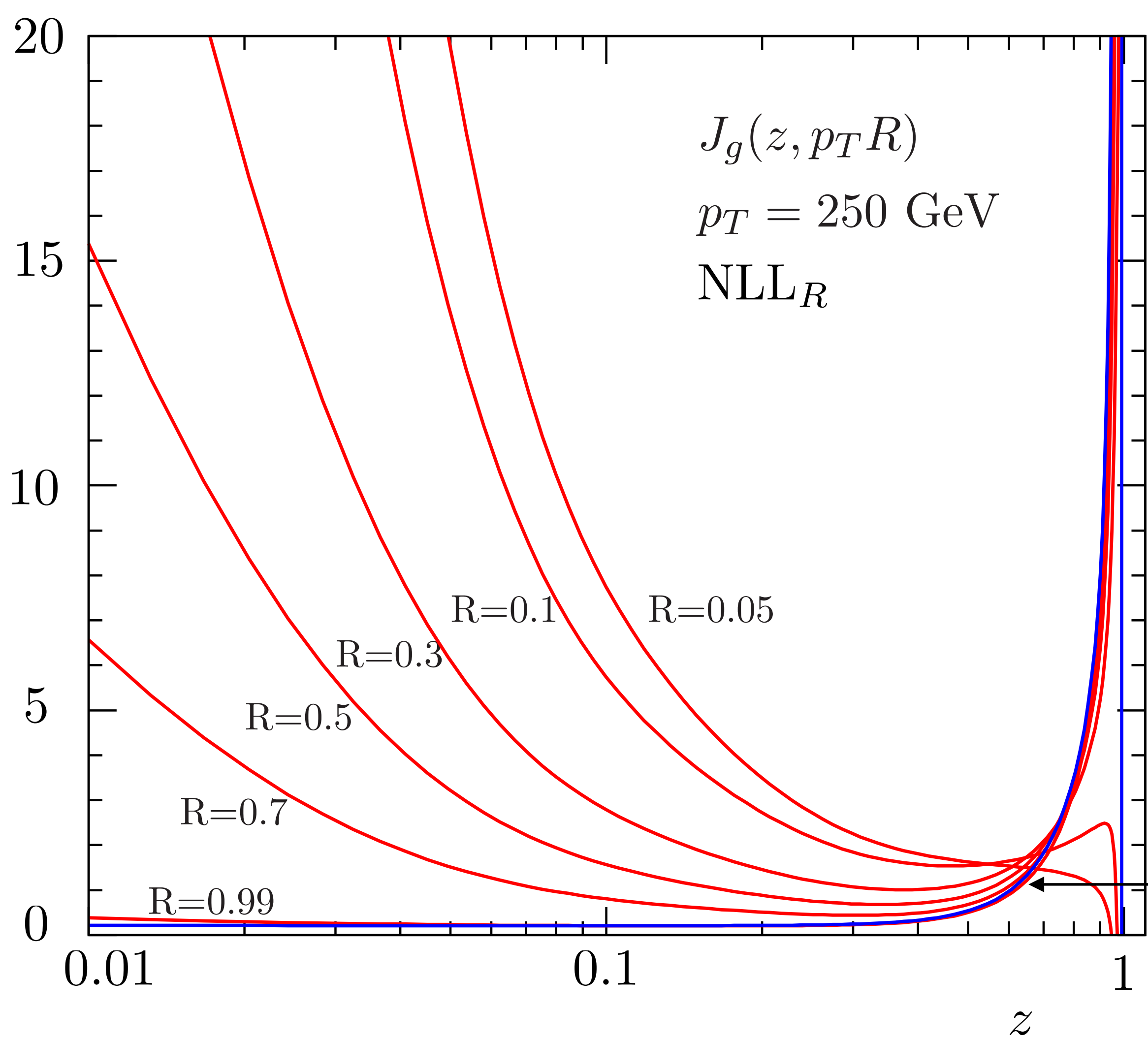
initial condition
for the evolution



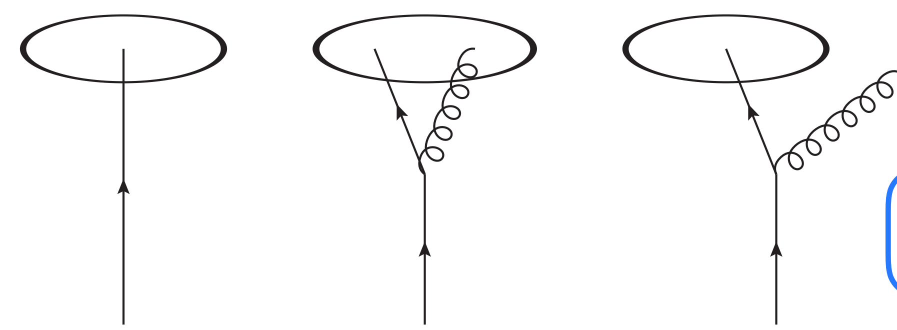
$$
\begin{aligned}
J_q(z, p_T R, \mu) = \delta(1-z) &+ \frac{\alpha_s}{2\pi}\left(\frac{1}{\epsilon} + \ln\left(\frac{\mu^2}{p_T^2 R^2}\right)\right)\left[P_{qq}(z) + P_{gq}(z)\right] \\
&- \frac{\alpha_s}{2\pi}\Bigg\{C_F\left[2\left(1+z^2\right)\left(\frac{\ln(1-z)}{1-z}\right)_+ + (1-z)\right] - \delta(1-z)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

Jet functions in the vacuum

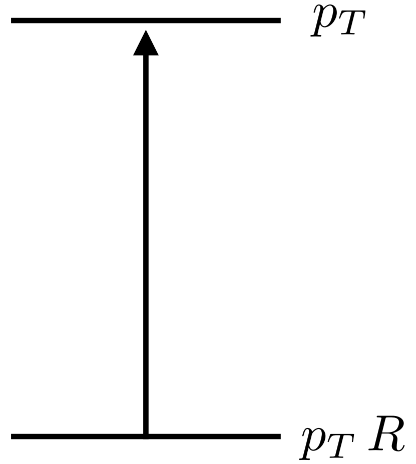
Kang, FR, Vitev `16



initial condition for the evolution



$z = p_T/p_T^c$



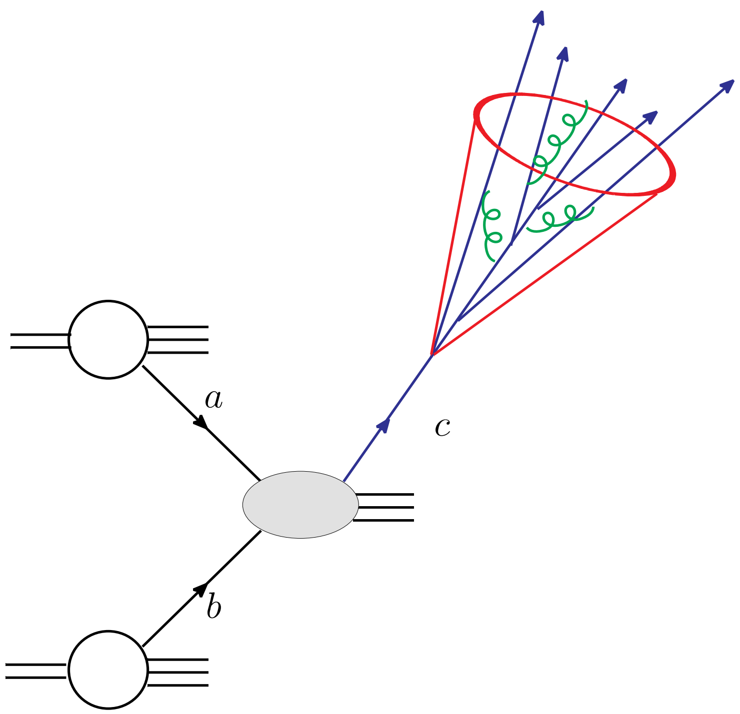
$$J_q(z, p_T R, \mu) = \delta(1-z) + \frac{\alpha_s}{2\pi}\left(\frac{1}{\epsilon} + \ln\left(\frac{\mu^2}{p_T^2 R^2}\right)\right)\left[P_{qq}(z) + P_{gq}(z)\right]$$

$$- \frac{\alpha_s}{2\pi}\left\{C_F\left[2\left(1+z^2\right)\left(\frac{\ln(1-z)}{1-z}\right)_+ + (1-z)\right] - \delta(1-z)d_J^{q,\mathrm{alg}}\right.$$

$$\left. + P_{gq}(z) 2\ln(1-z) + C_F z\right\}$$

QCD factorization

- Proton-proton
  - Proofs: Drell-Yan process *Collins, Soper, Sterman `85, Bodwin `85, see Iain Stewart's talk*
  - Partial proofs: $pp \to h + X$ *Nayak, Qiu, Sterman `05*
  - Phenomenologically established:
    Global analyses of PDFs gives a consistent picture!
    ABMP, CJ, CT, JAM, MMHT, NNPDF …



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

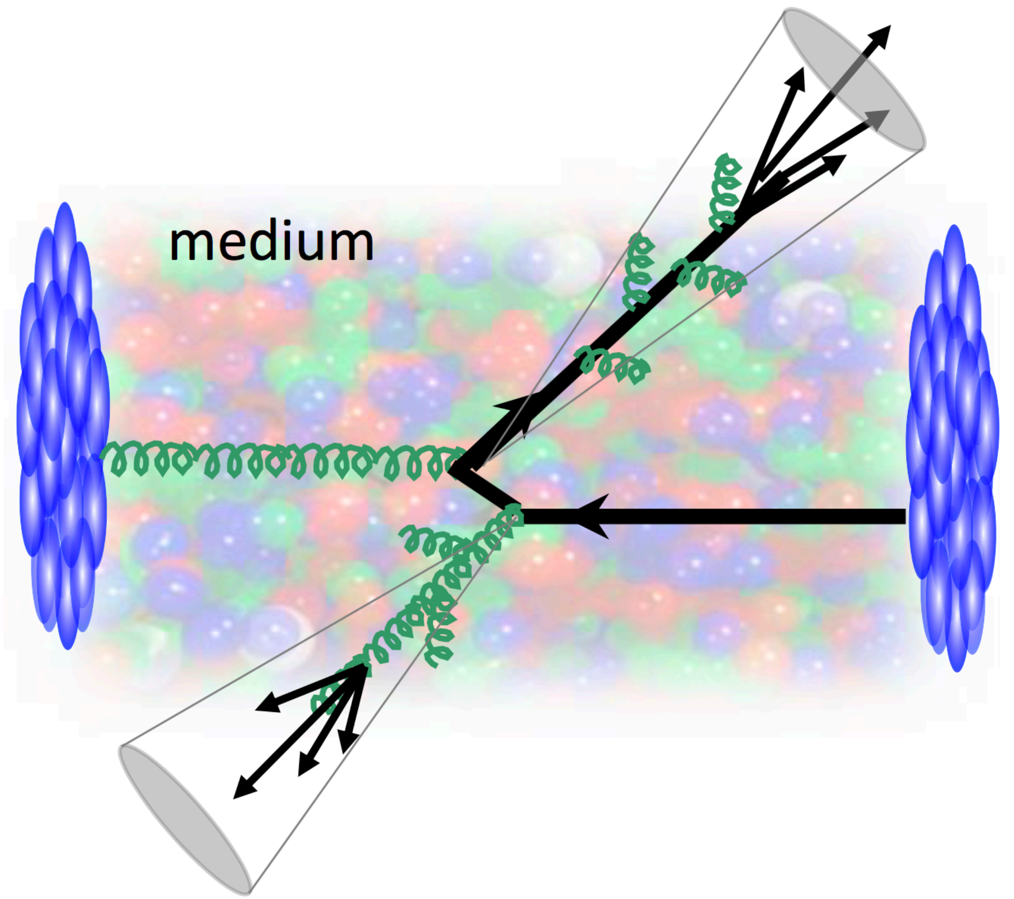
$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$

Gyulassy, Wang `94, Baier, Dokshitzer, Mueller, Peigne, Schiff `96, Zakharov `96, Gyulassy, Levai, Vitev `01, Wang, Guo `01, Arnold, Moore, Yaffe `02, Qiu, Vitev `06, Armesto et al. `12

QCD factorization in heavy-ion collisions

- Starting point is the factorization in the vacuum

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



- Factorization is an approximation
- Corrections are suppressed by inverse powers of a hard scale
- Corrections at subleading power in heavy-ion collisions are expected to be enhanced due to medium properties
- Coherent corrections

⟶ Potential problems with cancellation of Glaubers?

- Incoherent power corrections

⟶ Can be written in form of leading power factorization?

Factorization of jet cross sections in heavy-ion collisions

- Proton-proton at leading power

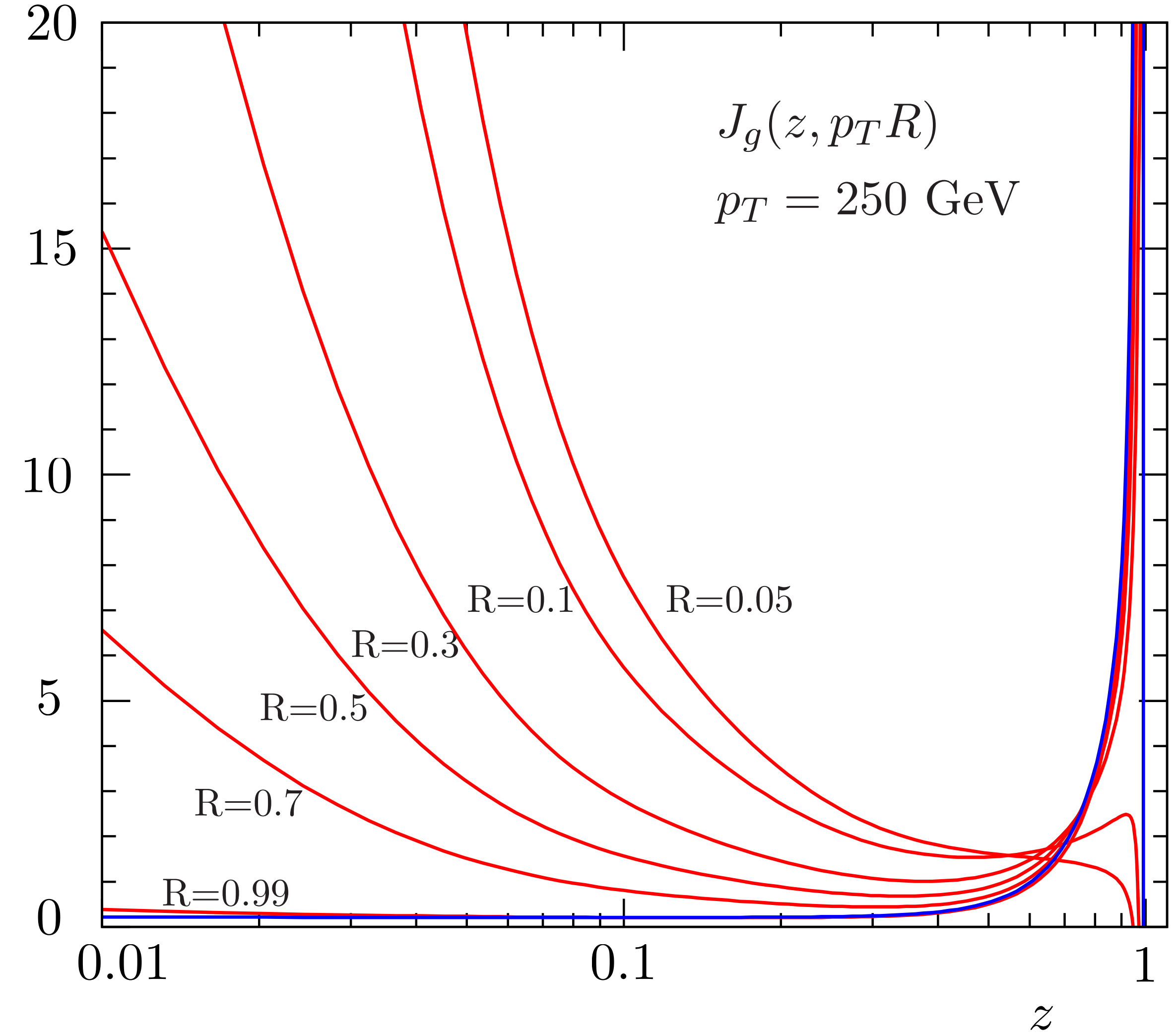
$$\frac{d\sigma^{pp\to \text{jet}+X}}{dp_T d\eta} = \sum_{a,b,c} f_{a/p} \otimes f_{b/p} \otimes H_{ab}^c \otimes J_c$$

- Heavy-ion

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

Initial state e.g. nPDFs

Medium jet functions



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

Factorization of jet cross sections in heavy-ion collisions

- Proton-proton at leading power

$$\frac{d\sigma^{pp\to \text{jet}+X}}{dp_T d\eta} = \sum_{a,b,c} f_{a/p} \otimes f_{b/p} \otimes H_{ab}^c \otimes J_c$$

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

- Heavy-ion

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

Initial state e.g. nPDFs

Medium jet functions

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

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

- Modified DGLAP evolution?
- Relevant at low p_T

Kang, Ma, Qiu, Sterman `14

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

Relation to a parton shower picture

For example:

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

  vacuum shower

  shower cutoff

- MATTER
  Majumder `13, Kordell, Majumder `17

  vacuum shower

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

  medium modified shower

- Medium jet functions
  Qiu, FR, Sato, Zurita `19

  vacuum shower

  $p_T R$

  Fit to data

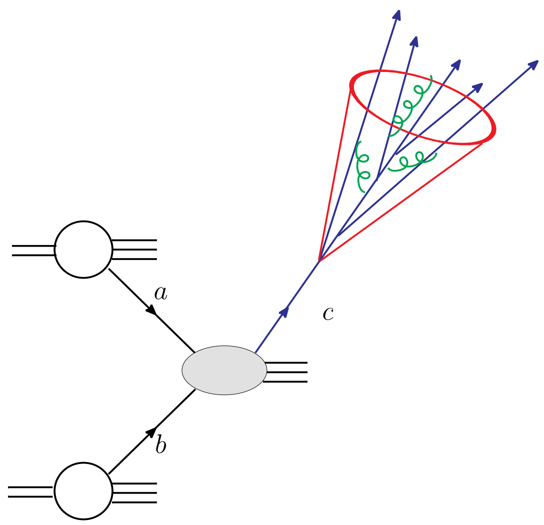
$$\boldsymbol{J}(N, p_T) = \left(\frac{\alpha_s(p_T)}{\alpha_s(p_T R)}\right)^{-\boldsymbol{P}^{(0)}(N)/\beta_0} \boldsymbol{J}(N, p_T R)$$

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

A first global analysis

Qiu, FR, Sato, Zurita `19

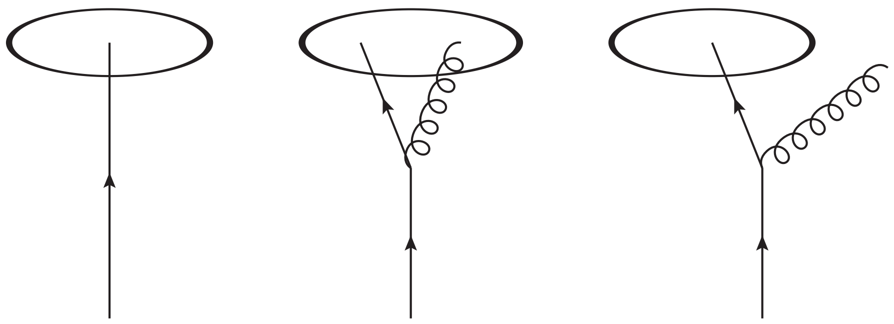
- Introduce medium modified jet function at the jet scale



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

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

- Momentum sum rule



$$\int_0^1 dz\, z\, J_c(z, p_T^c R, \mu) = 1$$

- 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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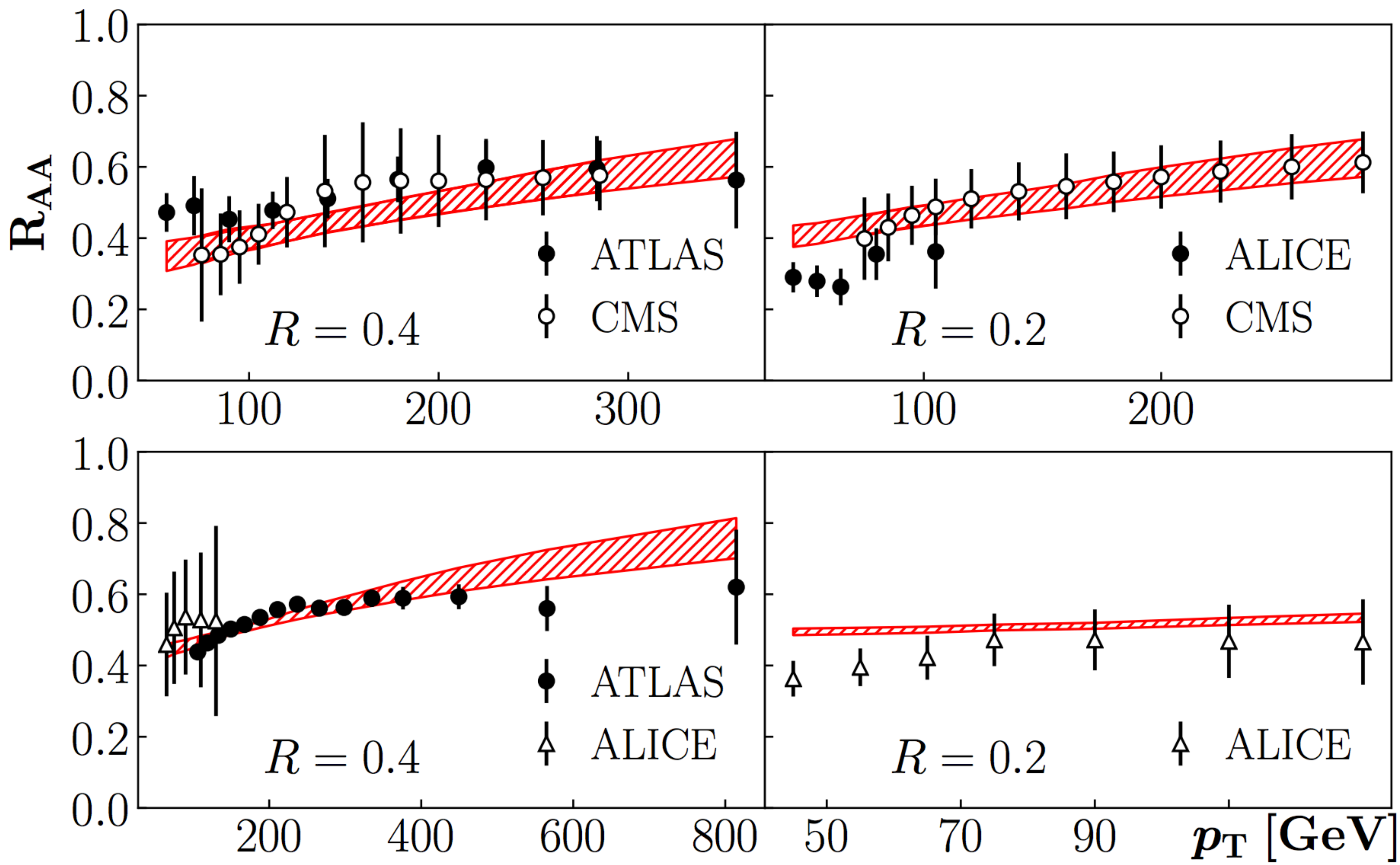
Inclusive jet production PbPb at the LHC

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

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

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

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

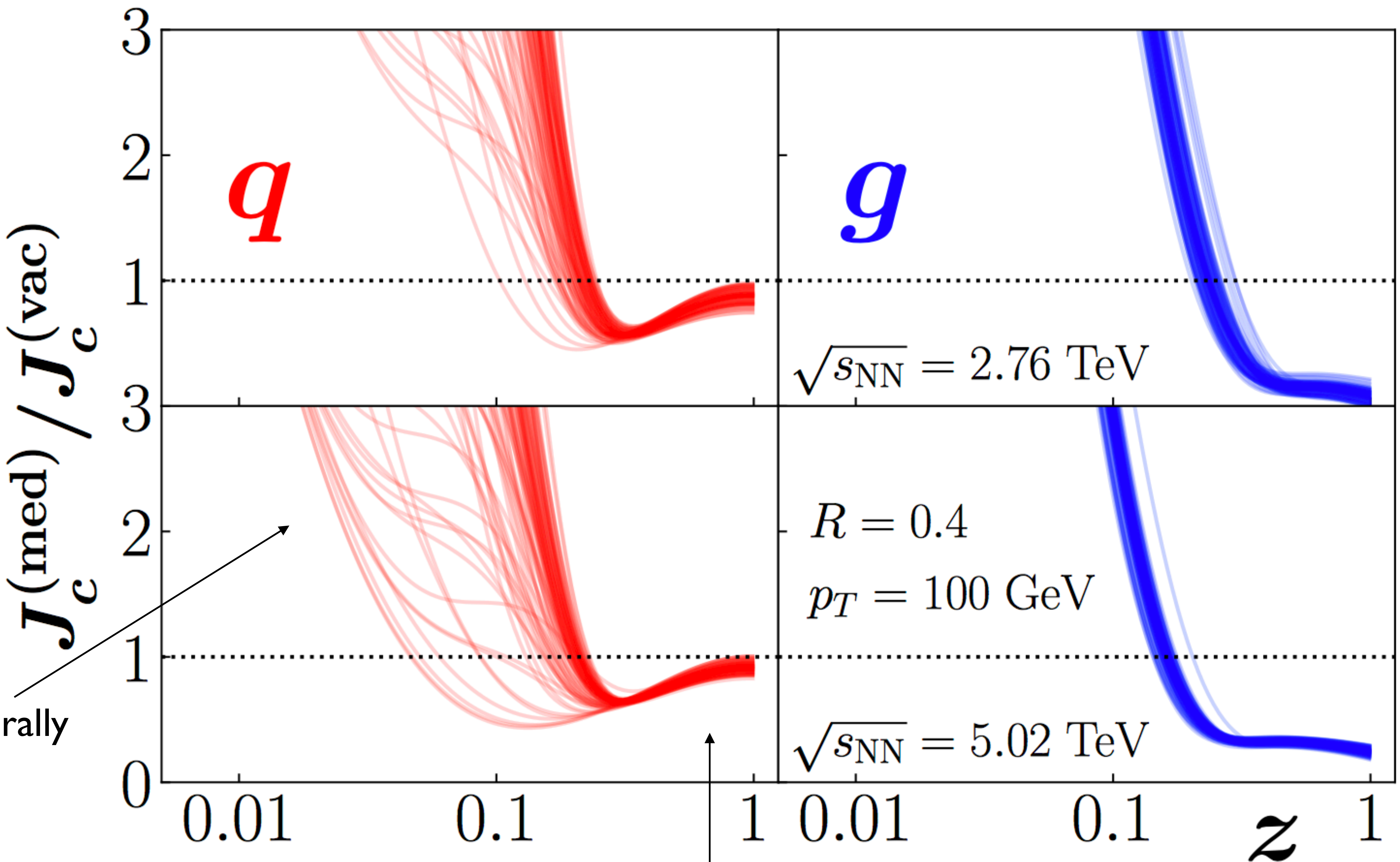


ALICE, PLB 746 (2015) 1
ATLAS, PRL 114 (2015) 072302
CMS, PRC 96 (2017) 015202

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

No initial state effects or nPDFs

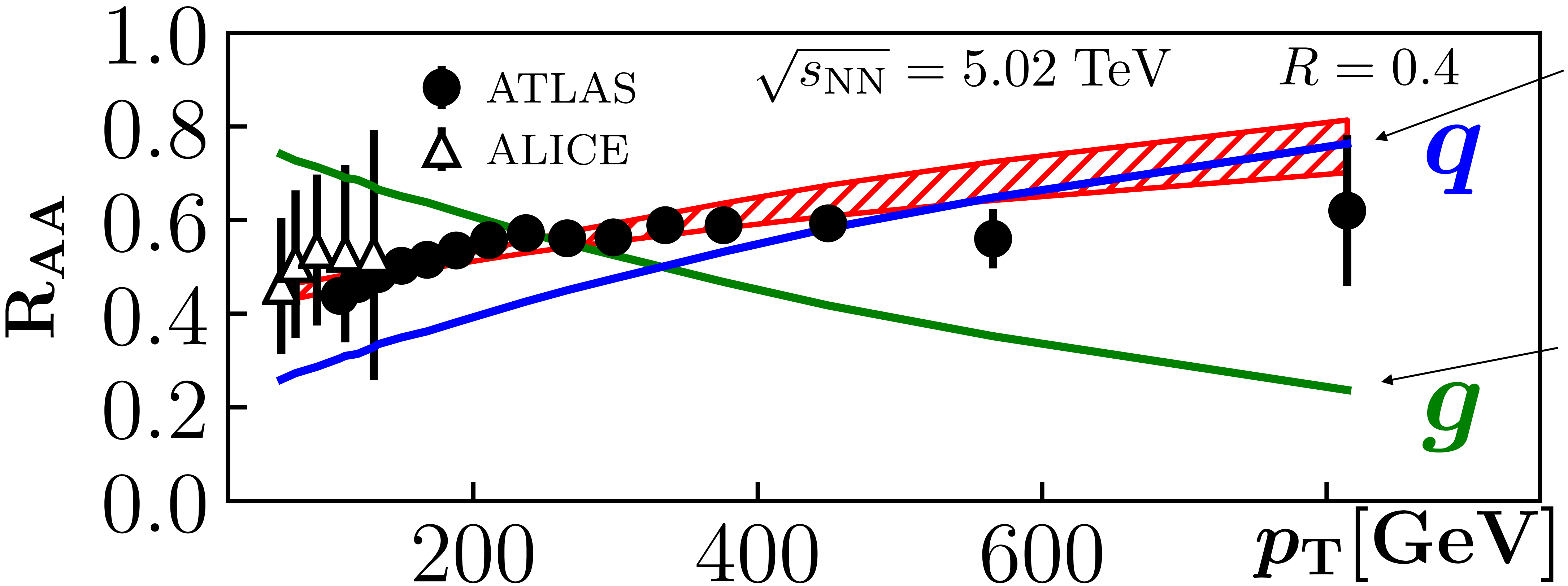
The medium modified jet functions



Small-z region generally less constrained

Potentially requires threshold resummation for $z \to 1$

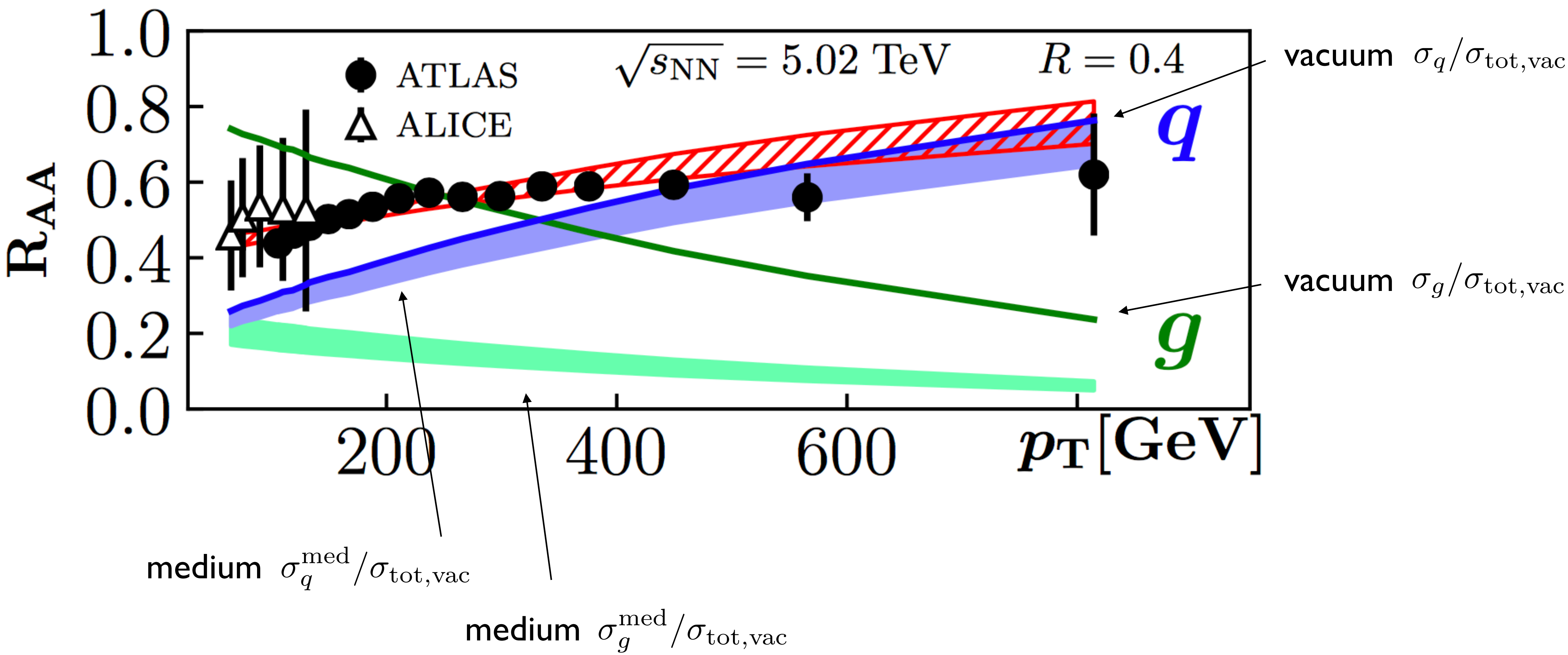
Quark/gluon jets



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

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

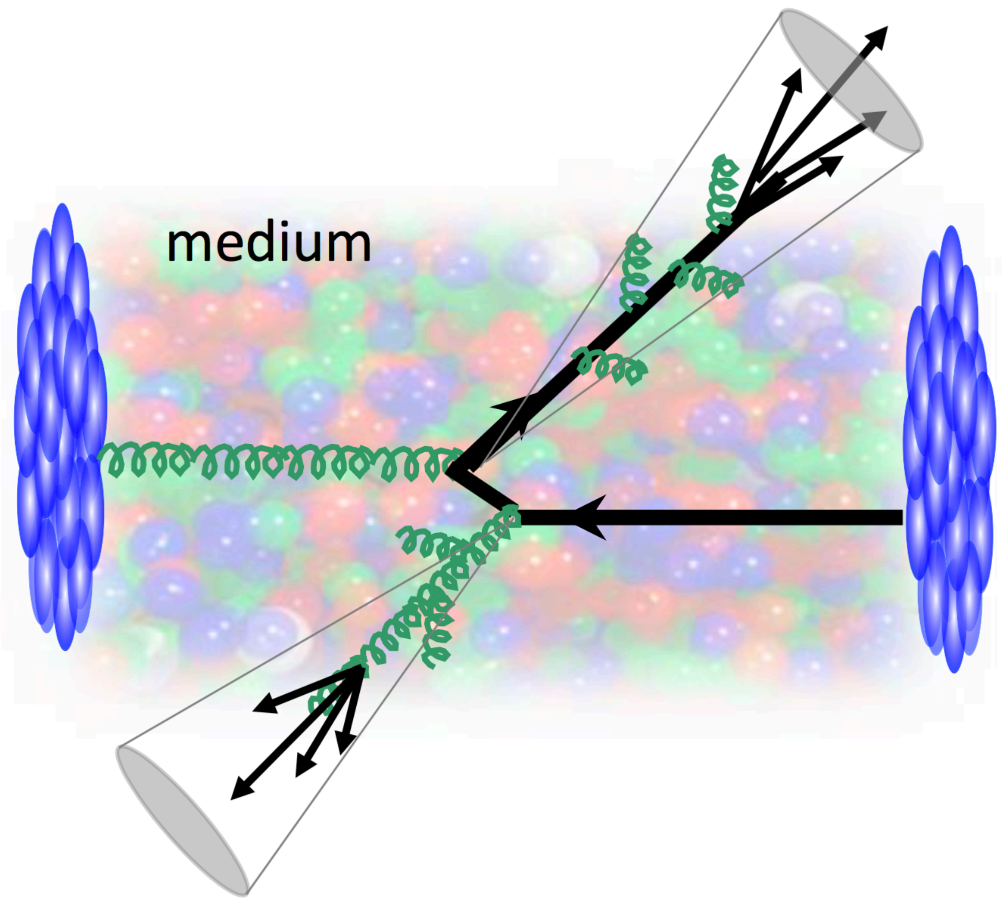
Quark/gluon jets



- Gluons significantly more suppressed than quark jets
- Different than many model calculations
- But likely supported by other observables …

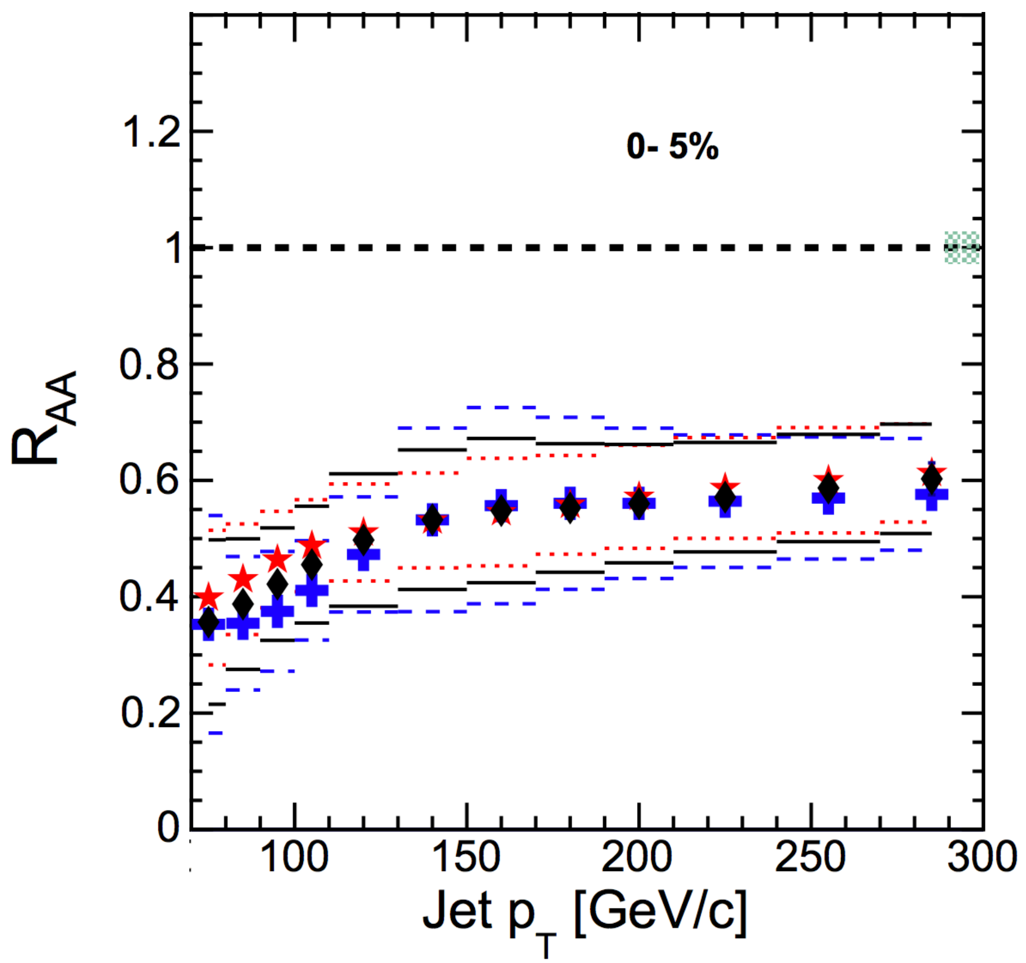
Dependence of the R_{AA} on the jet radius

- Large-R: Parton energy loss recovered in larger cone $R_{AA} \uparrow$

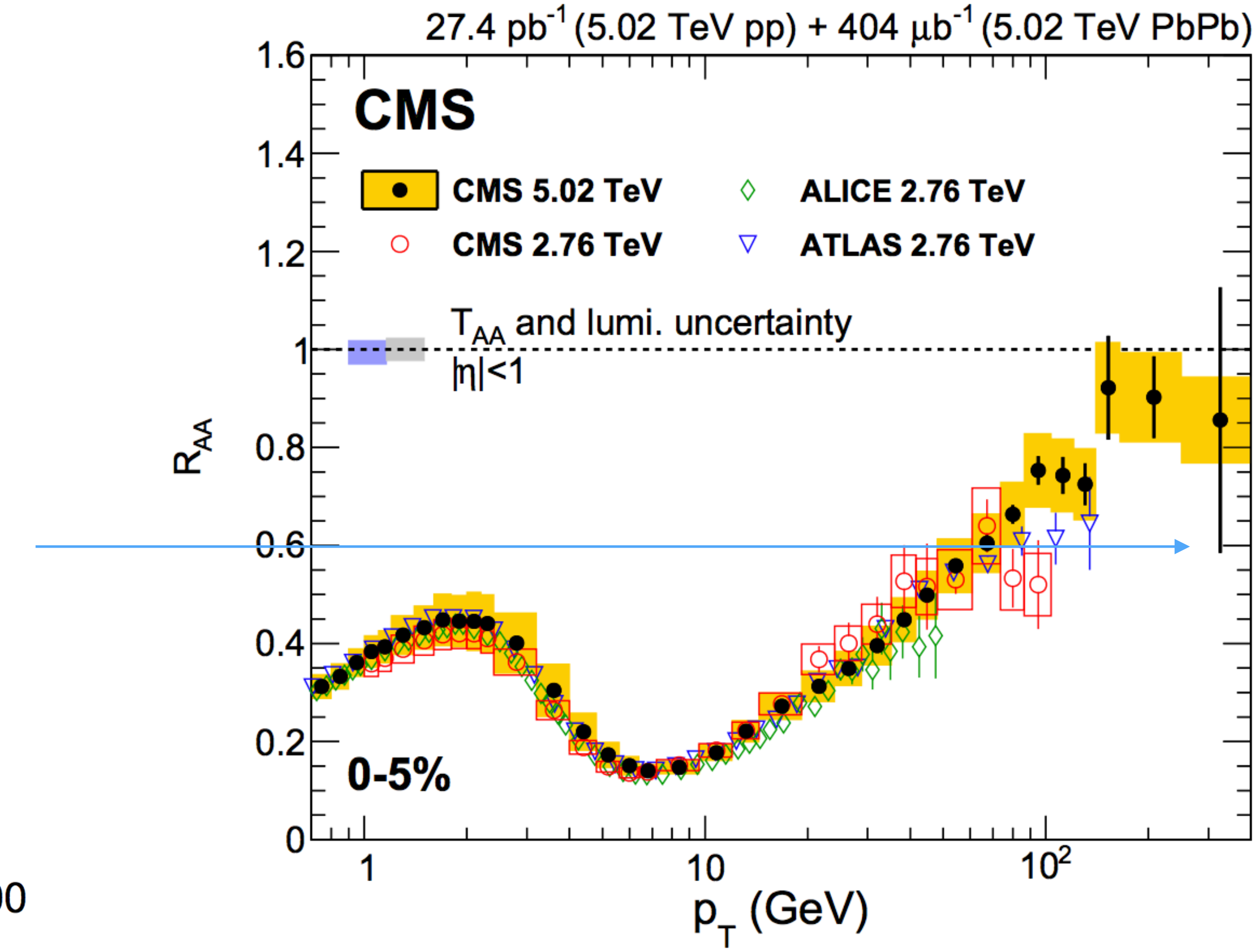


Dependence of the R_{AA} on the jet radius

- Large-R: Parton energy loss recovered in larger cone $R_{AA} \uparrow$
- Small-R: For $R \to 0$ the hadron R_{AA} should be obtained $R_{AA} \uparrow$

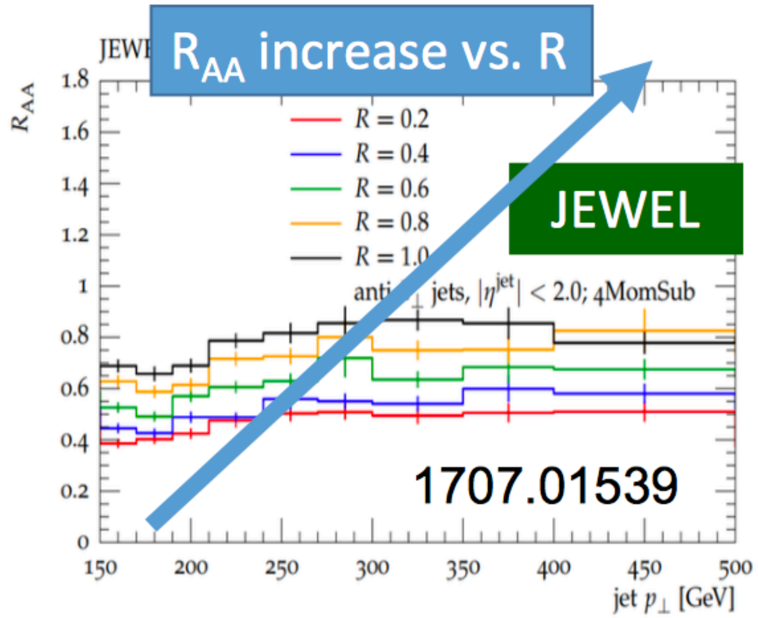


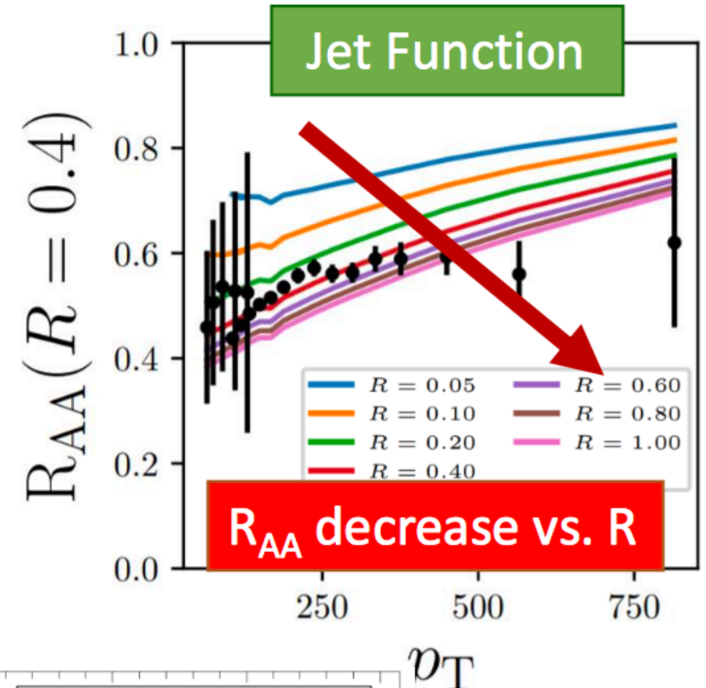
CMS, PRC 96 (2017) 015202

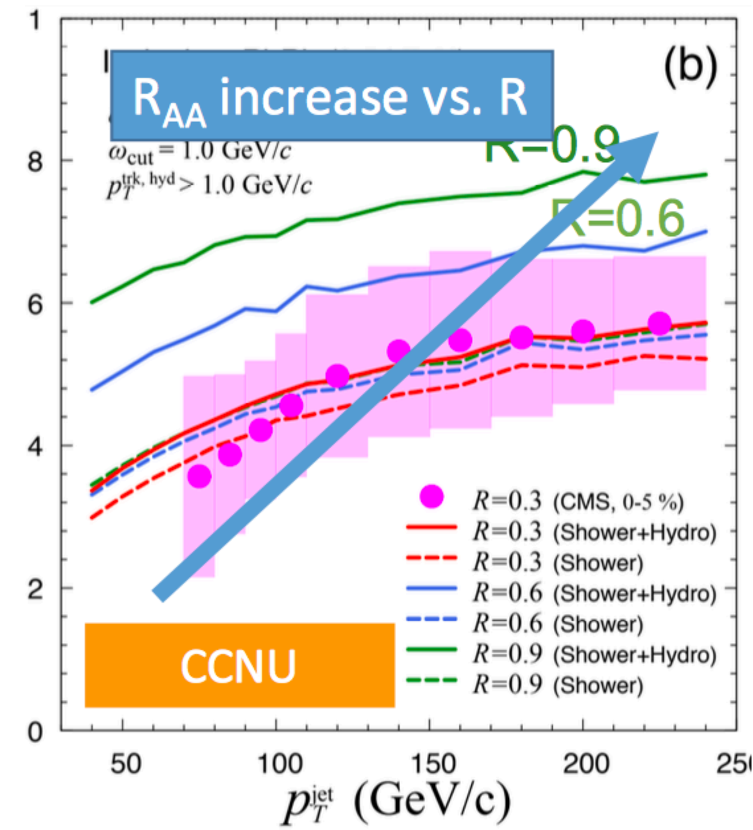


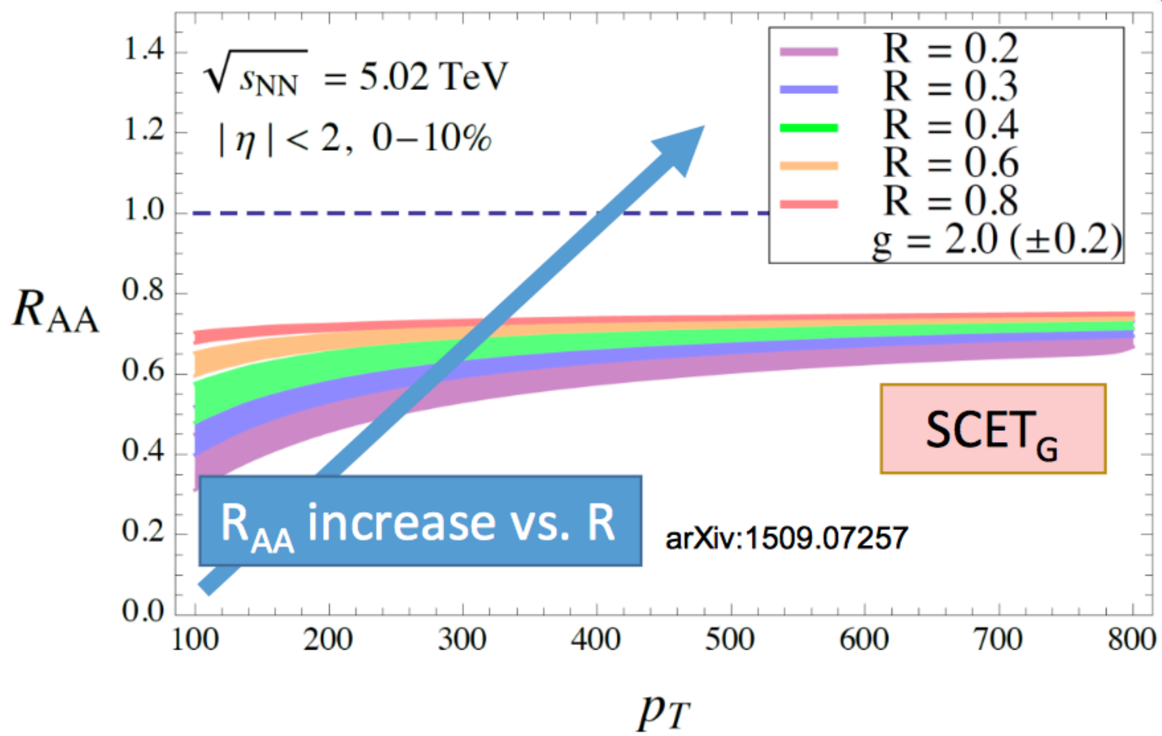
CMS, JHEP 1704 (2017) 039

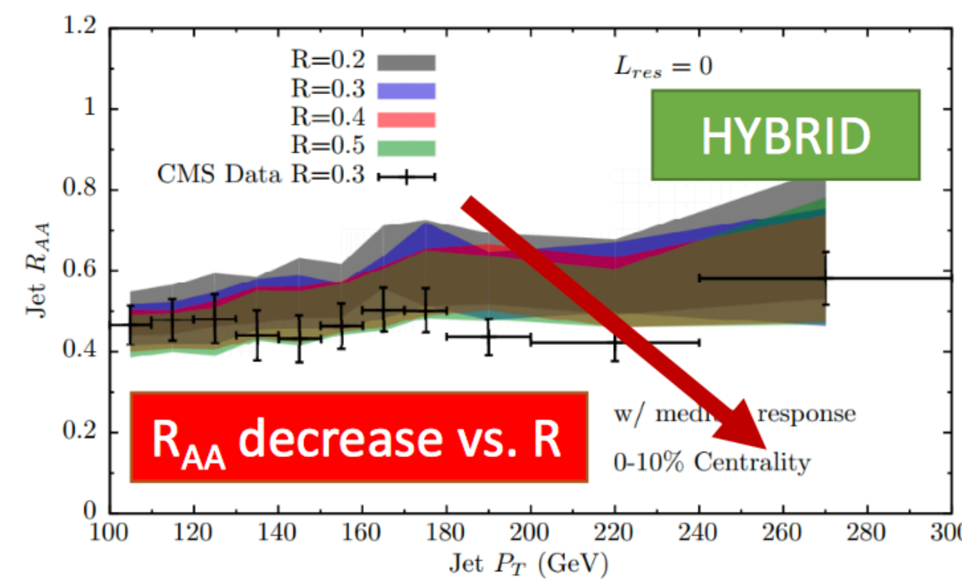
Dependence of the R_{AA} on the jet radius





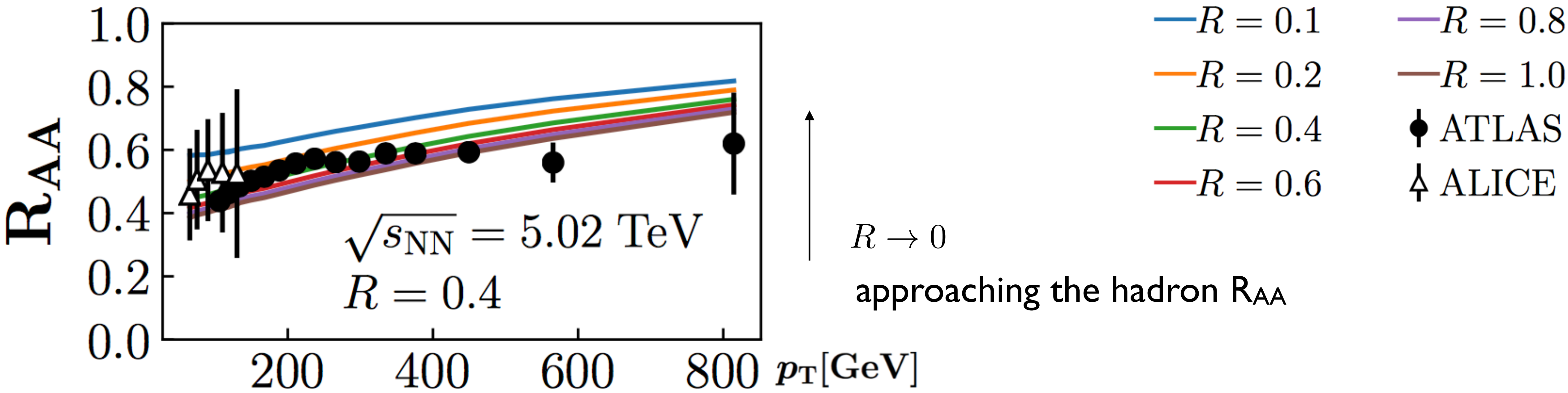






Yen-Jie Lee, UCLA Santa Fe Jet and Heavy Flavor workshop `19

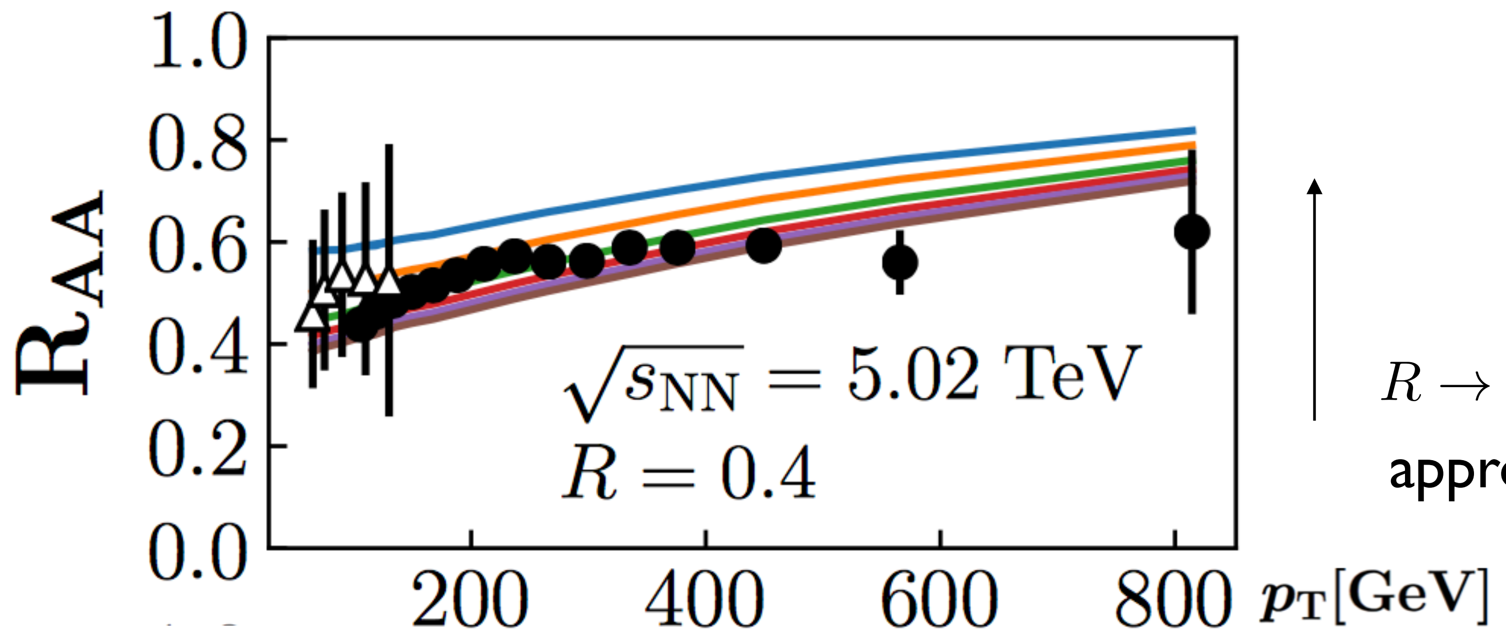
The jet radius dependence



$R \to 0$

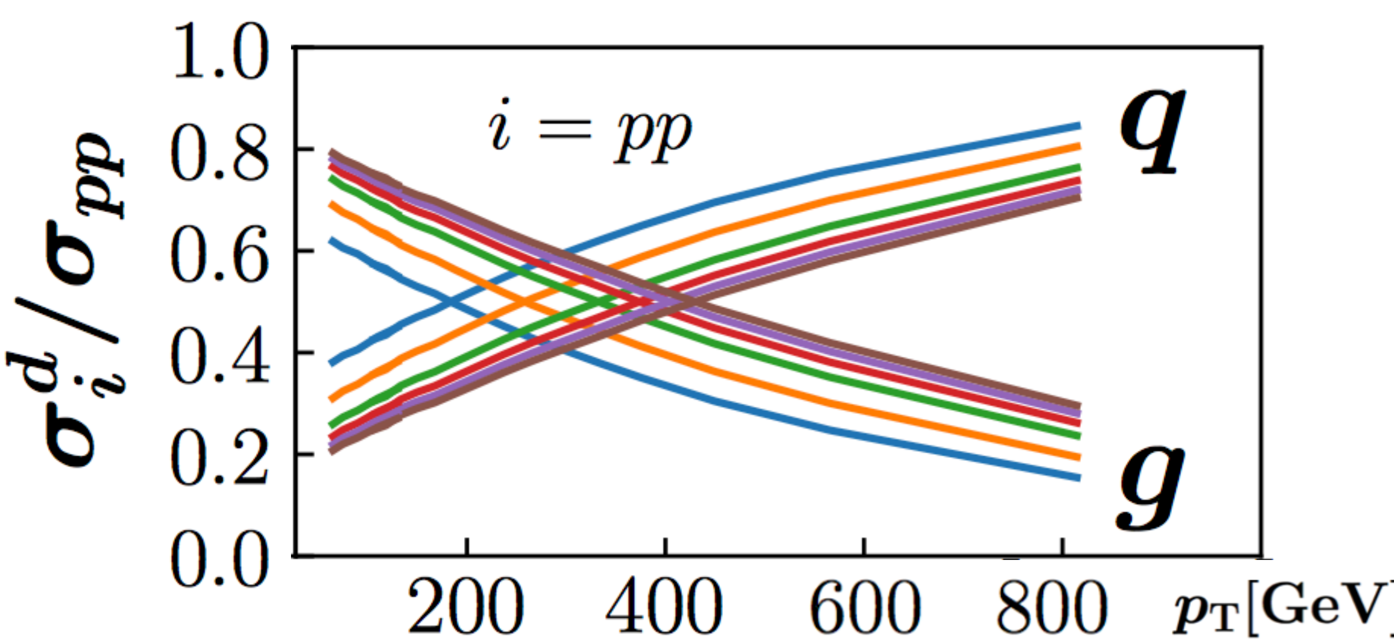
approaching the hadron R_{AA}

The jet radius dependence

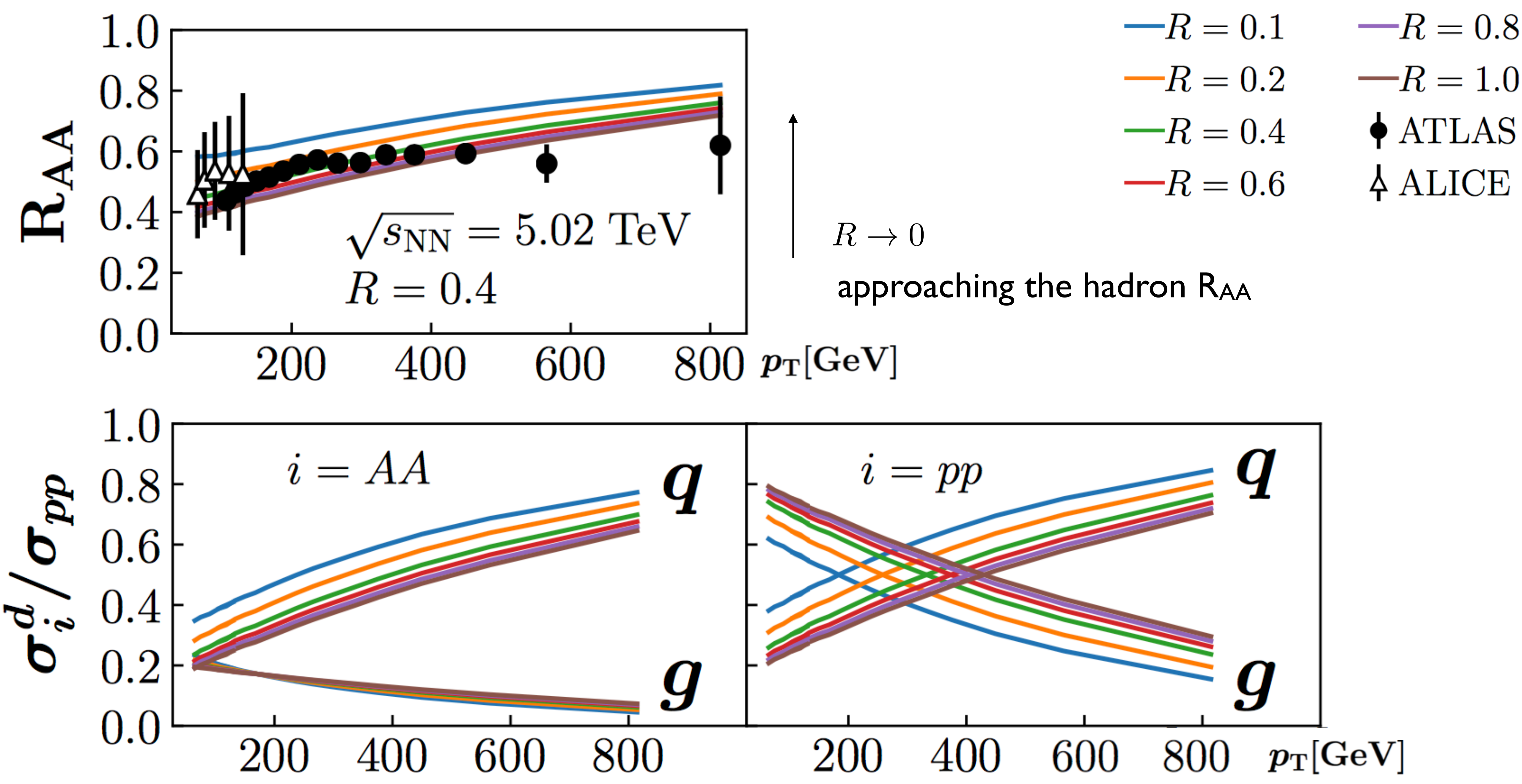


$R \to 0$

approaching the hadron $\mathrm{R_{AA}}$



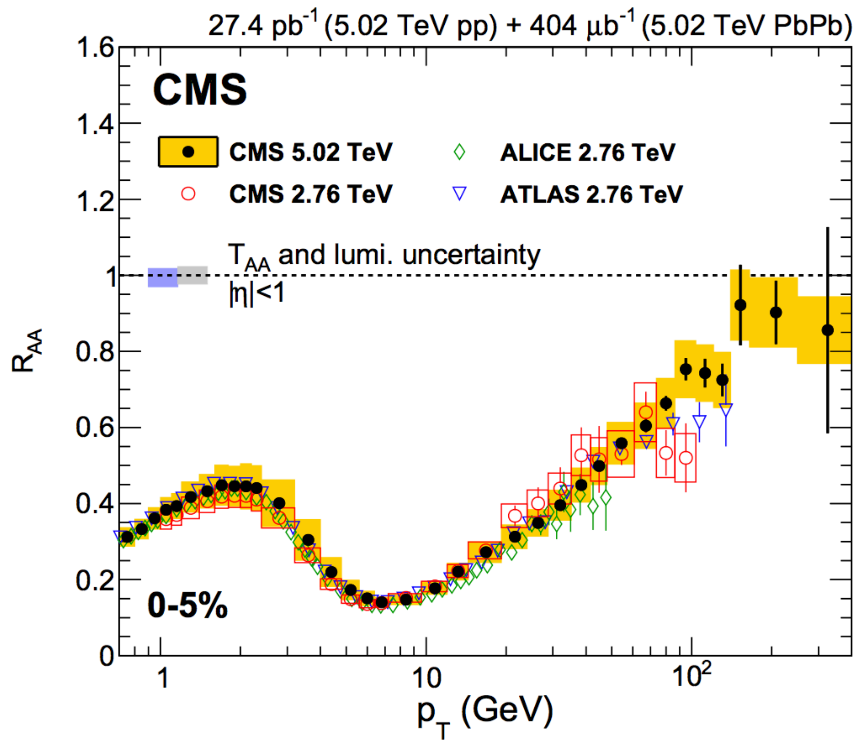
The jet radius dependence



- Direct relation with the relative suppression of quarks and gluons

Factorization and universality

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



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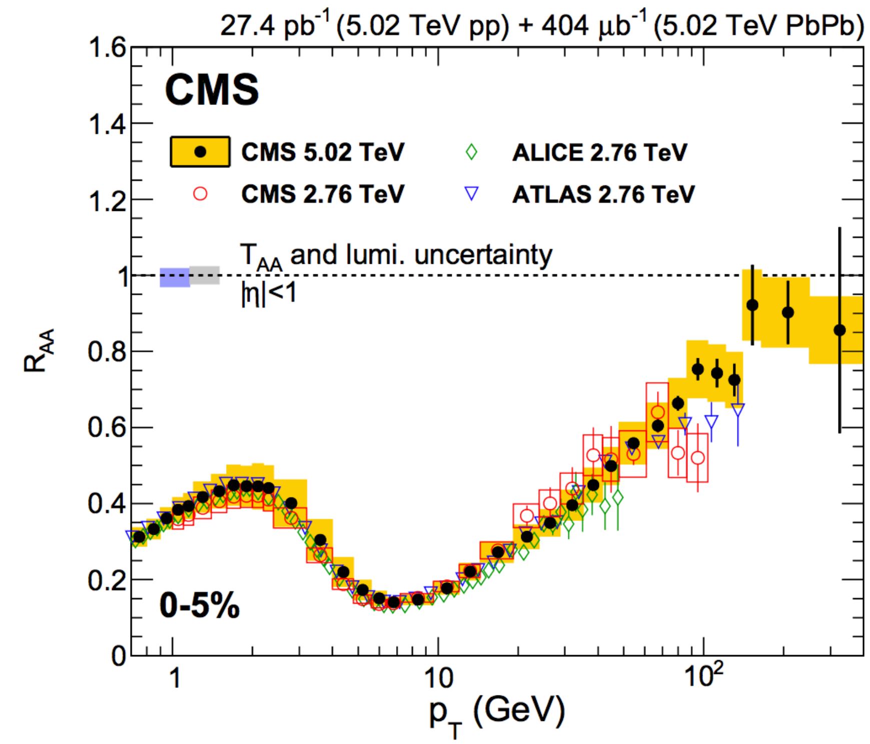
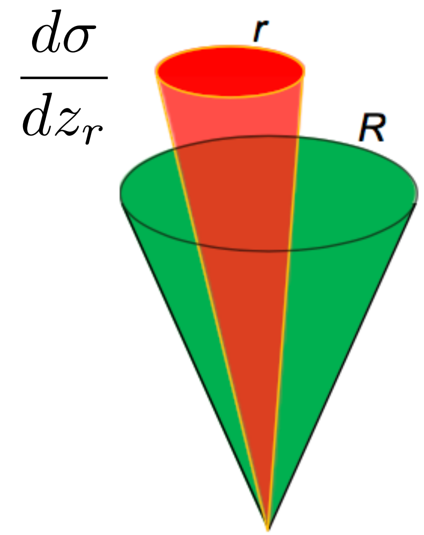
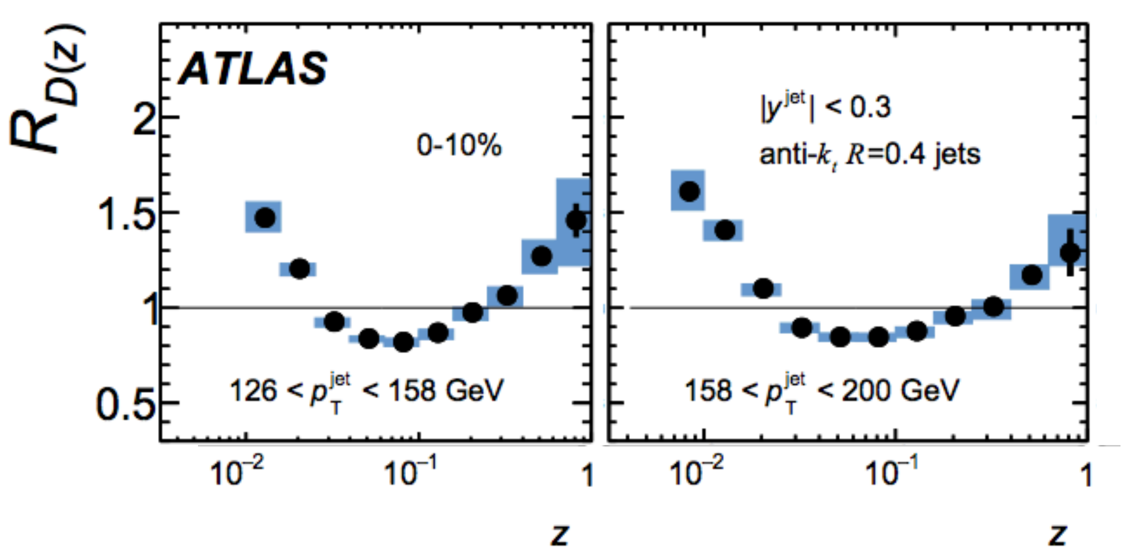


- Test universality using jet substructure observables
- Similar collinear factorization theorems

Hadrons and subjets inside jets

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





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 $\gamma + \text{jet}$
- Test of universality by using jet substructure data
- Understand the modification of the parton shower
- Provide guidance for constructing microscopic models of the QGP