Factorization of jet cross sections in heavy-ion collisions

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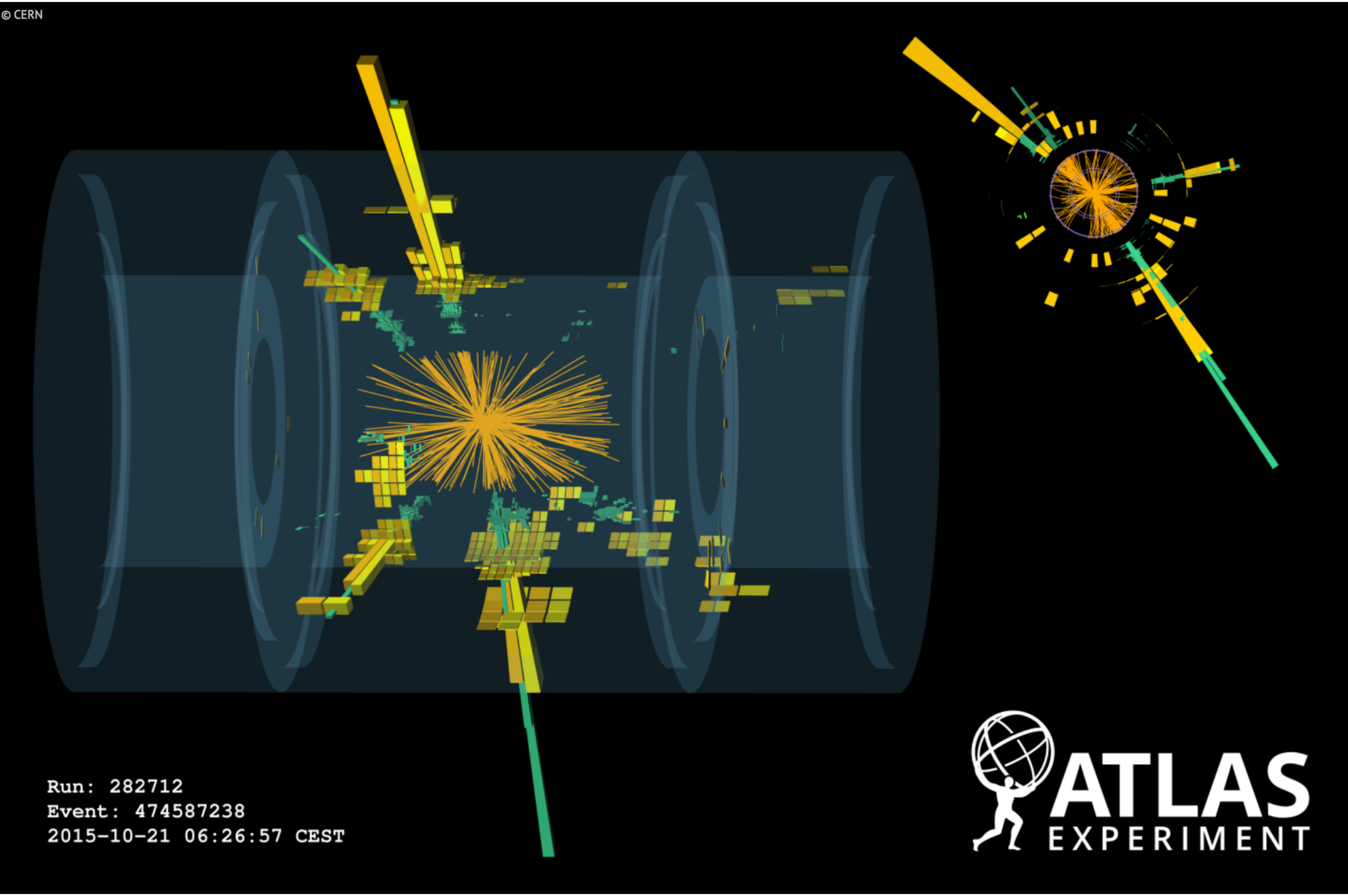
JLab, 03/20/19

BERKELEY LAB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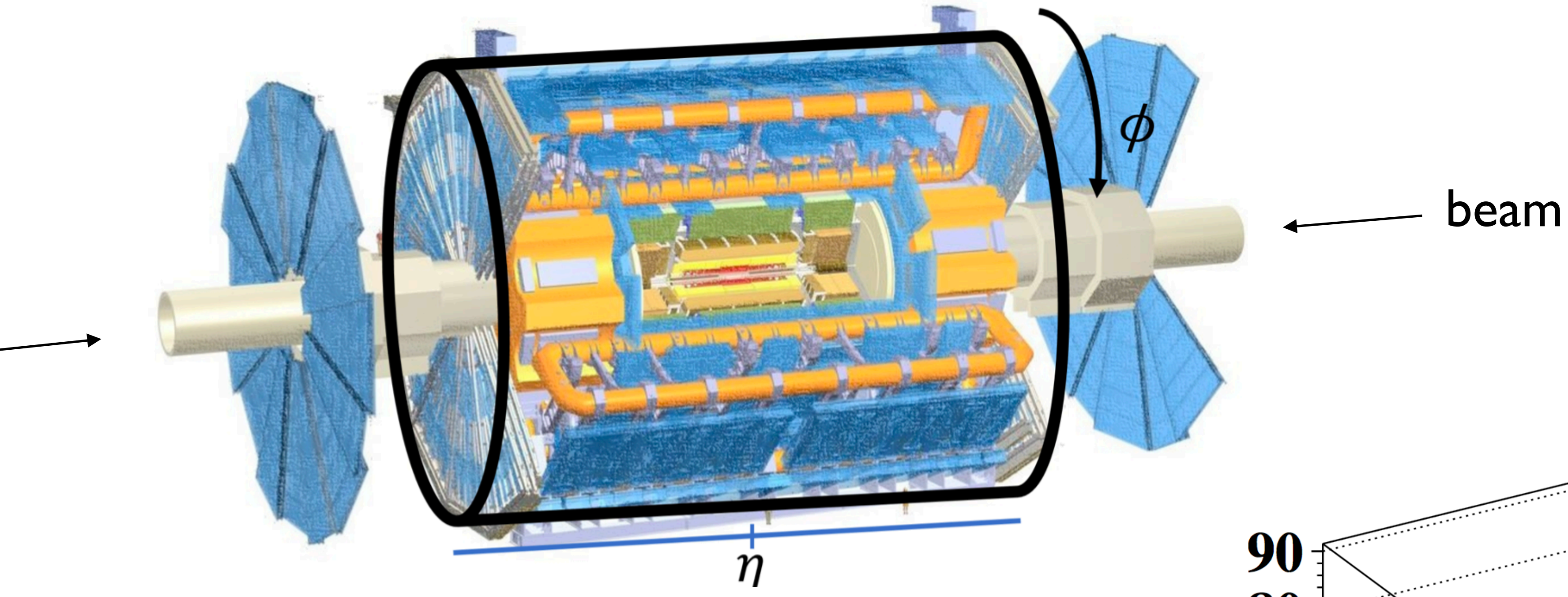
ATLAS
EXPERIMENT

Jets at the LHC

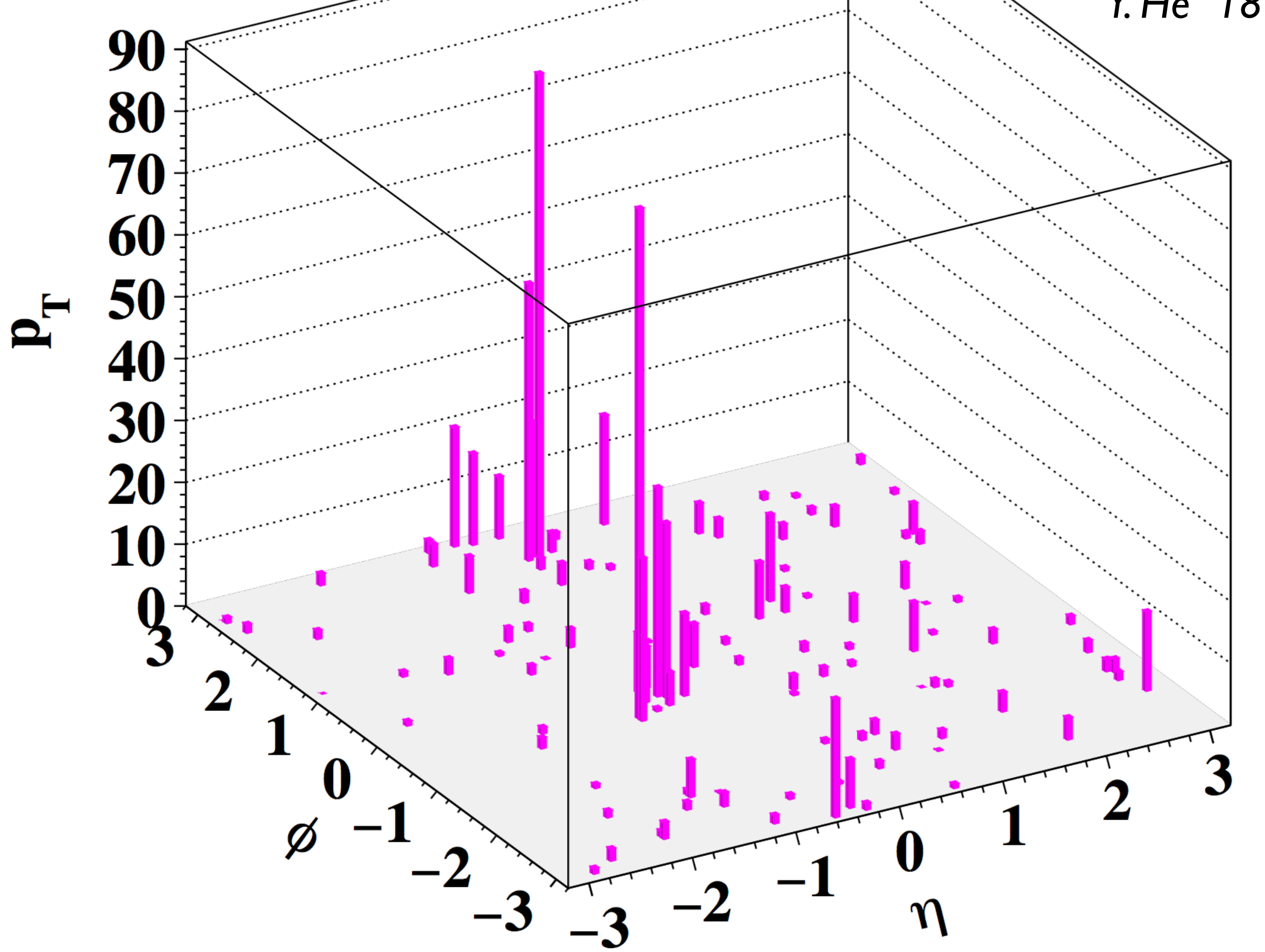
ATLAS detector



Pythia 8

$\sqrt{s} = 13$ TeV

Y. He `18



- Azimuthal angle ϕ
- Pseudorapidity $\eta = -\ln\tan\theta/2$

Jets at the LHC

- Pioneering work *Sterman, Weinberg `77*
- Jet algorithm, e.g. anti-k$_T$ *Cacciari, Salam, Soyez `08*

Define a distance between all particles

$$d_{ij} = \min\left(\frac{1}{p_{Ti}^2}, \frac{1}{p_{Tj}^2}\right) \frac{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}{R^2}$$

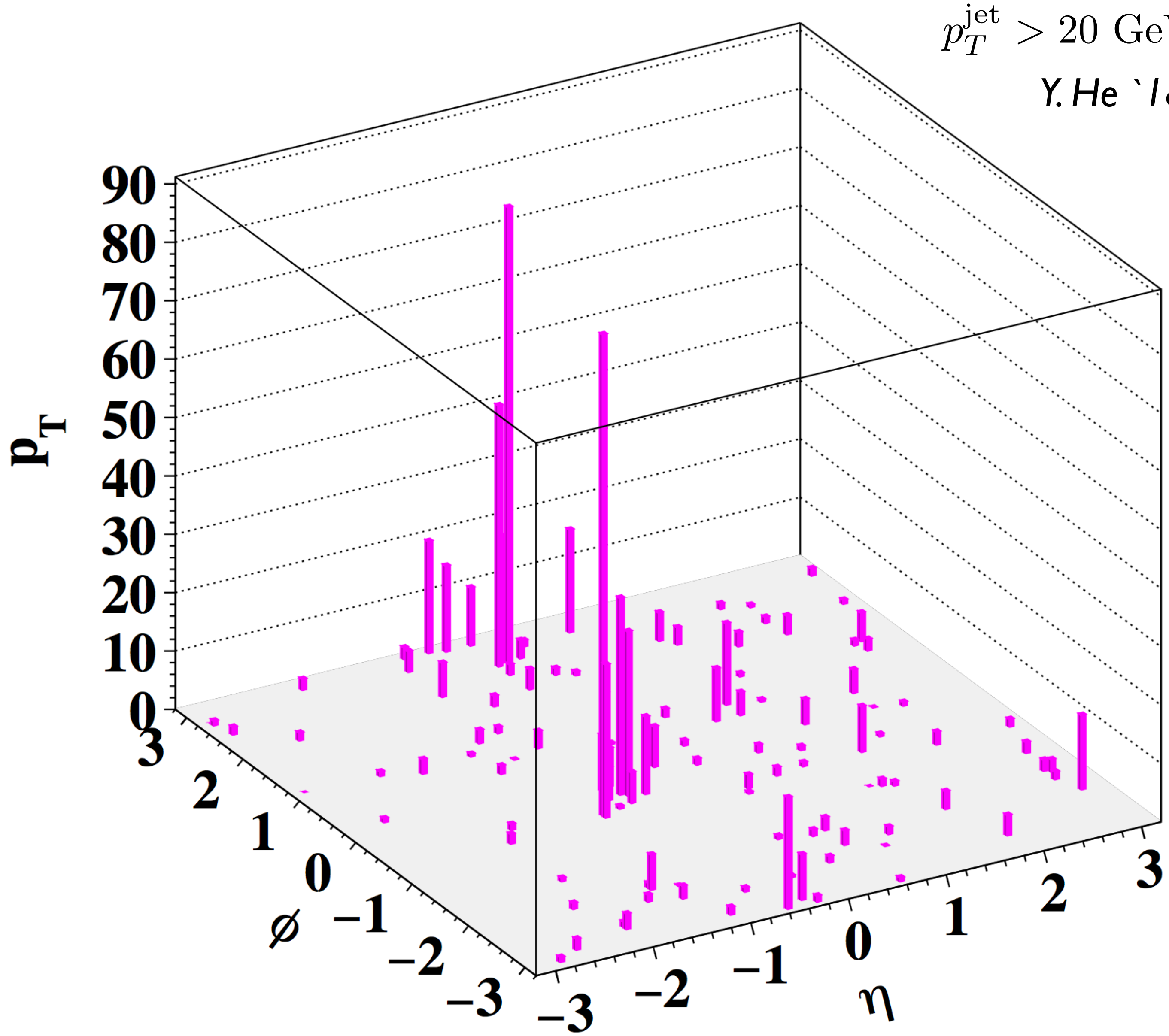
and recursively merge the particles with the smallest distance

Pythia 8, FastJet

$R = 0.4 \quad \sqrt{s} = 13$ TeV

$p_T^{\text{jet}} > 20$ GeV

Y. He `18



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and recursively merge the particles with the smallest distance

$\longrightarrow$ R is the radius of the jet

Pythia 8, FastJet

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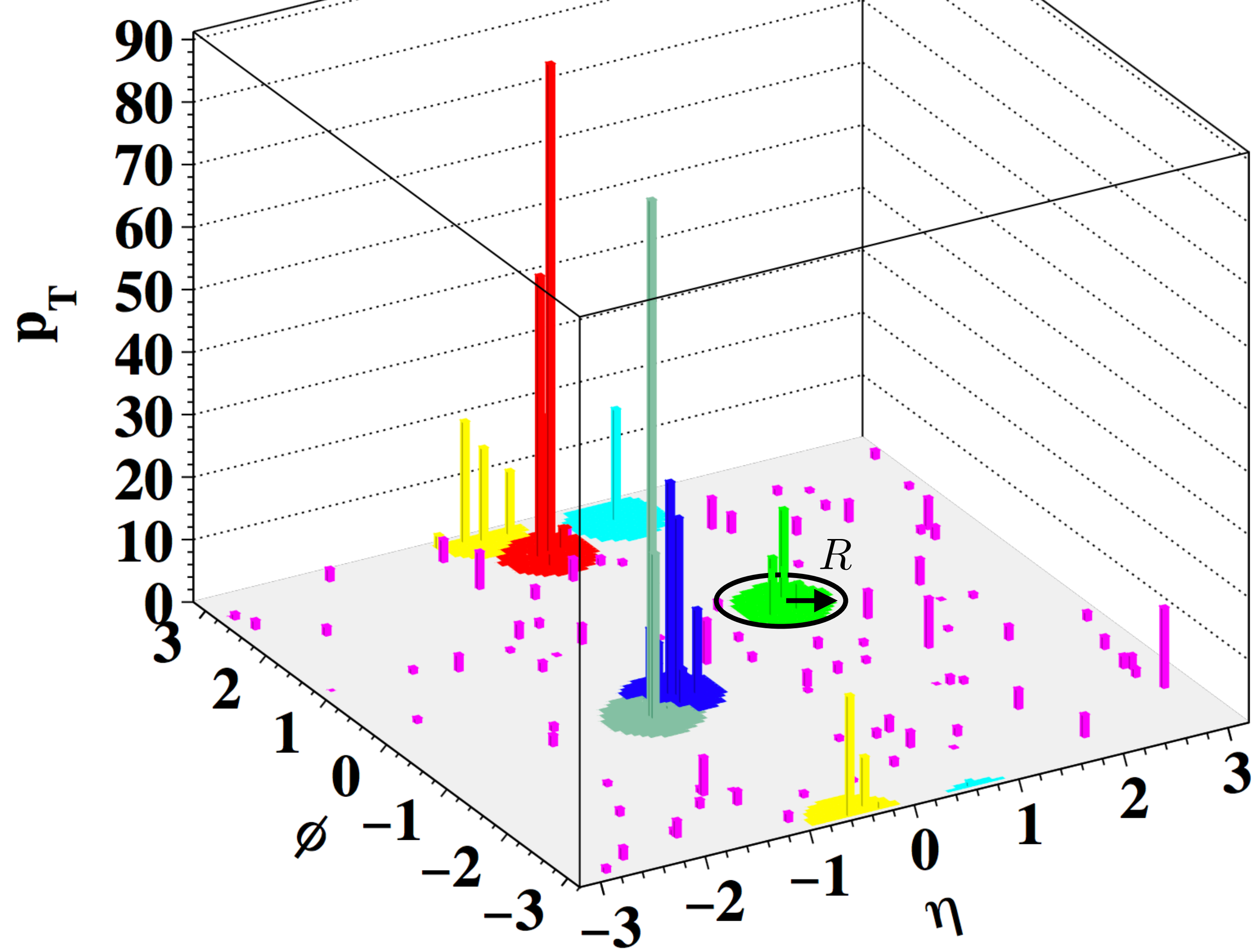
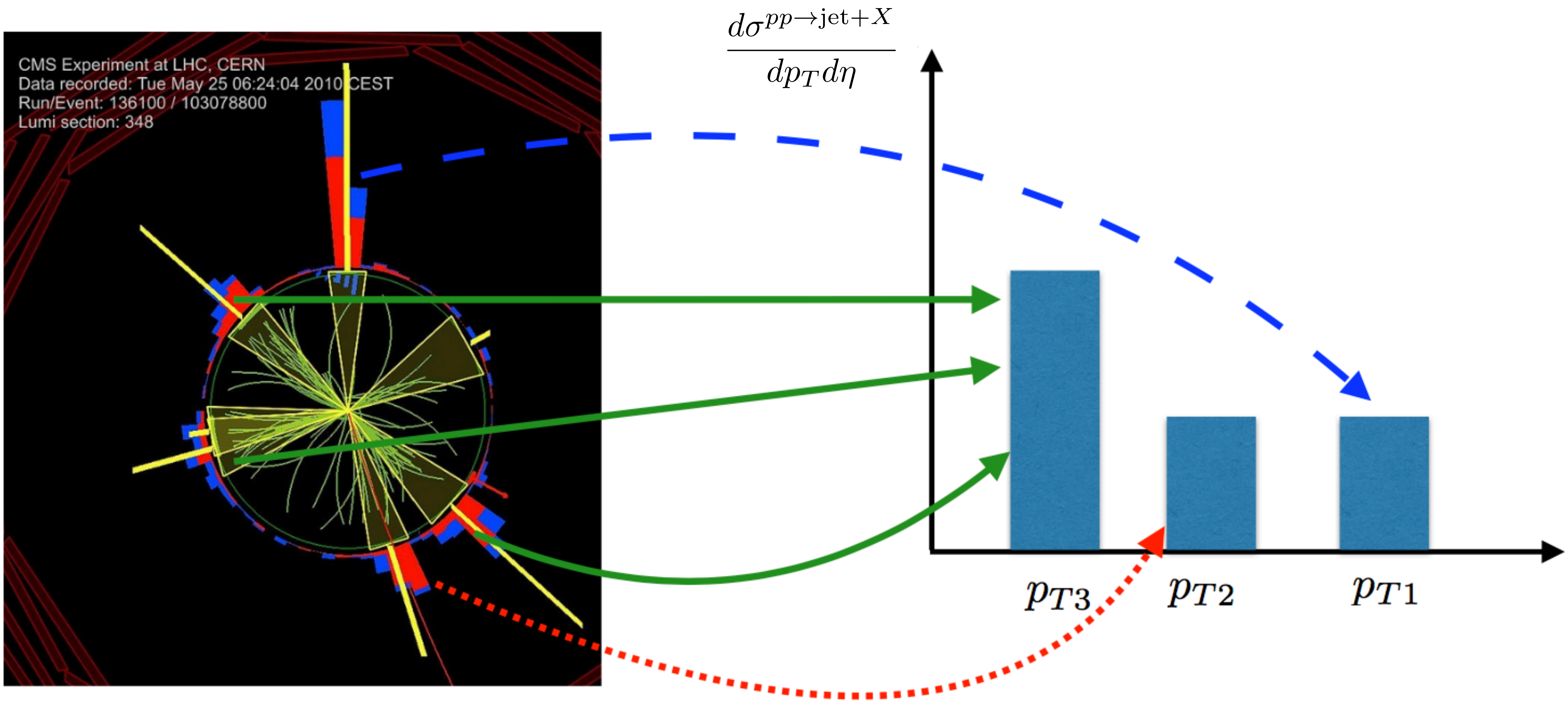
Y. He `18



The inclusive jet cross section

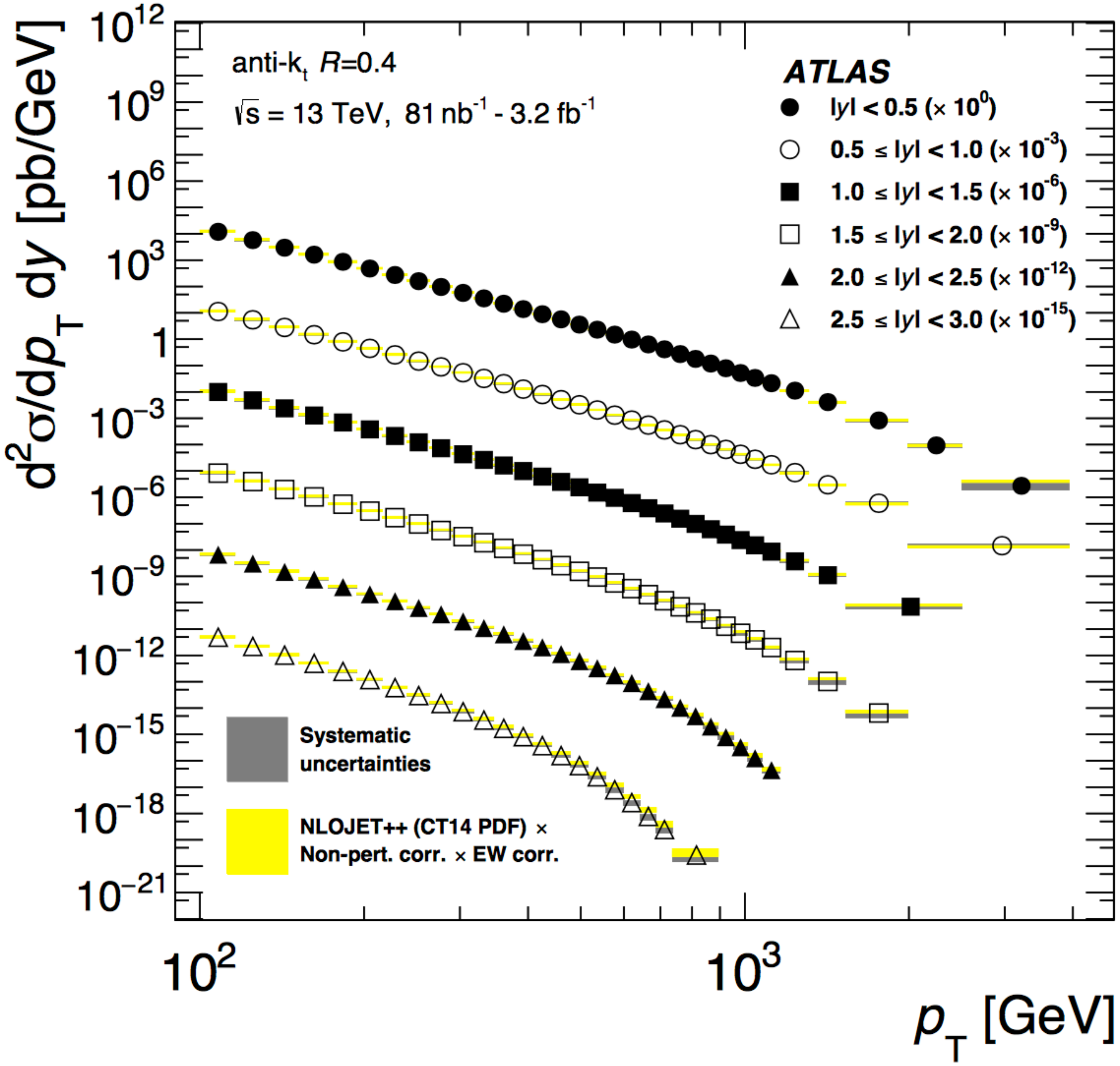


E. Eren `18

Counting the number of jets

Inclusive jet production at the LHC

- Proton-proton



- Fixed order - NNLO

  Currie, Glover, Pires `16

- All order resummation

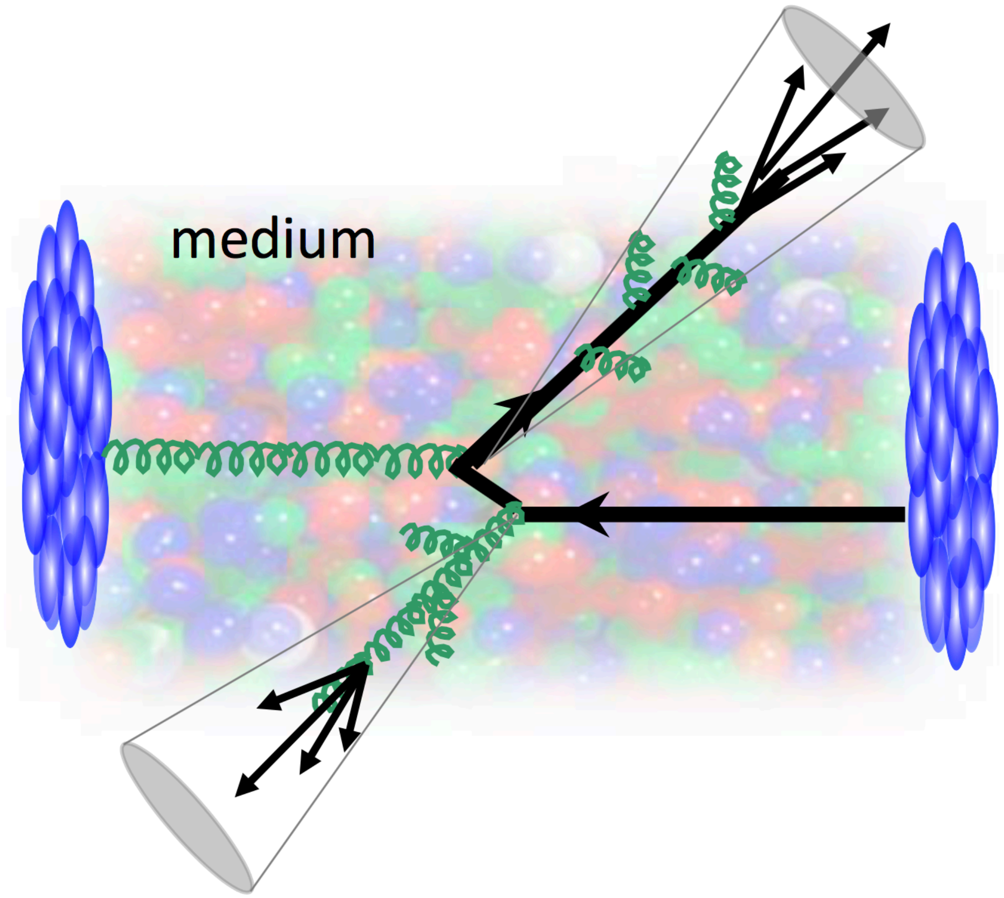
  Threshold and jet radius

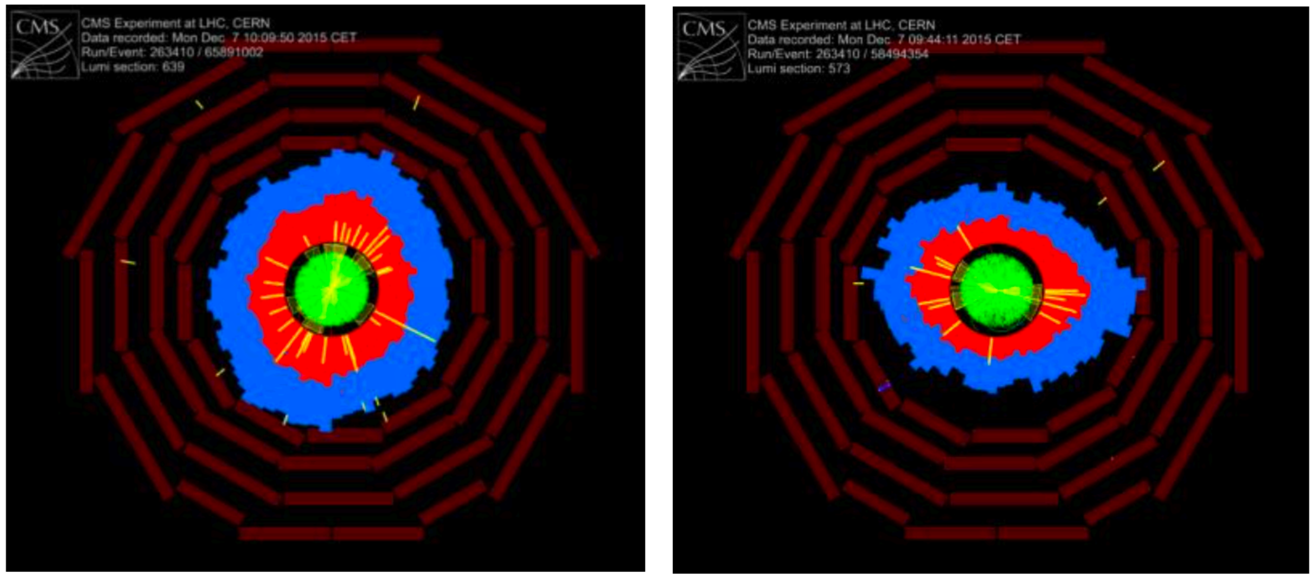
  Dasgupta, Dreyer, Salam, Soyez `14
  Kang, FR, Vitev `16
  Liu, Moch, FR `17

⟶ Precision physics

ATLAS, JHEP 1805 (2018) 195

Hard and soft probes in heavy-ion collisions





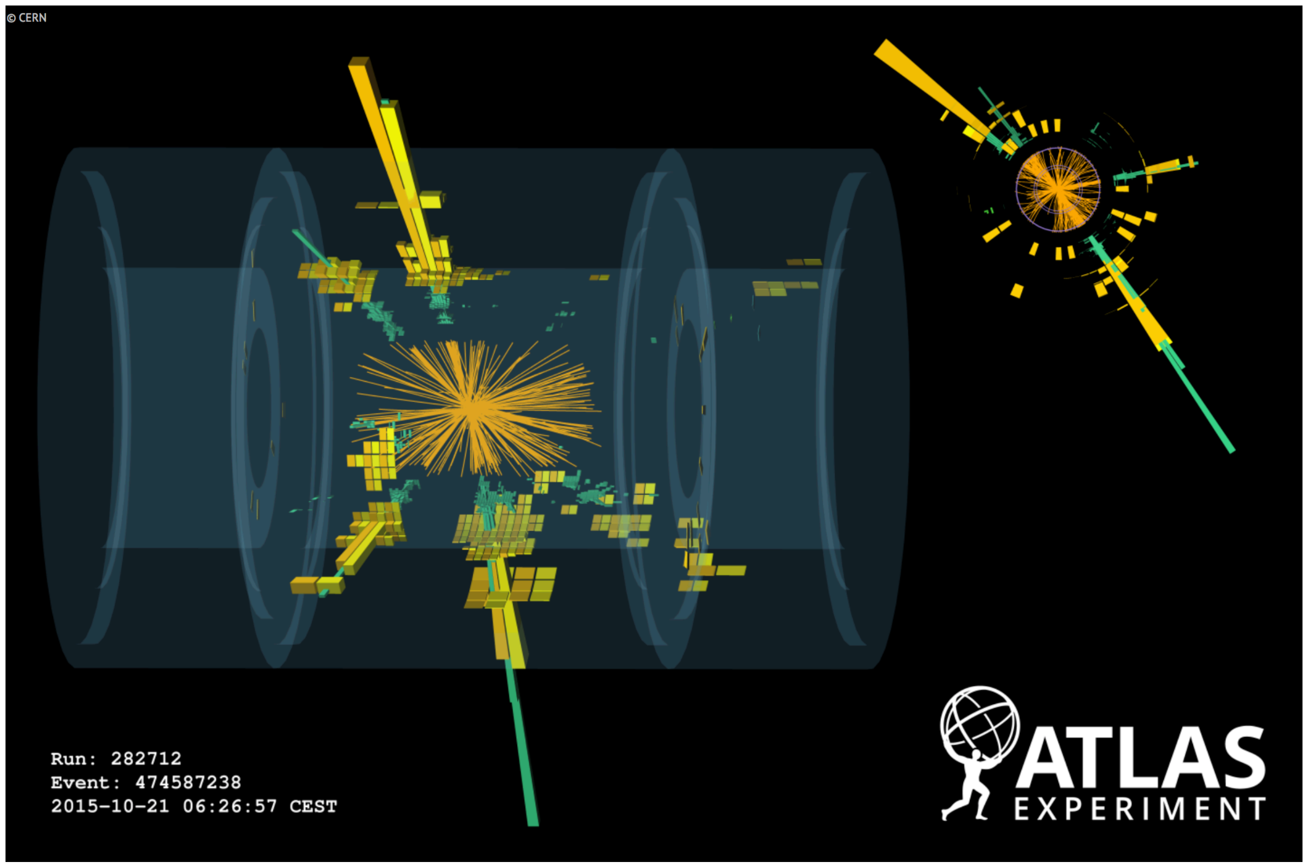
- Highly energetic particles and jets
- QCD Factorization?

- Charged particle counting
- Elliptic flow/collectivity

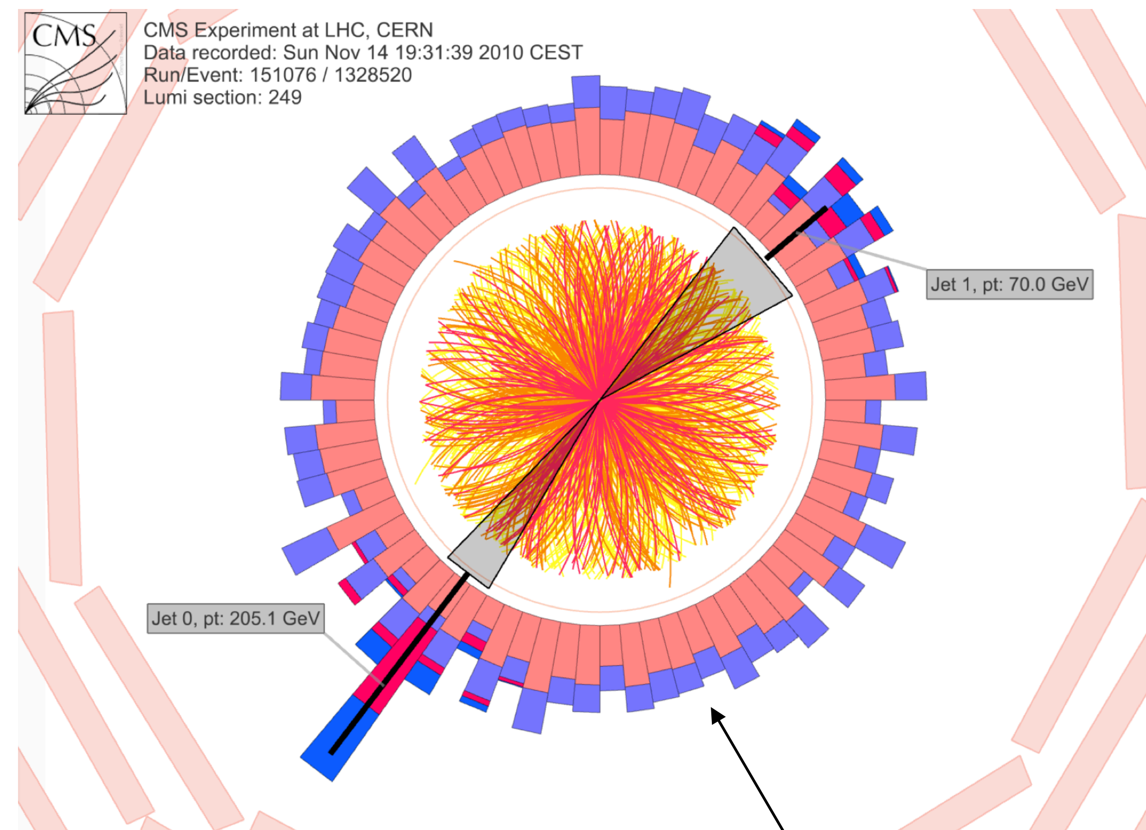
→ Extract properties of the medium

Inclusive jet production

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



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



Subtract background

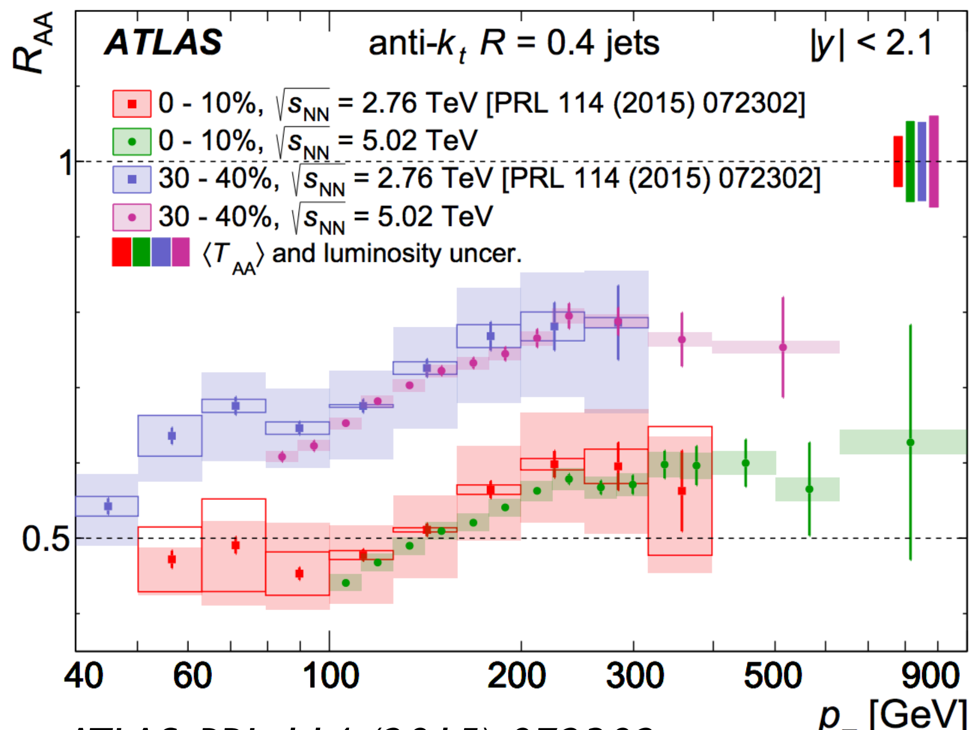
Inclusive jet cross section

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

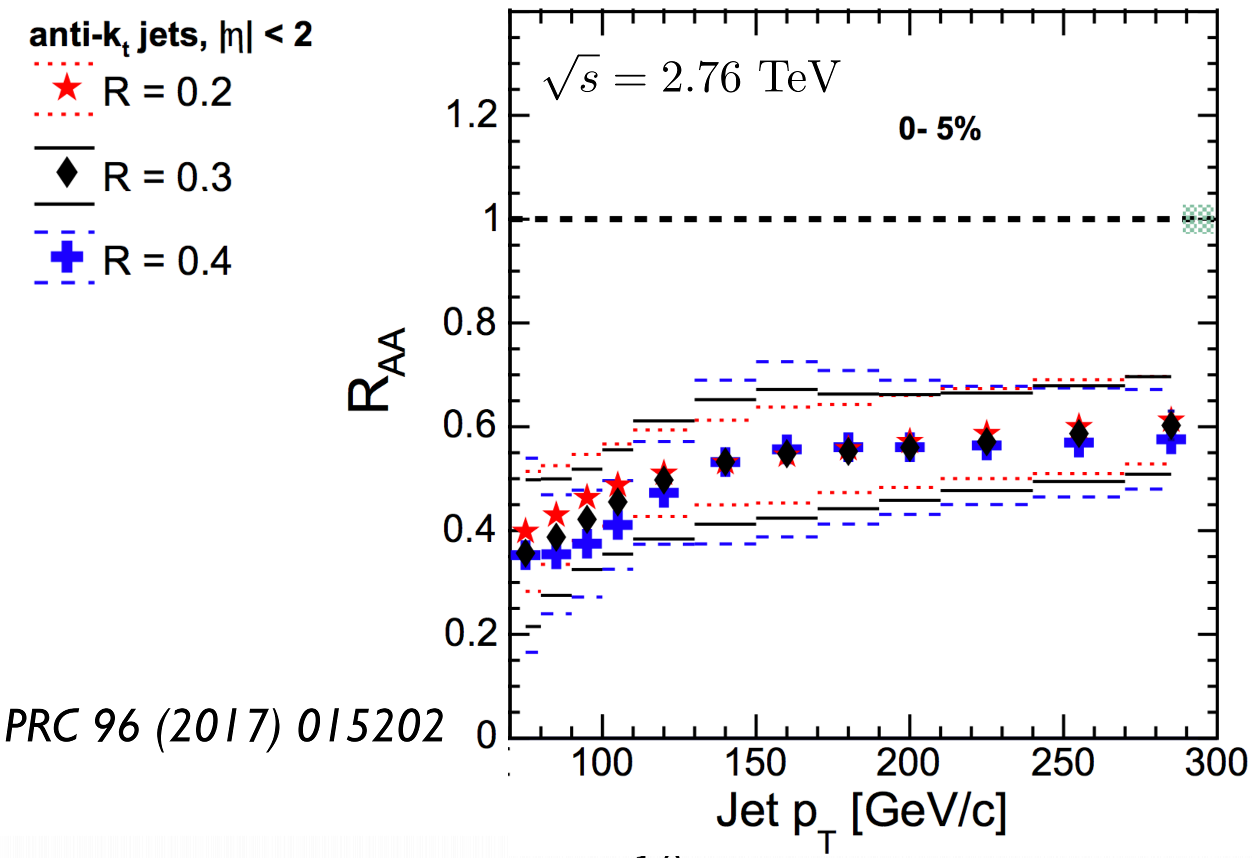
Nuclear modification factor

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

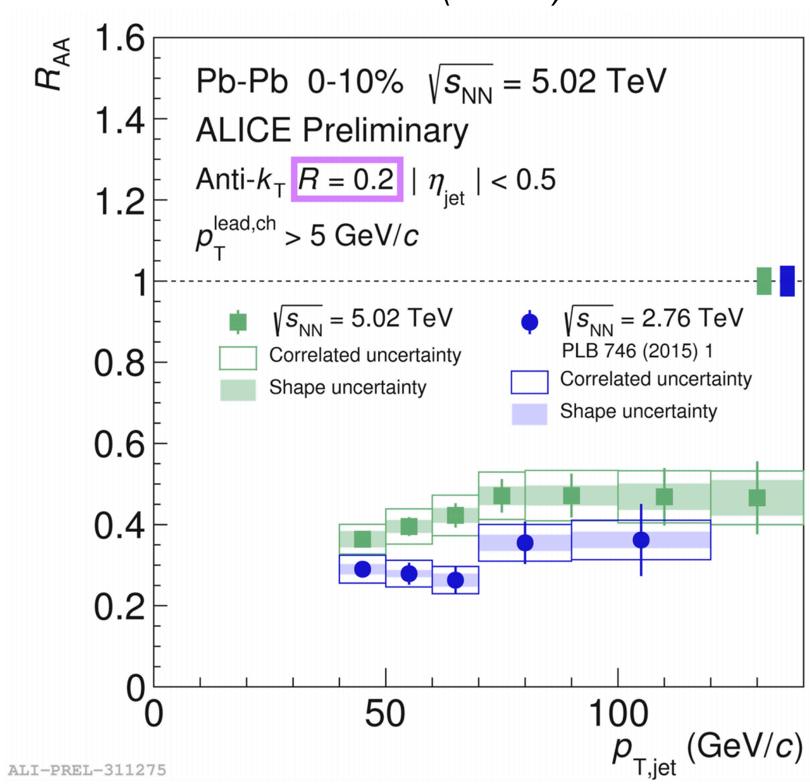
Inclusive jet production at the LHC



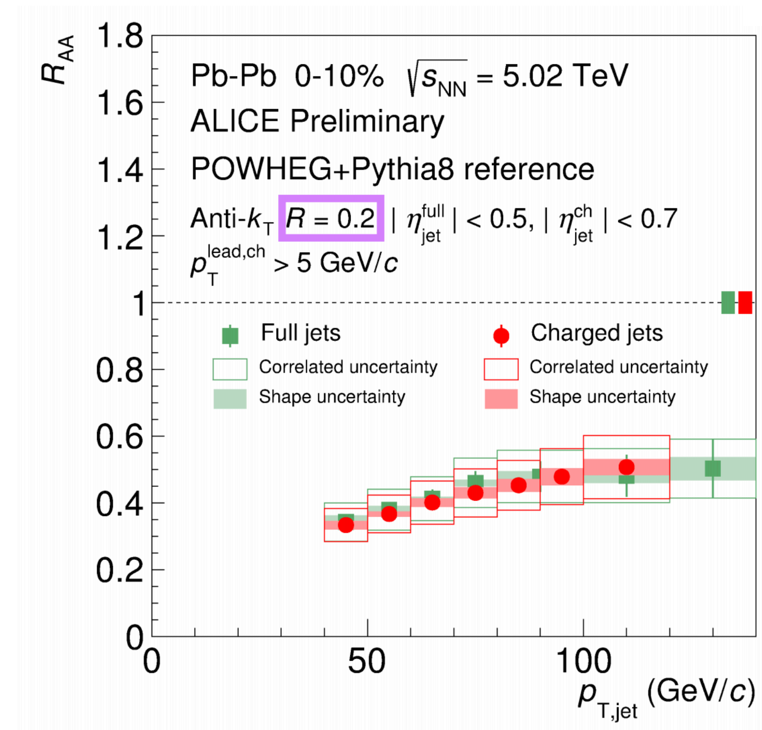
ATLAS, PRL 114 (2015) 072302, PLB 790 (2019) 108

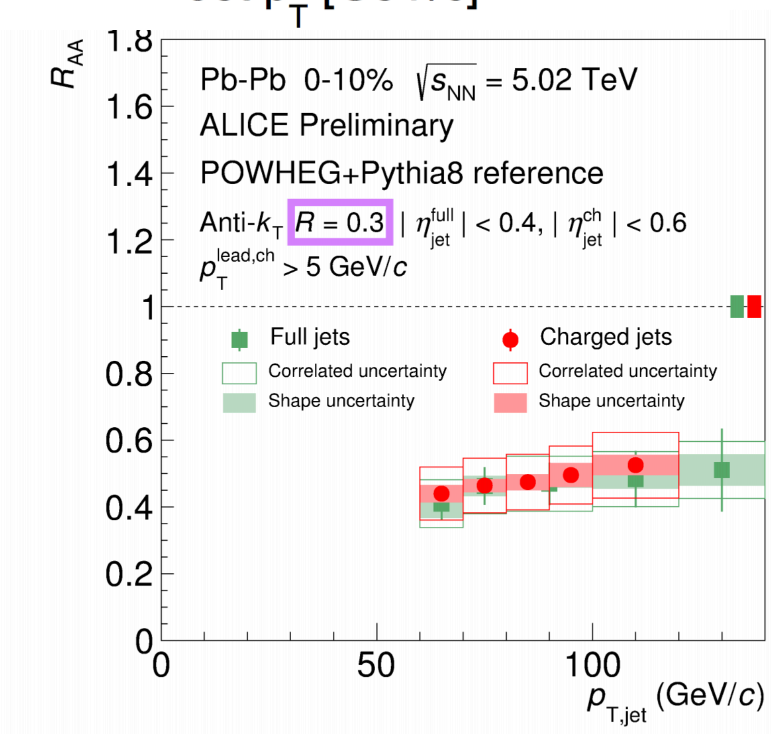


CMS, PRC 96 (2017) 015202



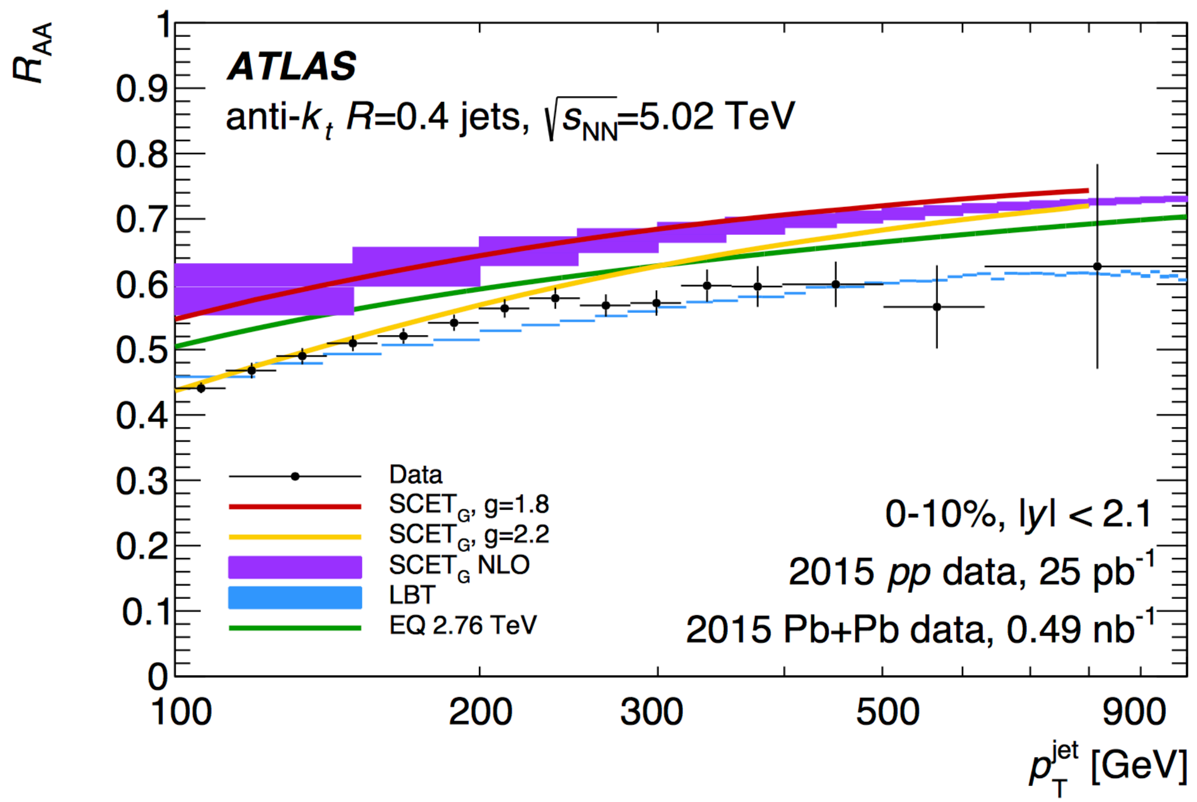
ALICE, PLB 746 (2015) 1



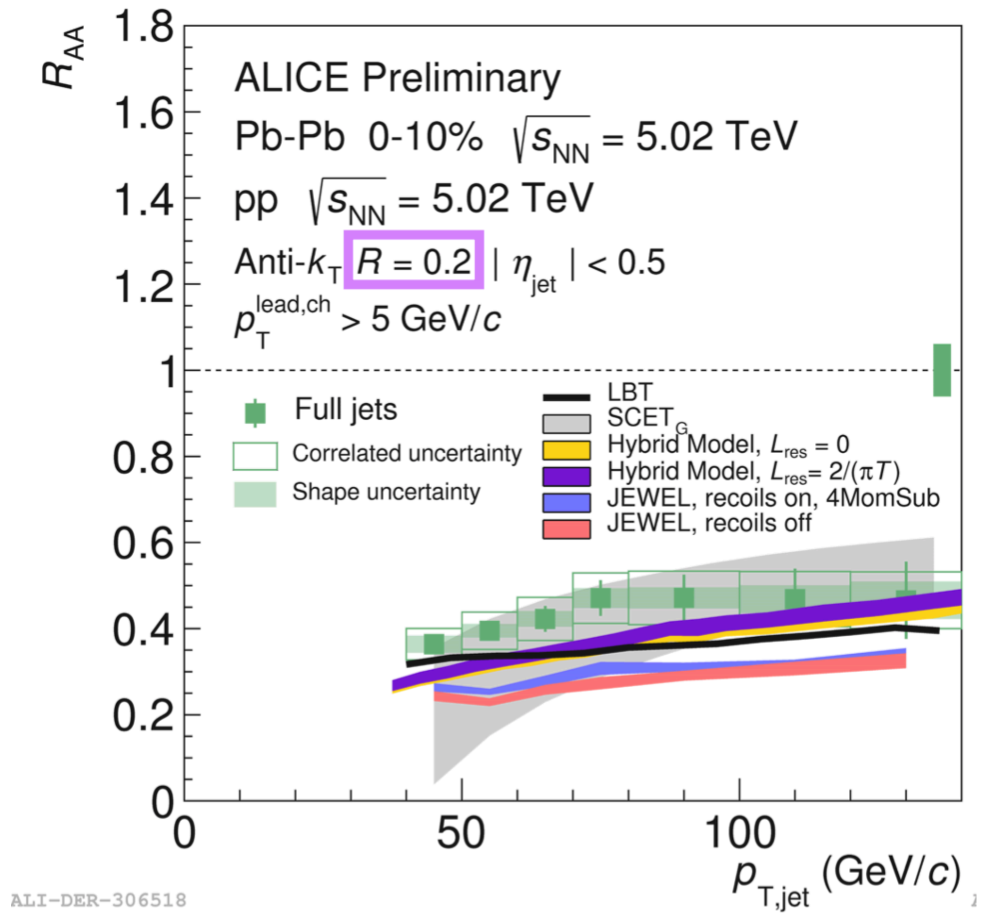


ALICE preliminary, J. Mulligan, HardProbes18

Inclusive jet production at the LHC



ATLAS, PLB 790 (2019) 108

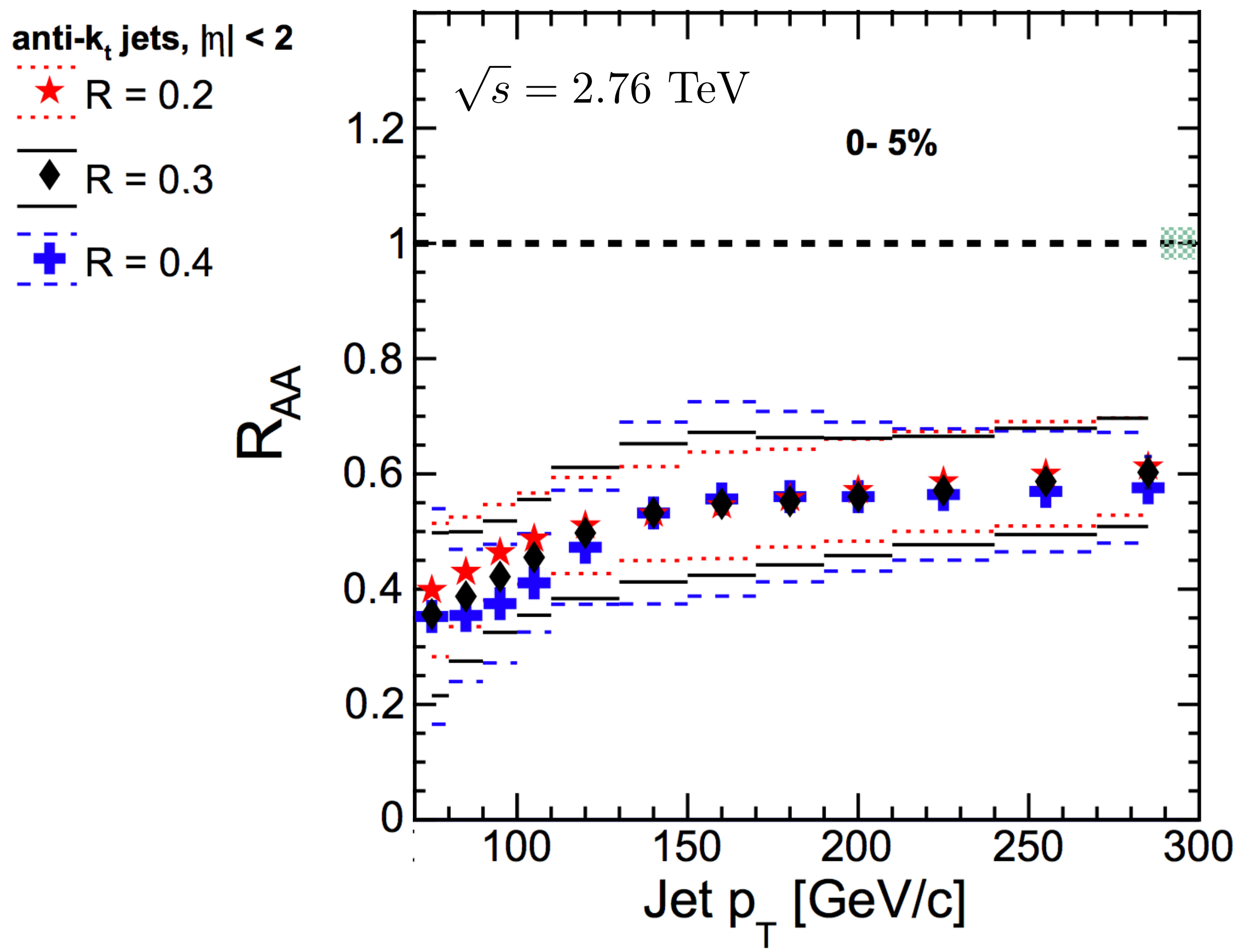


ALICE preliminary, J. Mulligan, HardProbes18

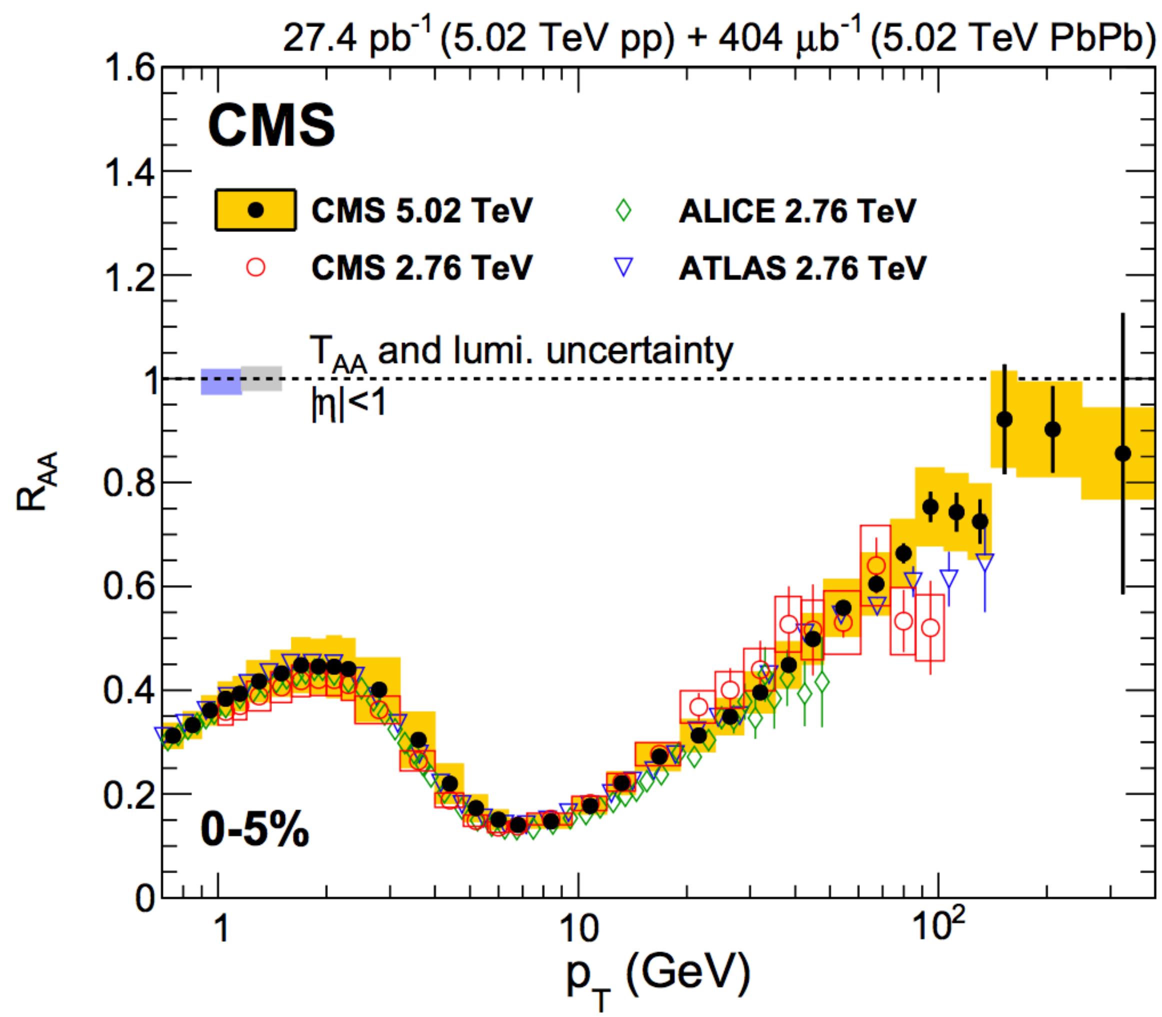
This talk …

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

Jet vs hadron R_{AA} - Factorization and universality?



CMS, PRC 96 (2017) 015202



CMS, JHEP 1704 (2017) 039

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

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

- See also jet substructure measurements

Outline

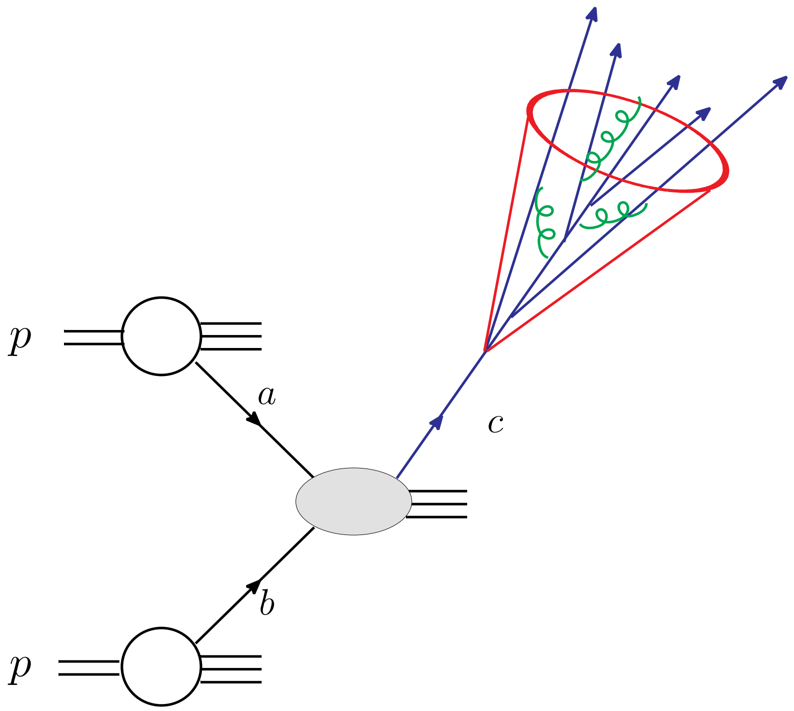
- Introduction
- Inclusive jet production
- Phenomenological results
- Conclusions

QCD factorization

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

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

Perturbatively calculable



Ellis, Kunszt, Soper `90

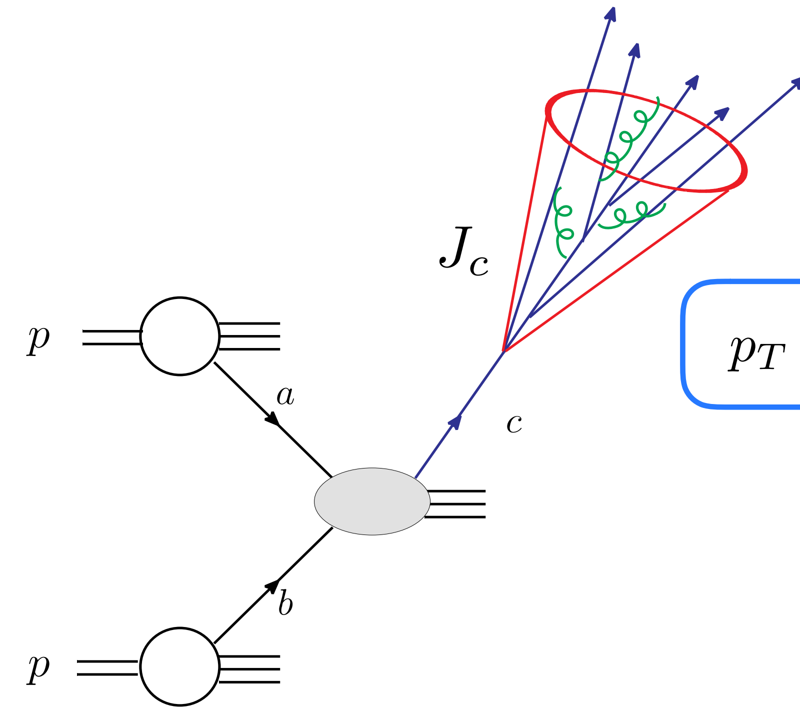
QCD factorization

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

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

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

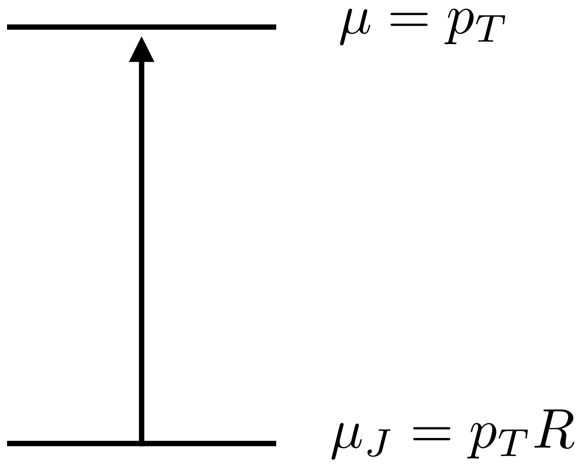
Perturbatively calculable



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

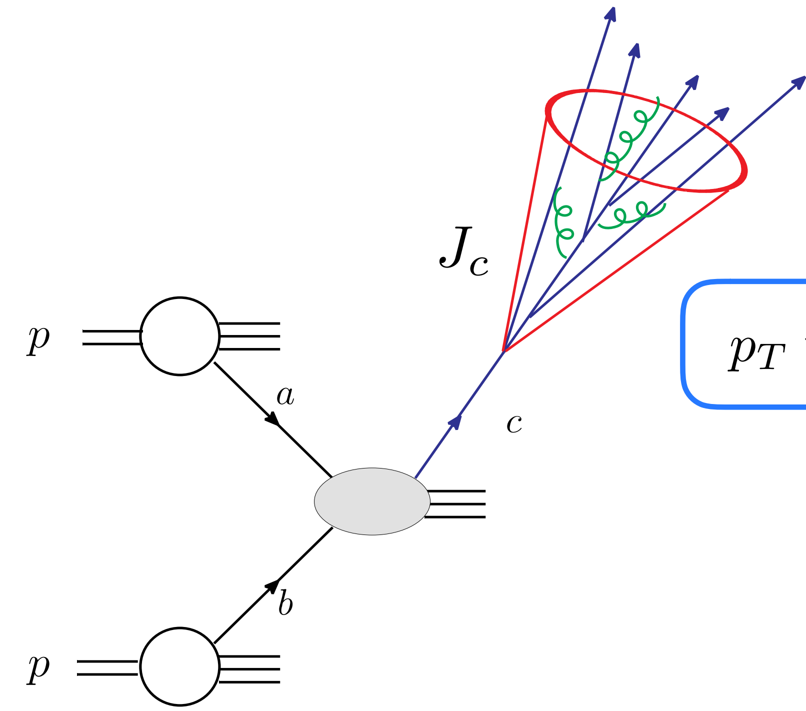
QCD factorization

- 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. $p_T R$

- Similar to $pp \to h + X$

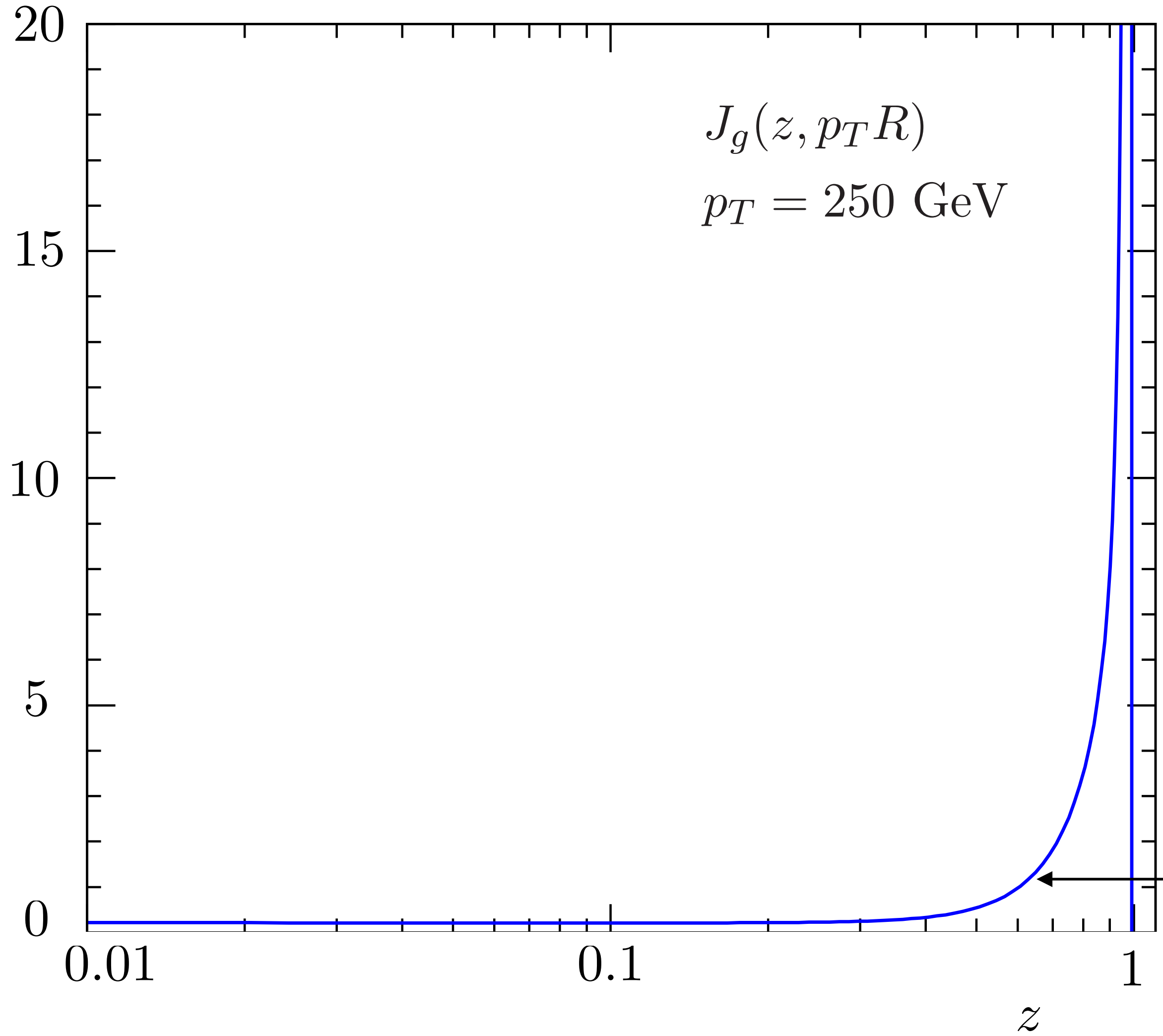
$$\frac{d\sigma^{pp\to h+X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes D_c^h$$

Non-perturbative FFs

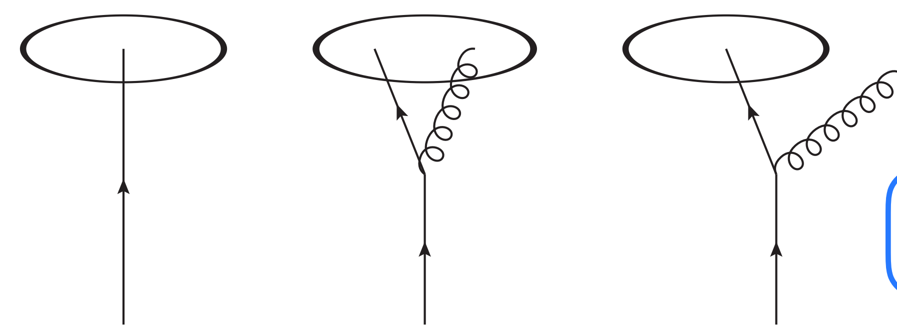
Ellis, Kunszt, Soper `90
Dasgupta, Dreyer, Salam, Soyez `15
Kaufmann, Mukherjee, Vogelsang `15
Kang, FR, Vitev `16
Dai, Kim, Leibovich `16

Jet functions in the vacuum

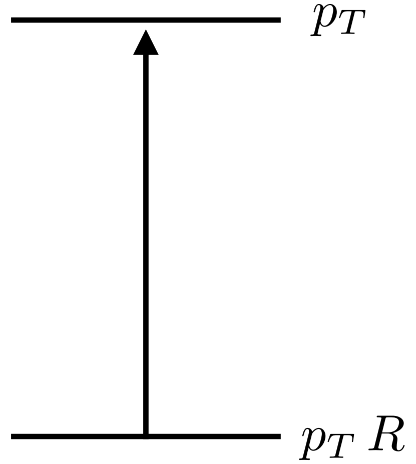
Kang, FR, Vitev `16



initial condition
for the evolution



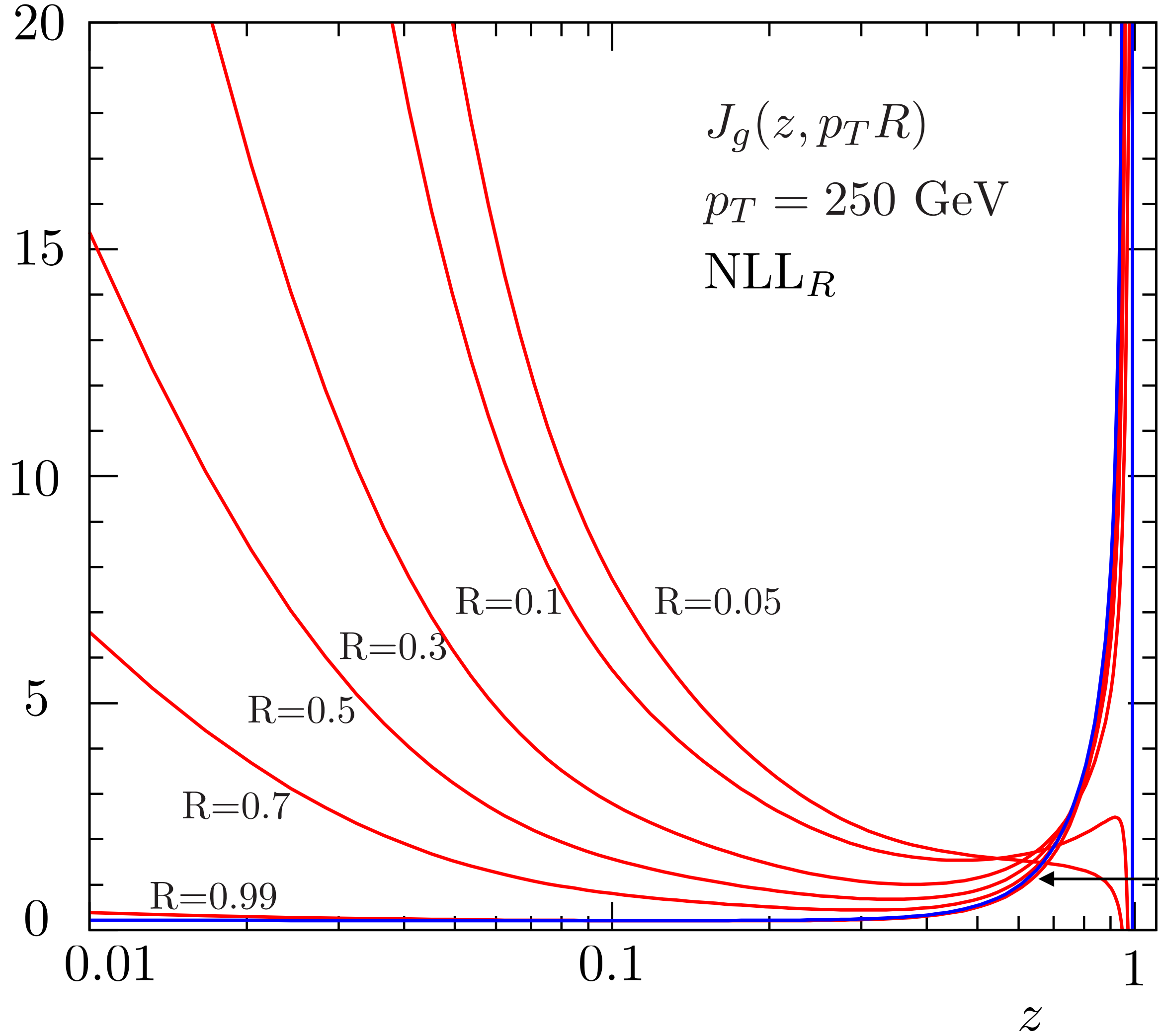
$z = p_T / p_T^c$



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

Jet functions in the vacuum

Kang, FR, Vitev `16



initial condition
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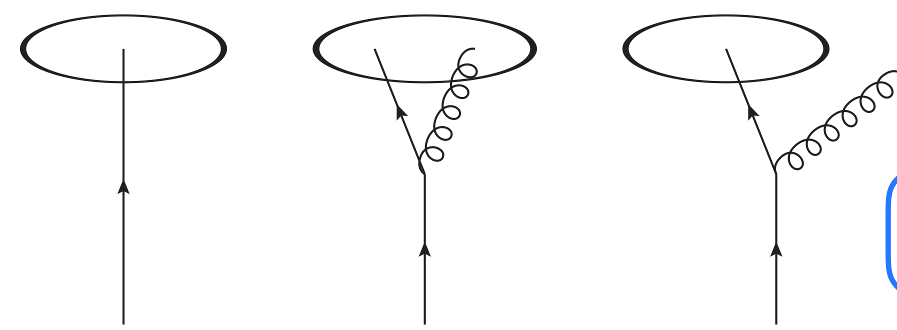
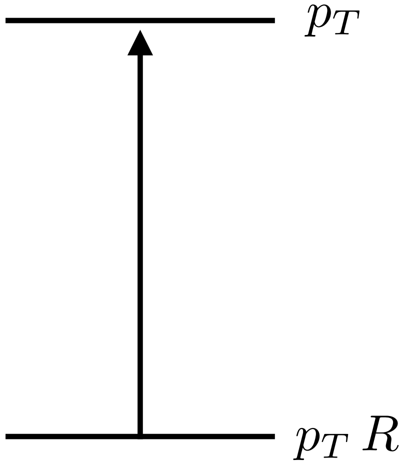


$z = p_T / p_T^c$



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

In-medium jet functions

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

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

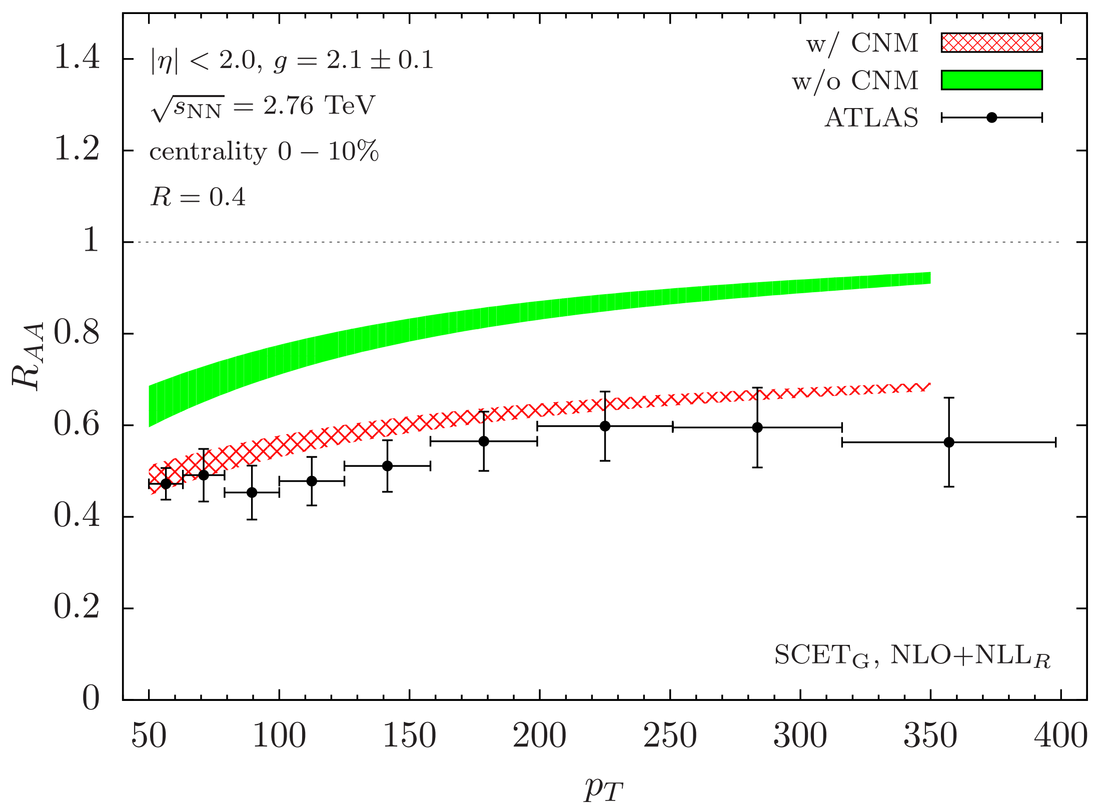
Allows for identifying jet quenching with the final state jet function

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

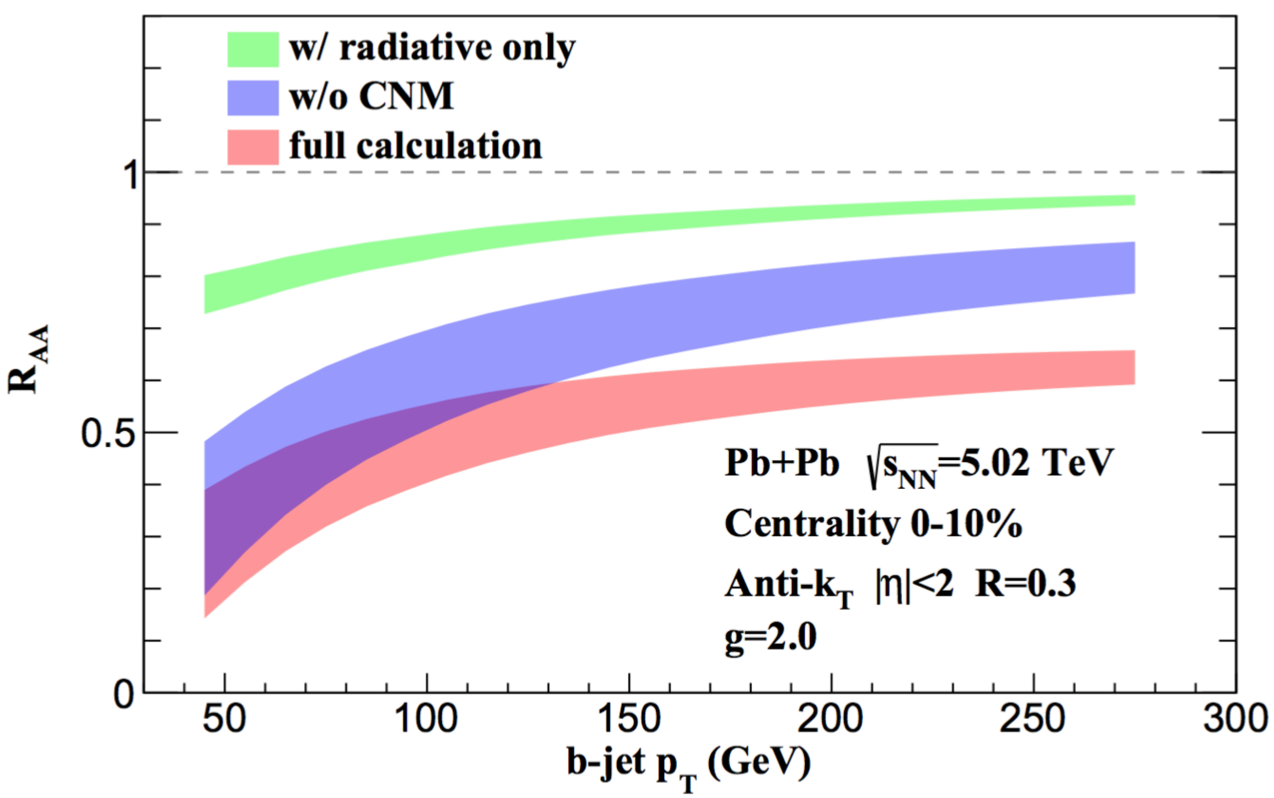
$$J_{qq}(z, p_T R, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P_{qq}(z, q_\perp) \right]_+$$

see also He, Pang, Wang `18
Sirimanna, Cao, Majumder `19

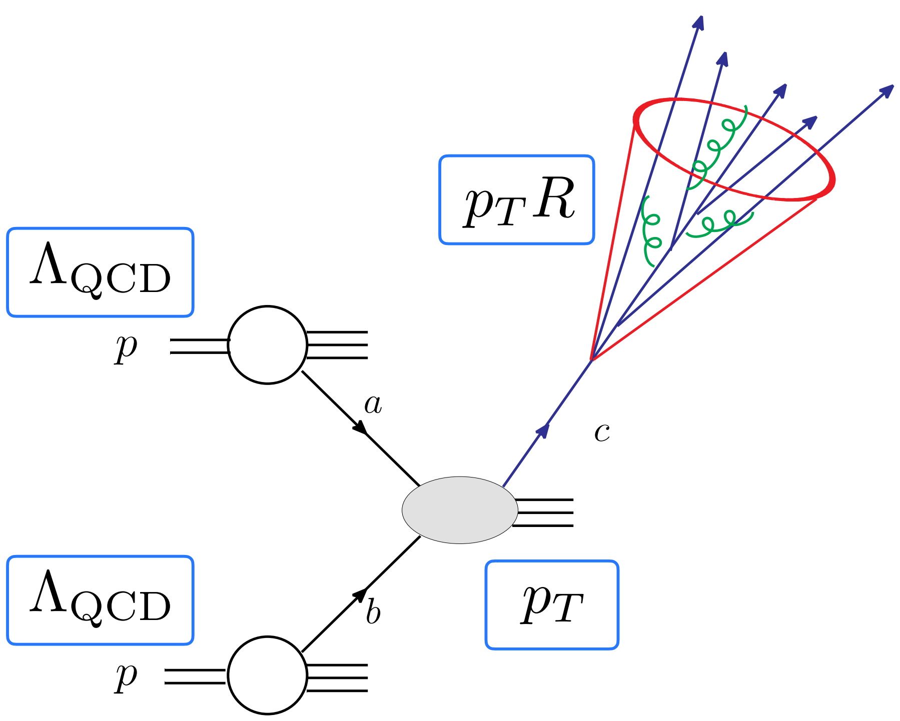
- Inclusive jets



- b-jets *Li, Vitev `18*



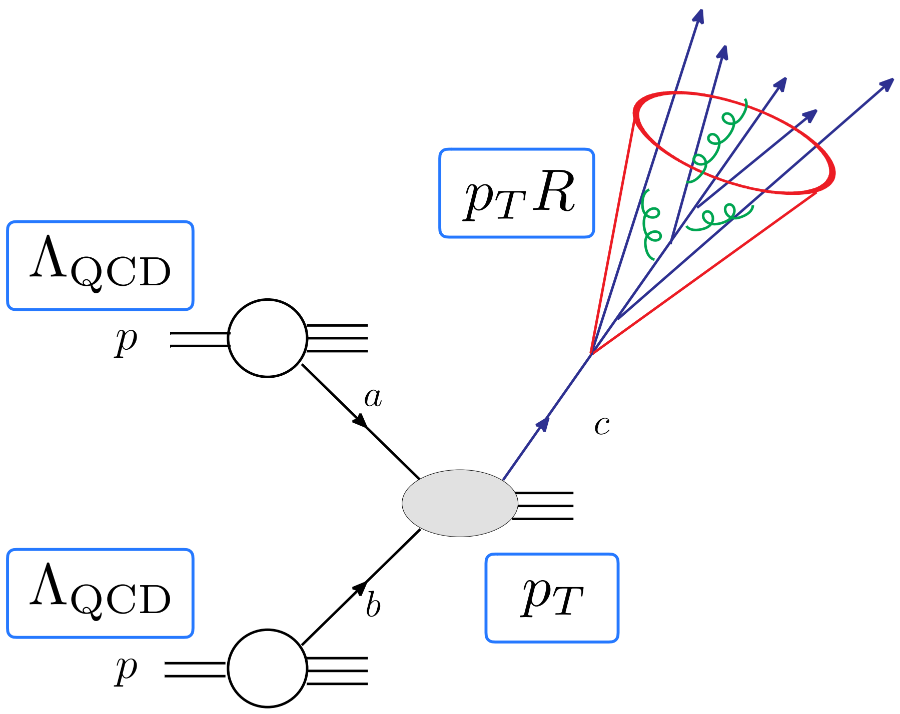
QCD factorization



Separation of scales

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

QCD factorization



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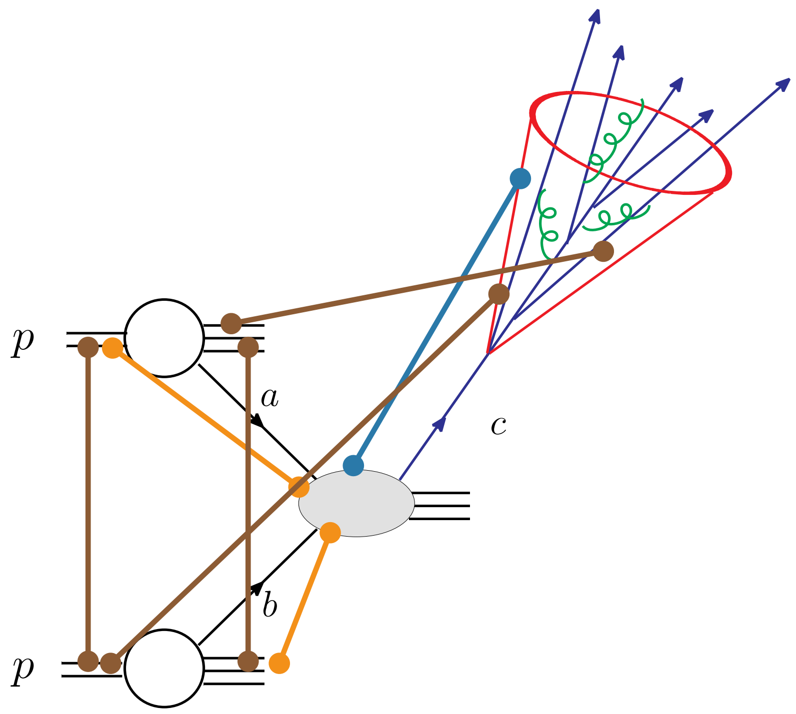


Separation of scales

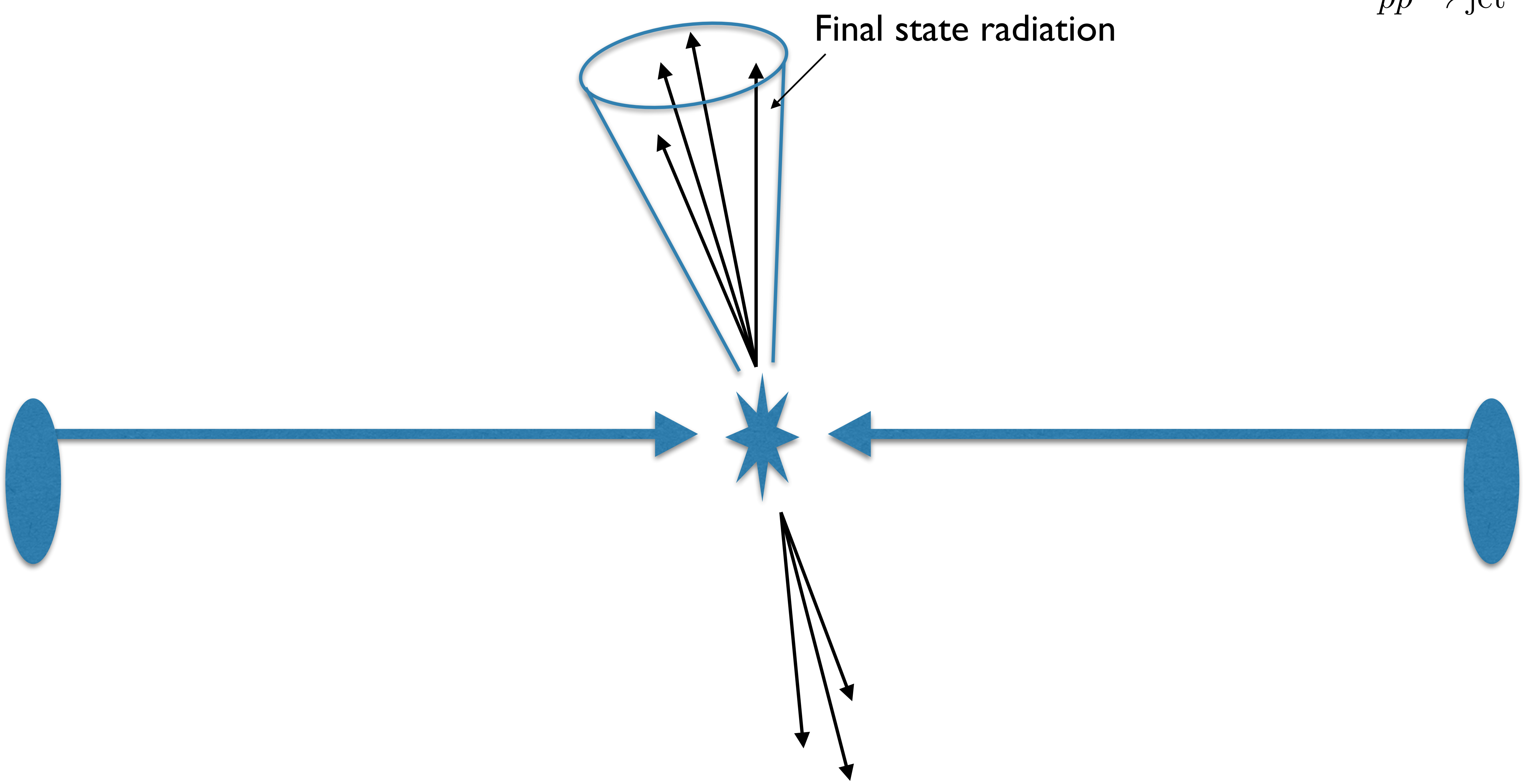
$$\frac{d\sigma^{pp\to {\rm jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes J_c$$

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

- Cancellation of Glauber gluon exchange?
- Corrections at subleading power?
- Coherent/incoherent corrections?

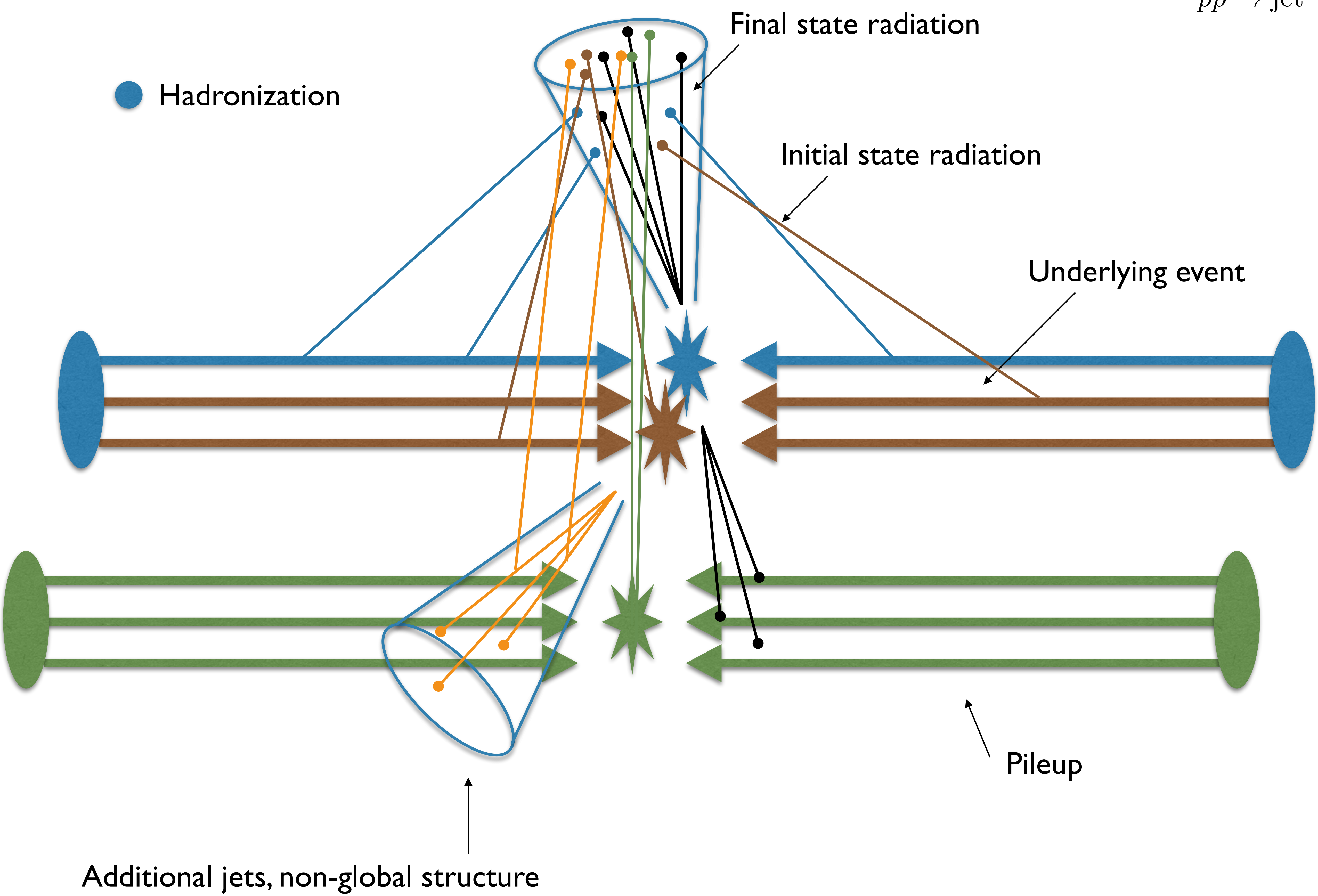
Qiu, Sterman `91, Botts, Qiu, Sterman `91

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



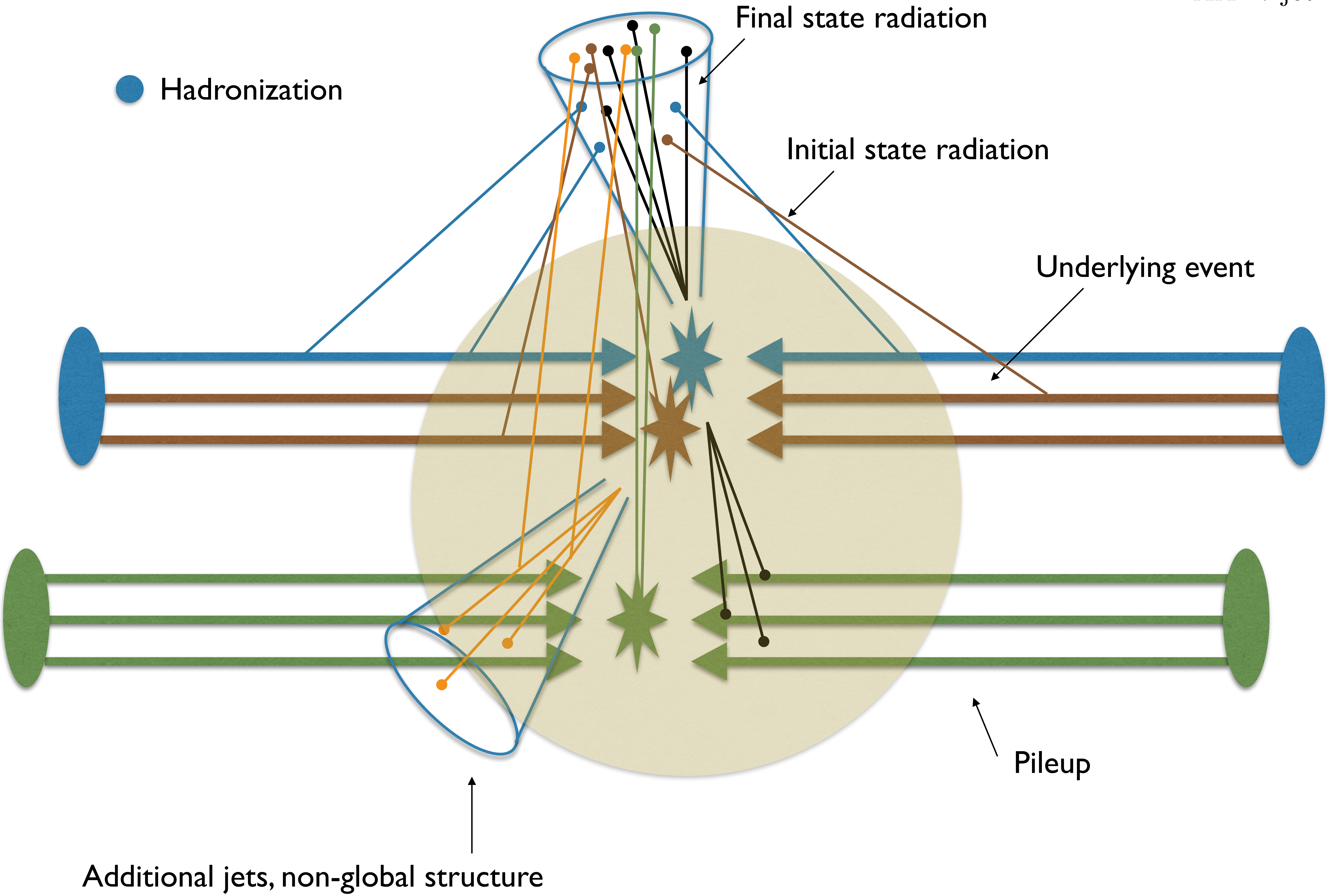
adapted from M. Schwartz `17

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



adapted from M. Schwartz `17

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



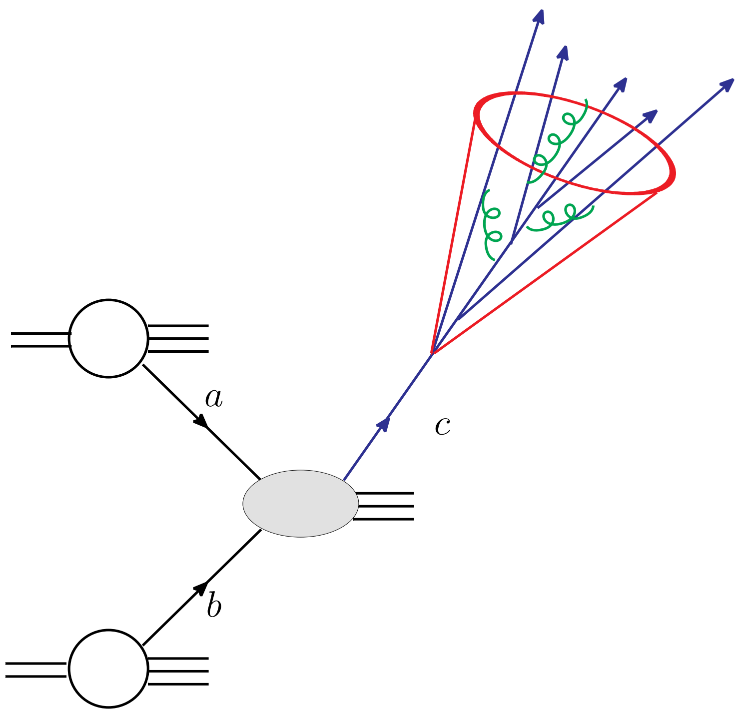
adapted from M. Schwartz `17

QCD factorization

- Proton-proton
  - Proofs: Drell-Yan process *Collins, Soper, Sterman `85, Bodwin `85*
  - Partial proofs: $pp \to h + X$ *Nayak, Qiu, Sterman `05*
  - Factorization breaking effects *Mulders, Rogers `10*
  - Phenomenologically established:

  Global analyses of PDFs gives a consistent picture!

  ABMP, CJ, CT, JAM, MMHT, NNPDF …



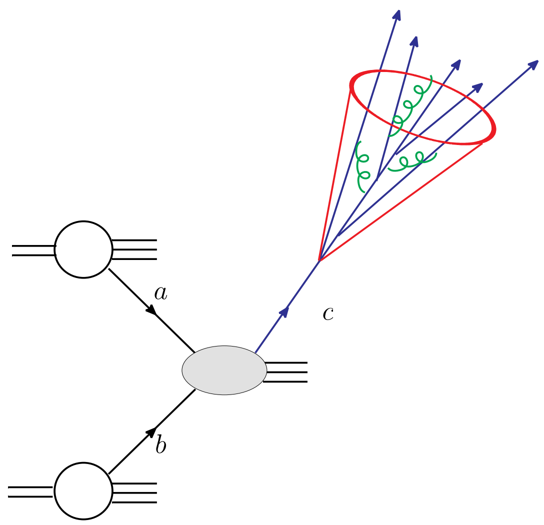
- Heavy-ion
  - Possibly broken. If so, how large is the effect?

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

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

A first global analysis

Qiu, FR, Sato, Zurita `19



- 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

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

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

⟶ 6 independent parameters

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

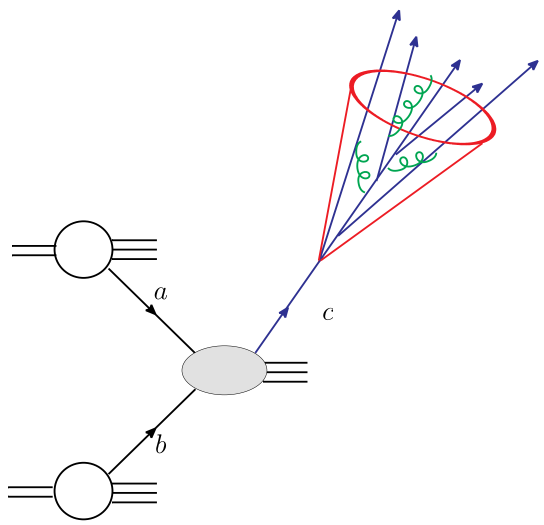
nFFs *Sassot, Stratmann, Zurita `10*

A first global analysis

Qiu, FR, Sato, Zurita `19

- RG evolution as in the vacuum

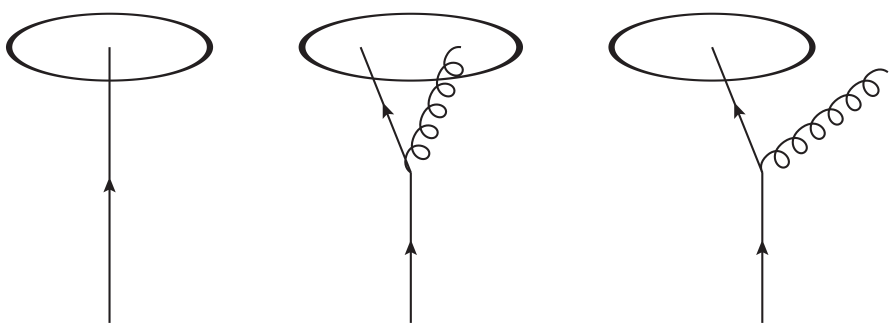
$$\frac{d}{d\mu} J_i(z, p_T R, \mu) = \sum_j P_{ji}(z) \otimes J_j(z, p_T R, \mu)$$



- Introduce medium modified jet function at the jet scale

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

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



- Momentum sum rule

$$\int_0^1 dz\, z\, J_i^{\rm med}(z, \hat{p}_T R, \mu_J) = 1$$ which is conserved by the evolution

Relation to a parton shower picture

For example:

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

vacuum shower

shower cutoff

Linearized Boltzmann Transport

see also JEWEL, Martini, Q-Pythia, JETSCAPE

- 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

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

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
  Qiu, FR, Sato, Zurita `19

vacuum shower

?

$p_T R$

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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

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

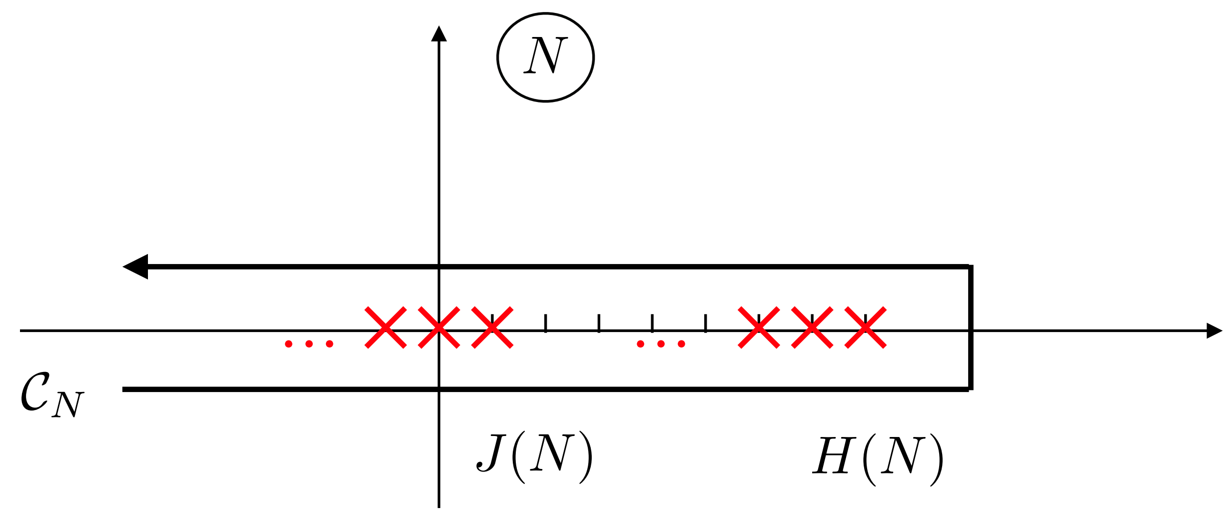
Actual convolution

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

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

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

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

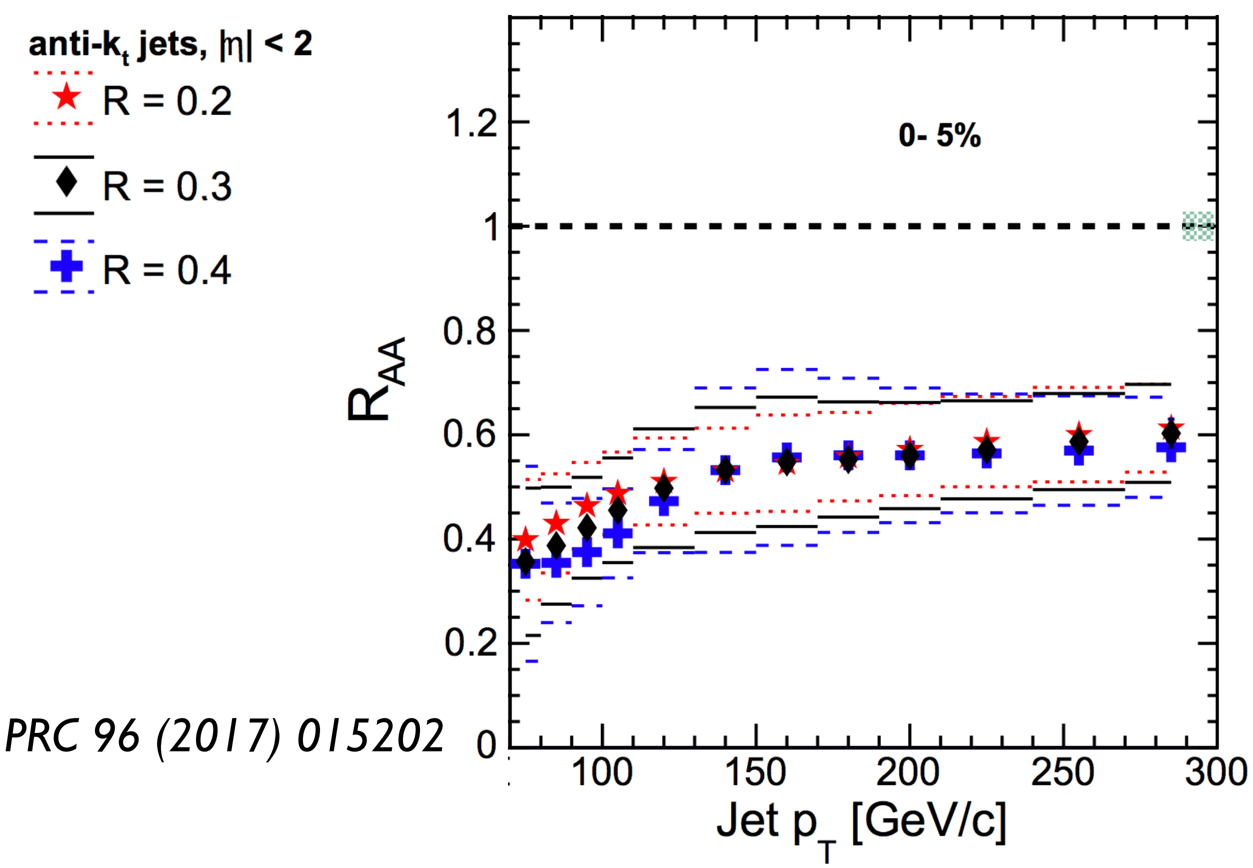


- Error analysis based on the technique from NNPDF, JAM

Ball et al. `17, Accardi, Brady, Melnitchouk, Owens, Sato `16

A first global analysis

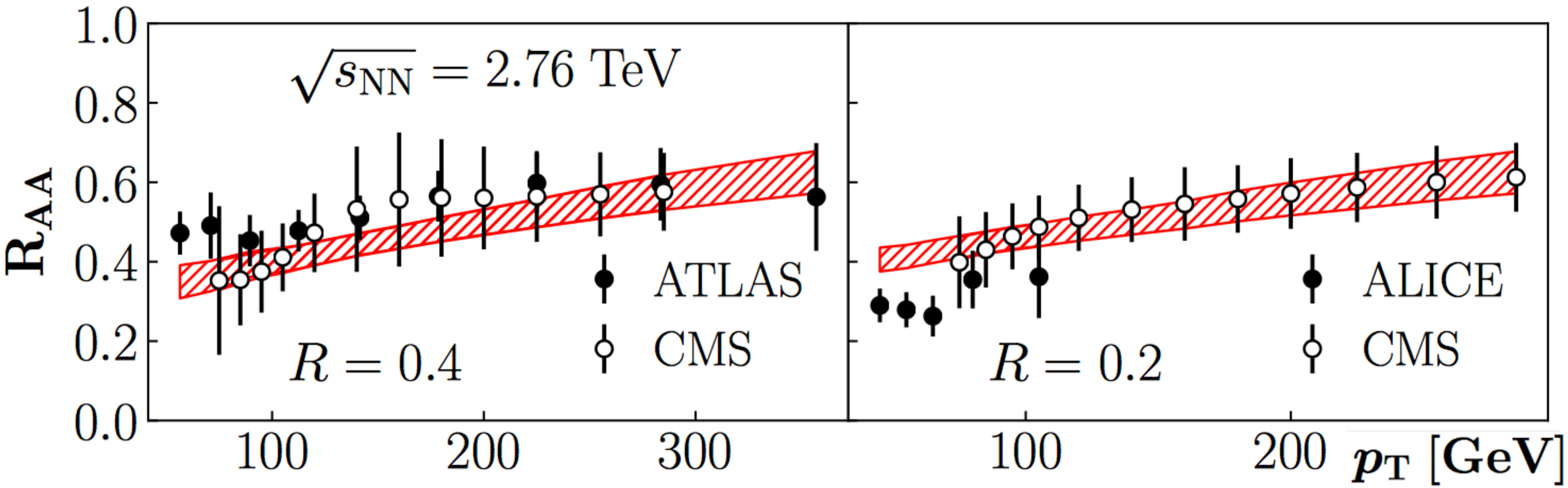
- Non-trivial χ^2 profile
- Require physical solutions
- It is not possible to fit the data with $W_q(z) = W_g(z)$ while requiring a "physical solution"



CMS, PRC 96 (2017) 015202

Inclusive jet production PbPb at the LHC

$\sqrt{s} = 2.76\ \mathrm{TeV}$ Fit with $\chi^2/\mathrm{d.o.f.} = 1.1$



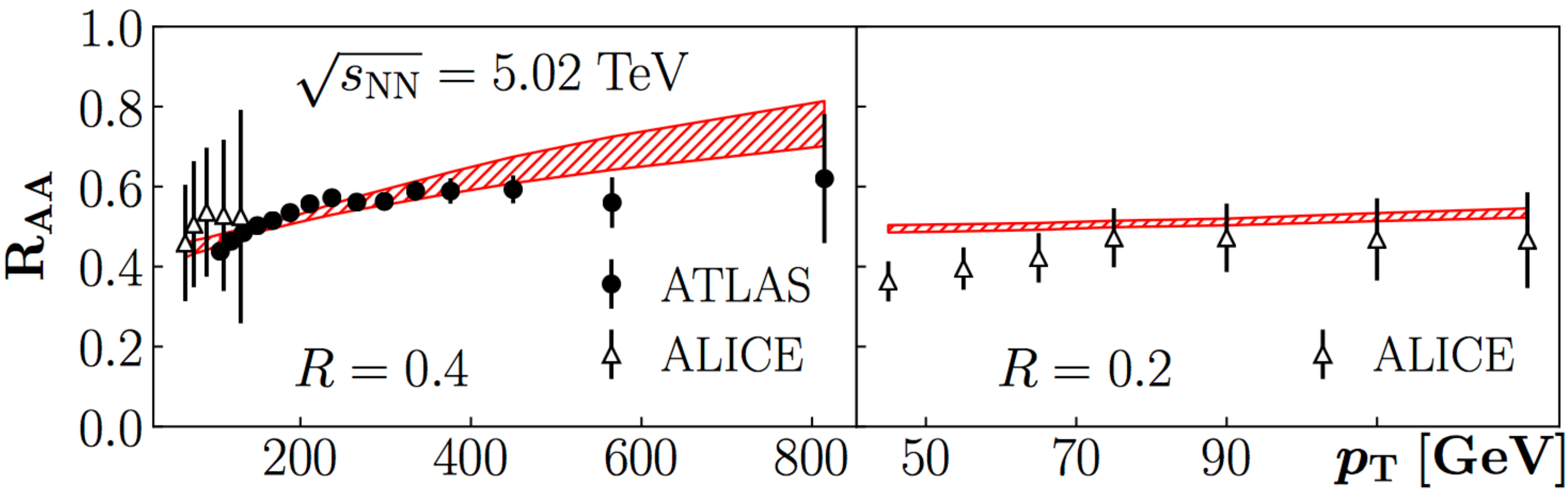
No initial state effects or nPDFs

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

CMS also $R = 0.3$

Inclusive jet production PbPb at the LHC

$\sqrt{s} = 5.02$ TeV Fit with $\chi^2/\text{d.o.f.} = 1.7$



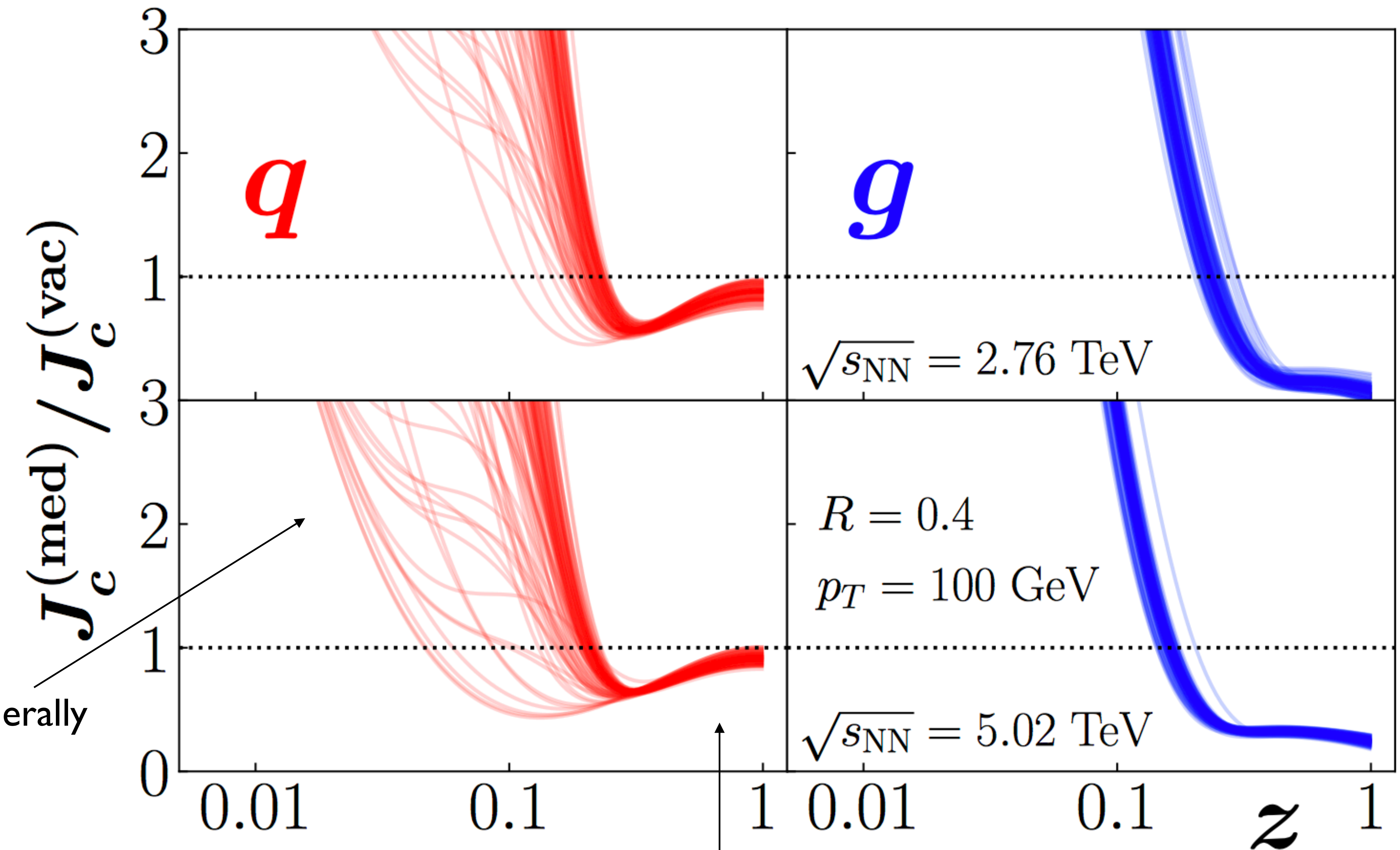
No initial state effects or nPDFs

- High p_T easy to fit
- Low p_T more difficult

→ Modification of DGLAP at low p_T?

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

The medium modified jet functions



Small-z region generally less constrained

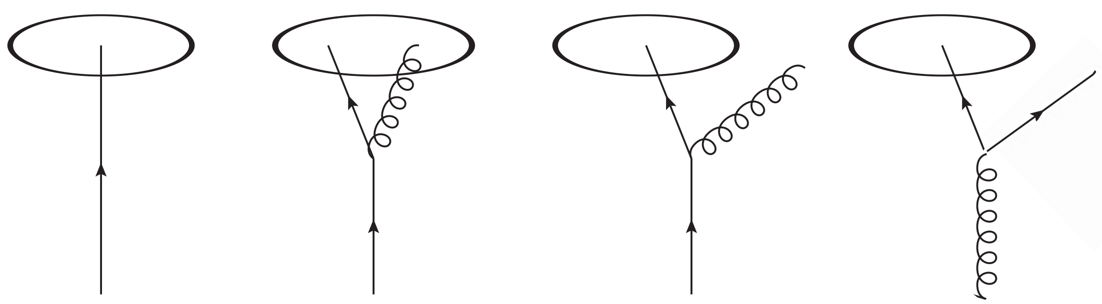
Potentially requires threshold resummation for $z \to 1$

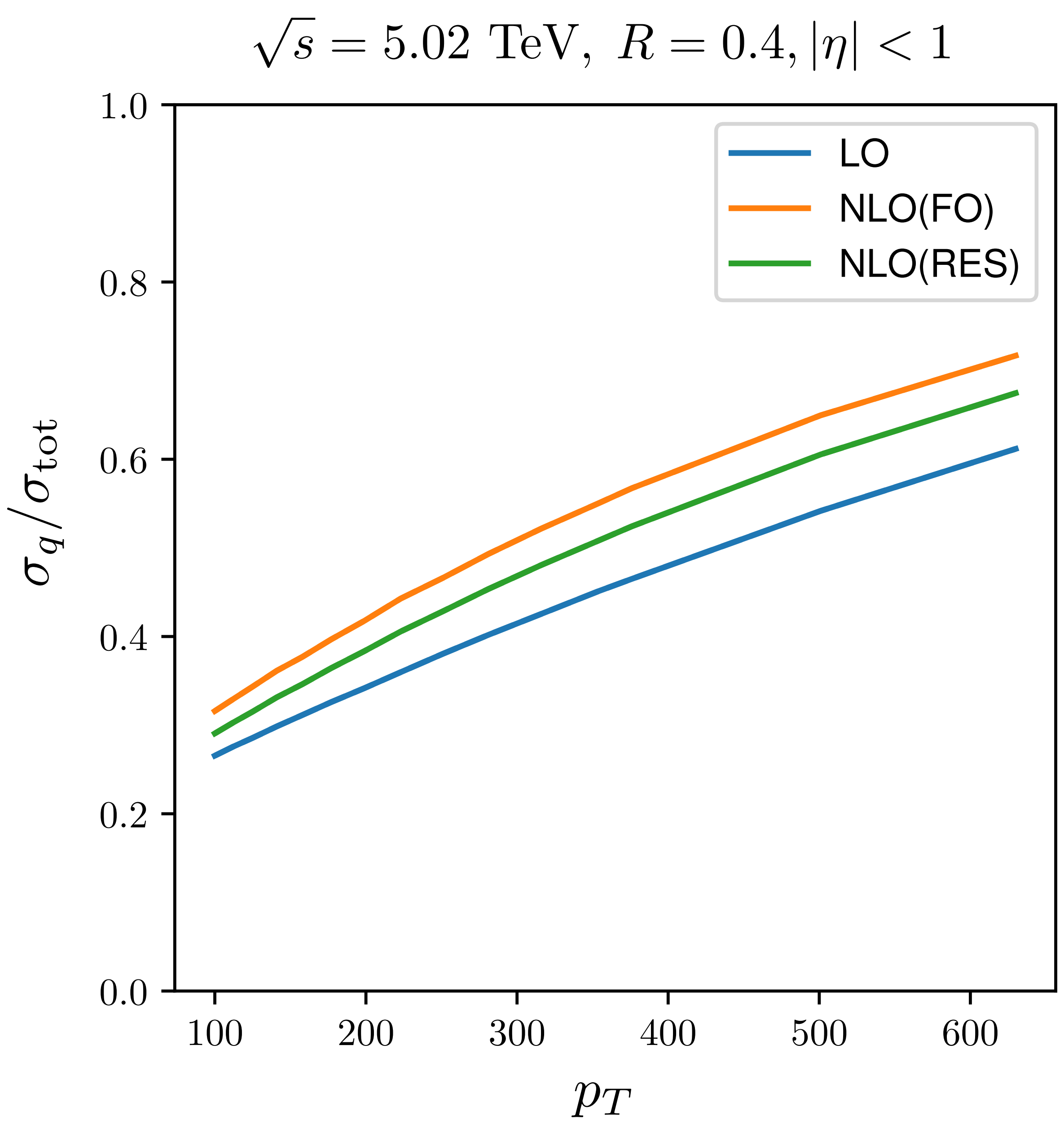
Quark/gluon jets

Keeping track of the flavor d of the jet

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

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

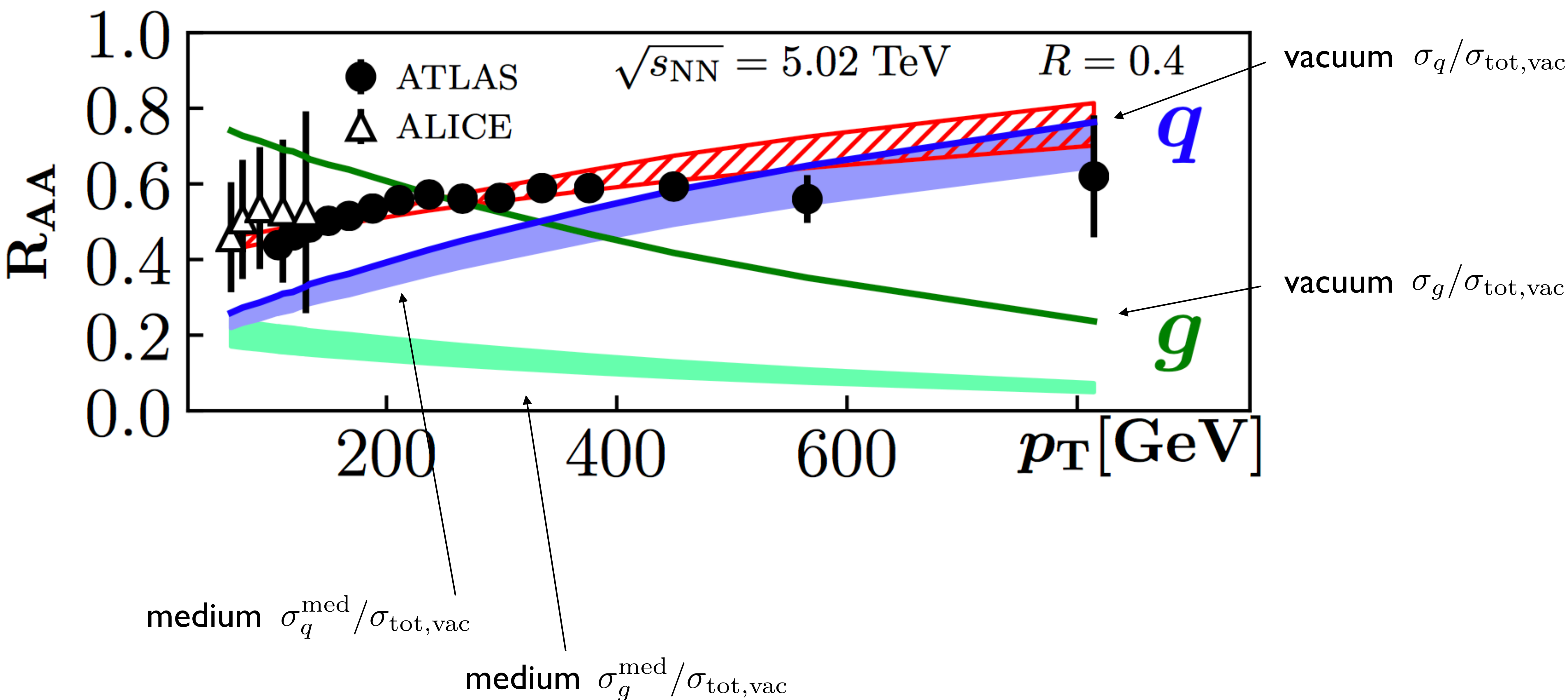




- R_{AA} is sensitive to q/g jets
- Dependence on the perturbative accuracy

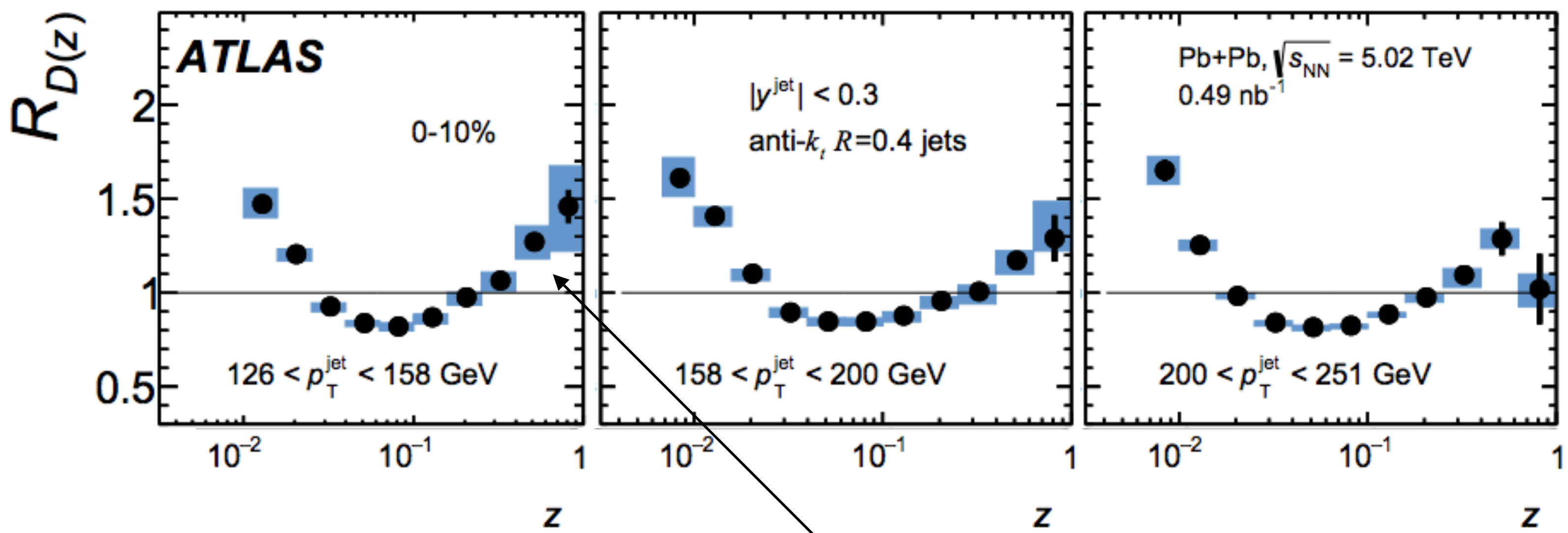
see also Banfi, Salam, Zanderighi `06
Cal, FR, Waalewijn `19

Quark/gluon jets



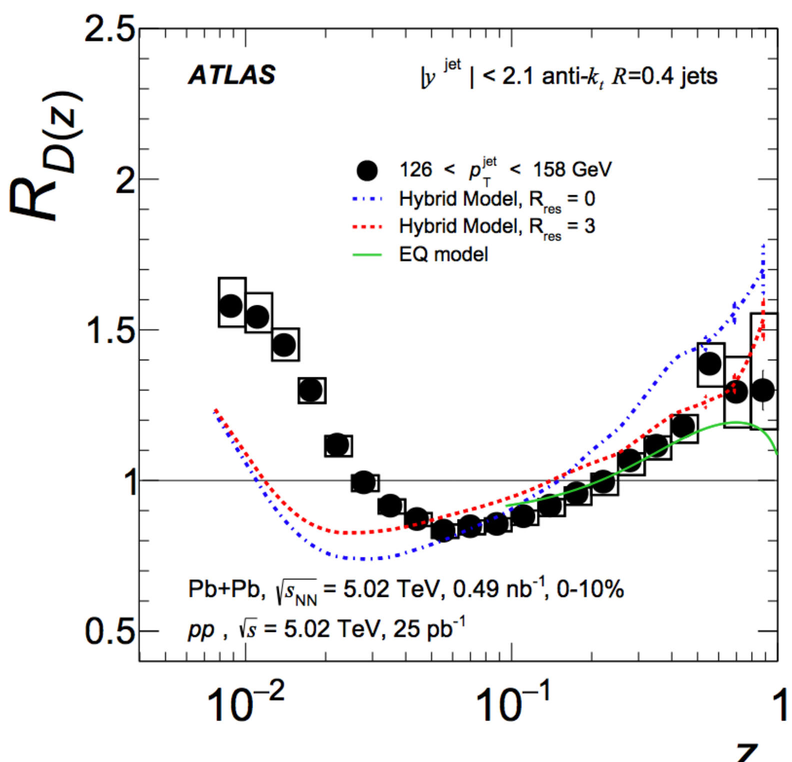
- Sensitivity to q/g
- Need additional handle from $\gamma + \text{jet}$

Results from jet substructure



ATLAS, PRC 98 (2018) 024908

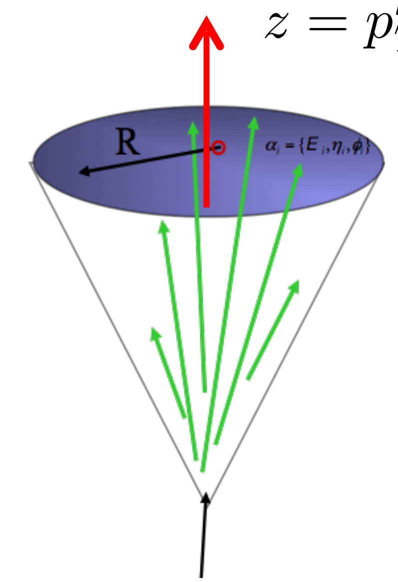
The jet fragmentation function



Spousta, Cole `15

Quark-like fragmentation at large-z

$z = p_T^h / p_T^{\rm jet}$



The R_{AA} as a function of the jet radius

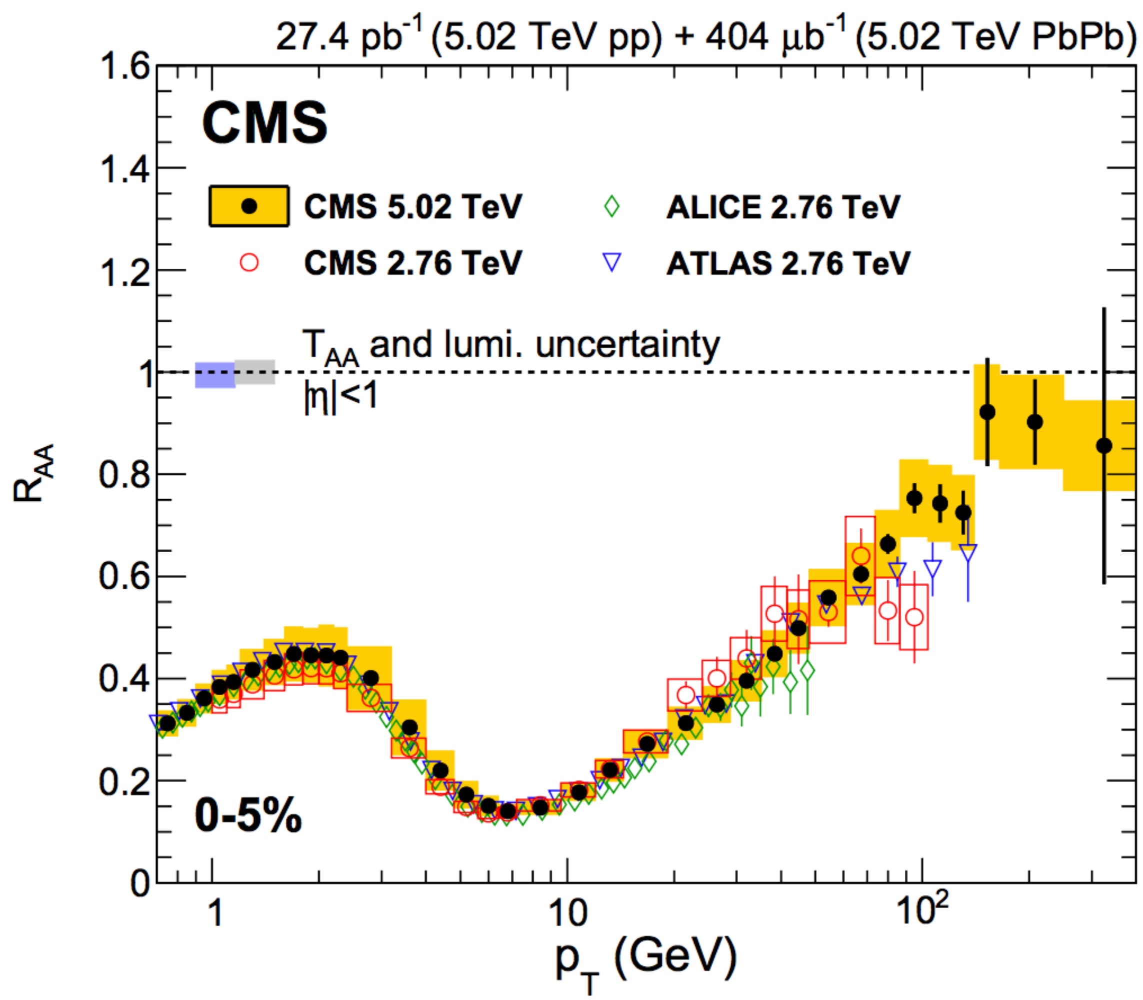
- Large-R - Parton energy loss recovered in larger jet $R_{AA}\uparrow$
- Small-R
  - Jet sample with harder fragmentation spectrum for fixed p_T $R_{AA}\uparrow$
  - Formally for $R\to 0$ the hadron R_{AA} should be obtained $R_{AA}\uparrow$

Factorization

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

$$R \to 0$$

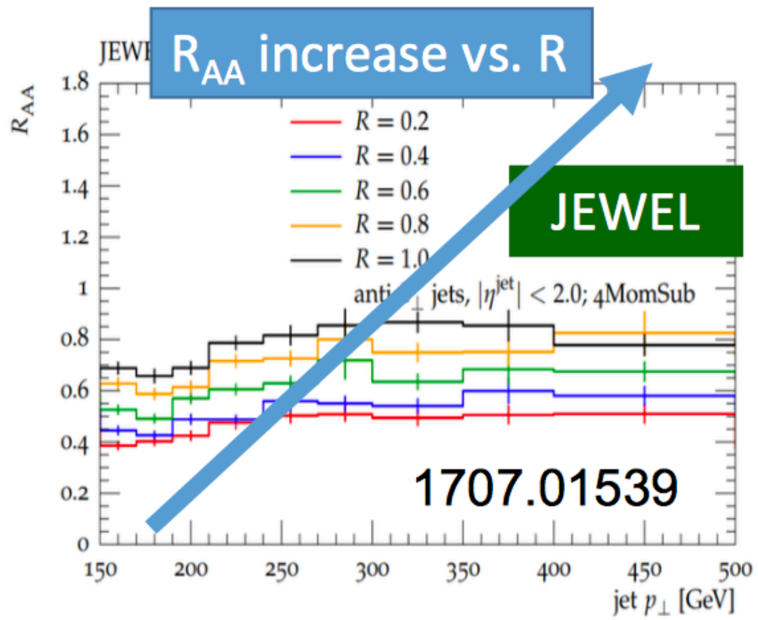
Non-perturbative fragmentation functions D_c^h

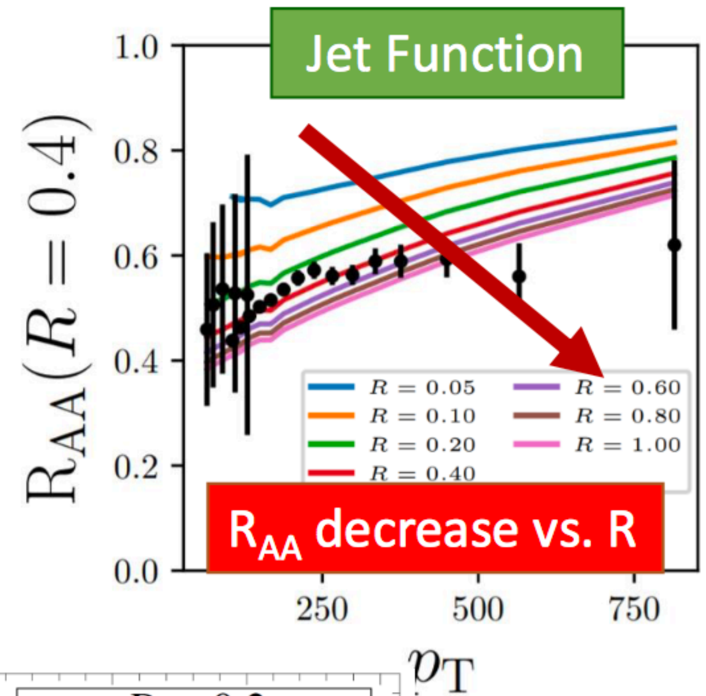


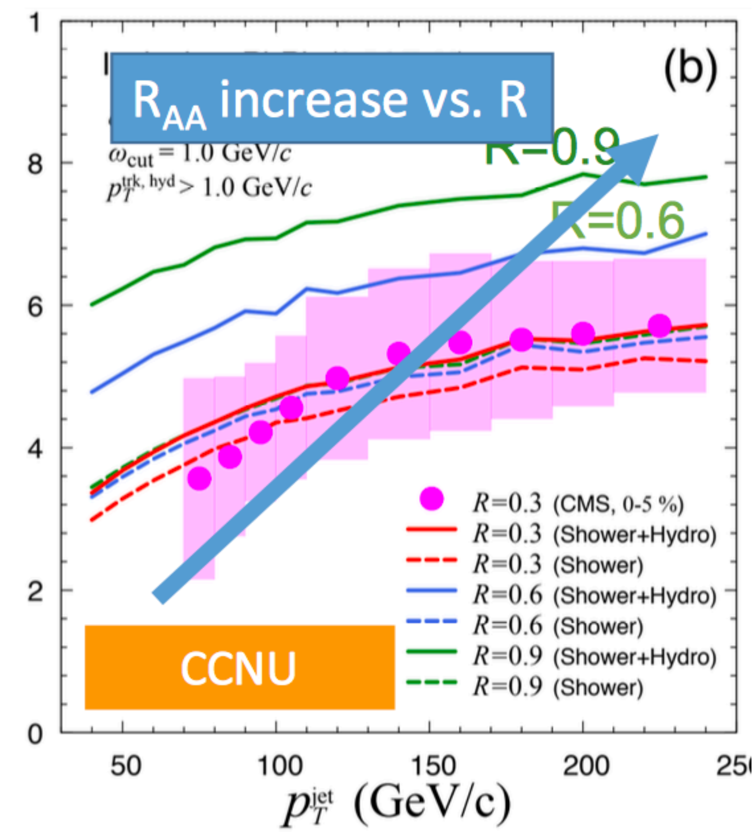
see also: Sirimanna, Cao, Majumder `19

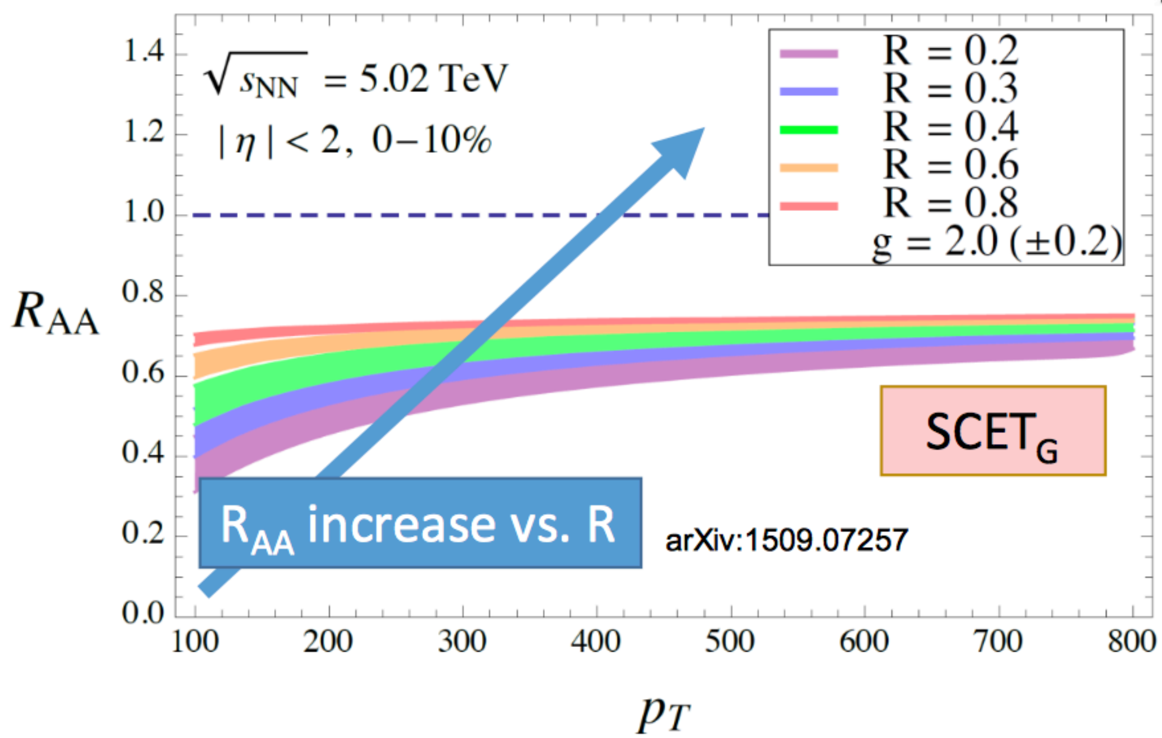
CMS, JHEP 1704 (2017) 039

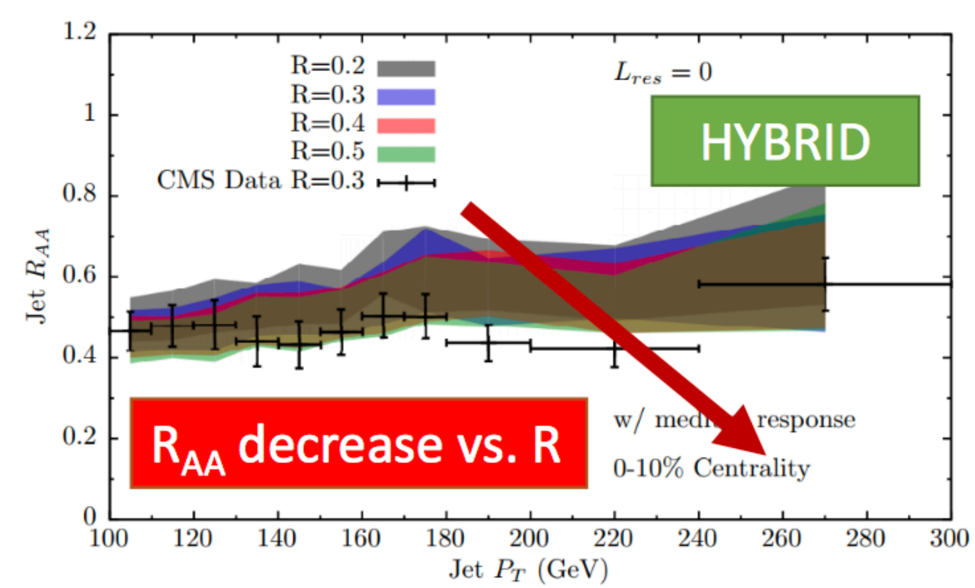
The R_{AA} as a function of the jet radius





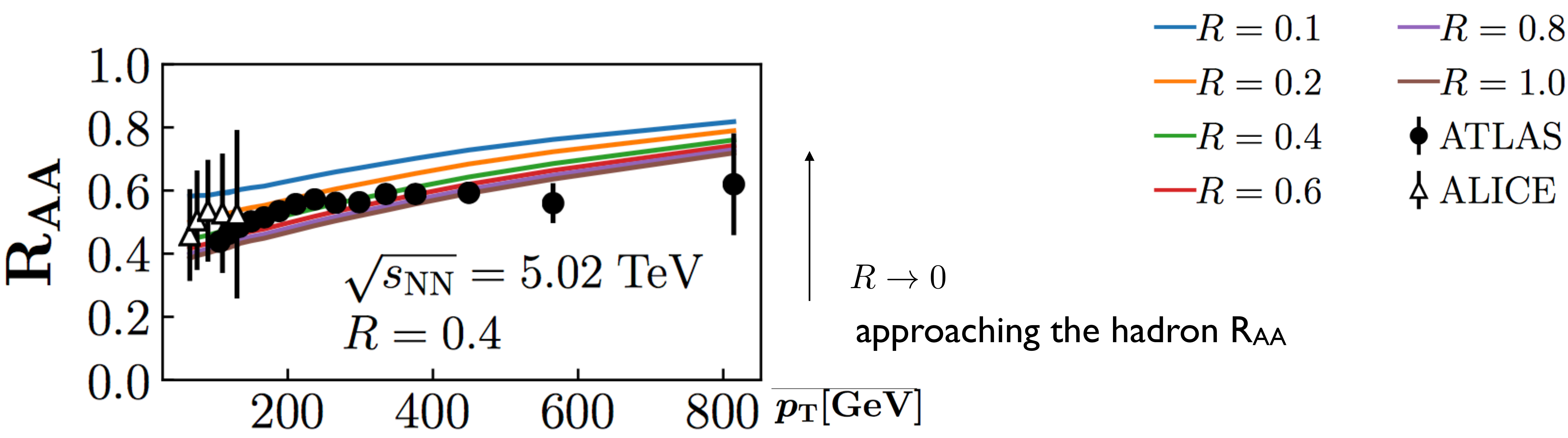






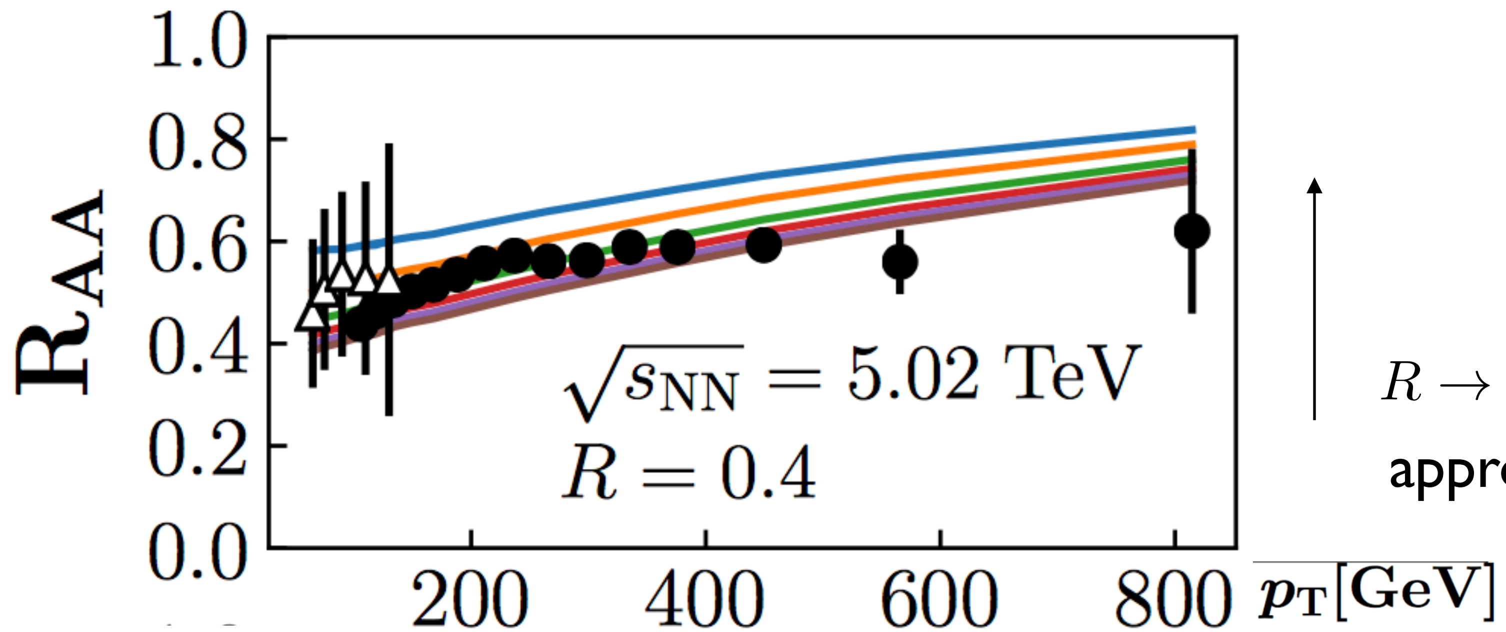
Yen-Jie Lee, UCLA Santa Fe workshop `19

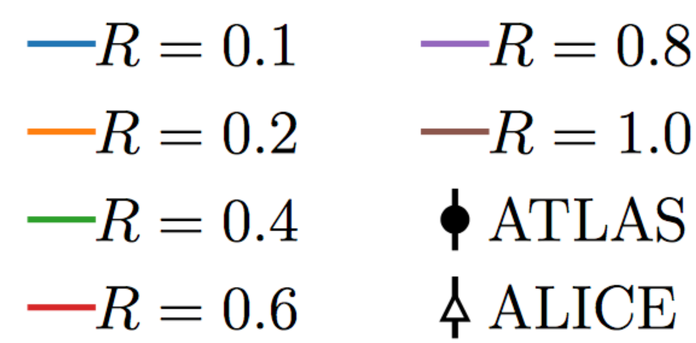
The jet radius dependence



approaching the hadron R_{AA}

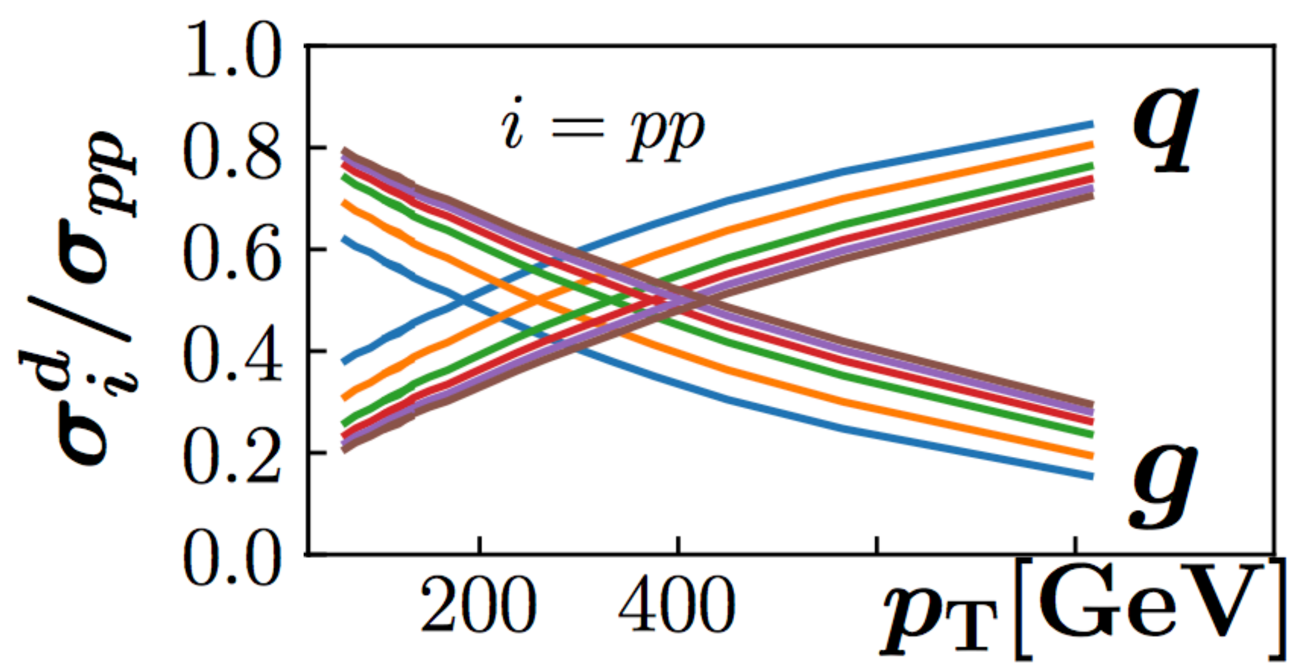
The jet radius dependence



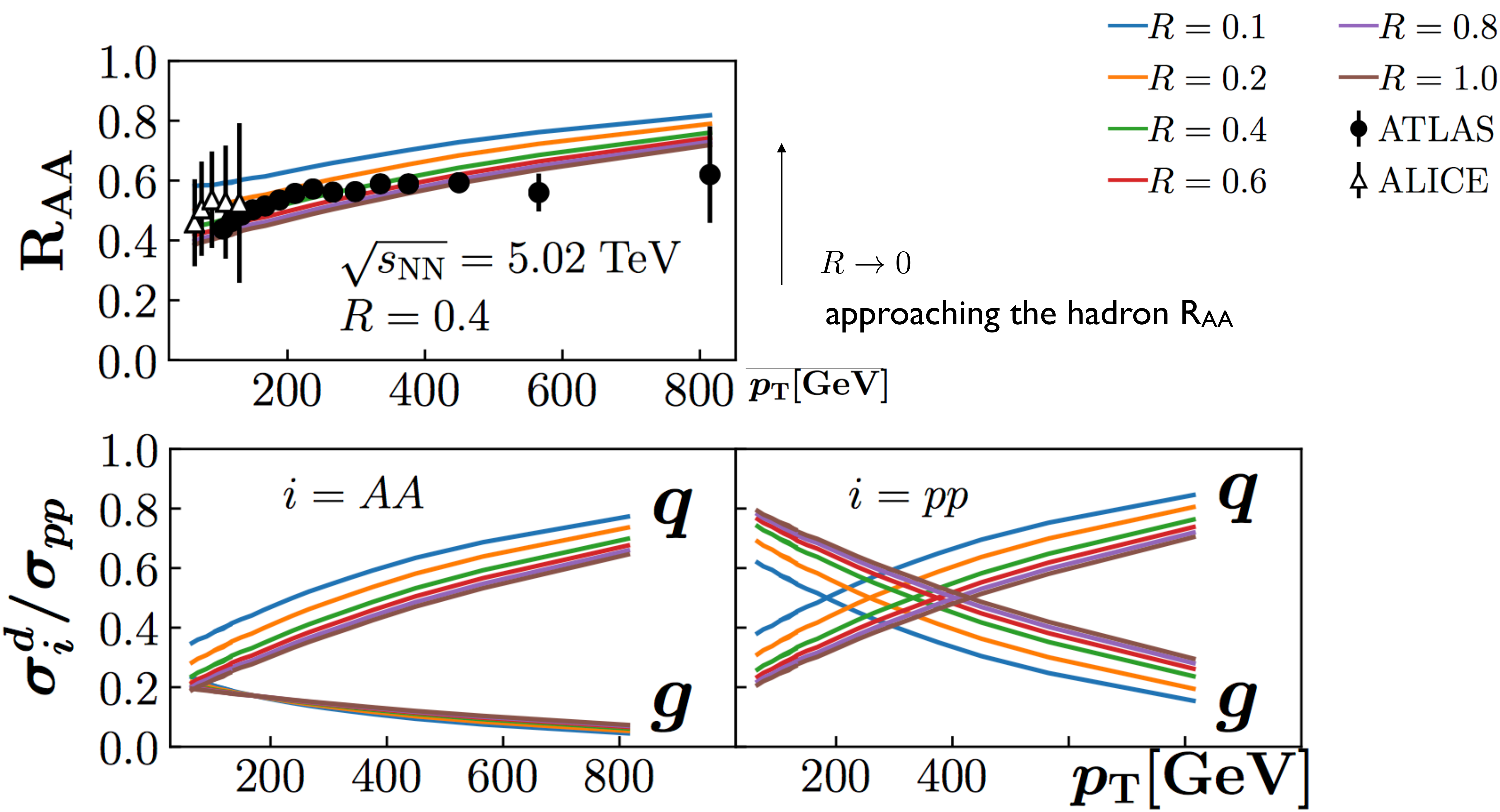


$R \to 0$

approaching the hadron R_{AA}

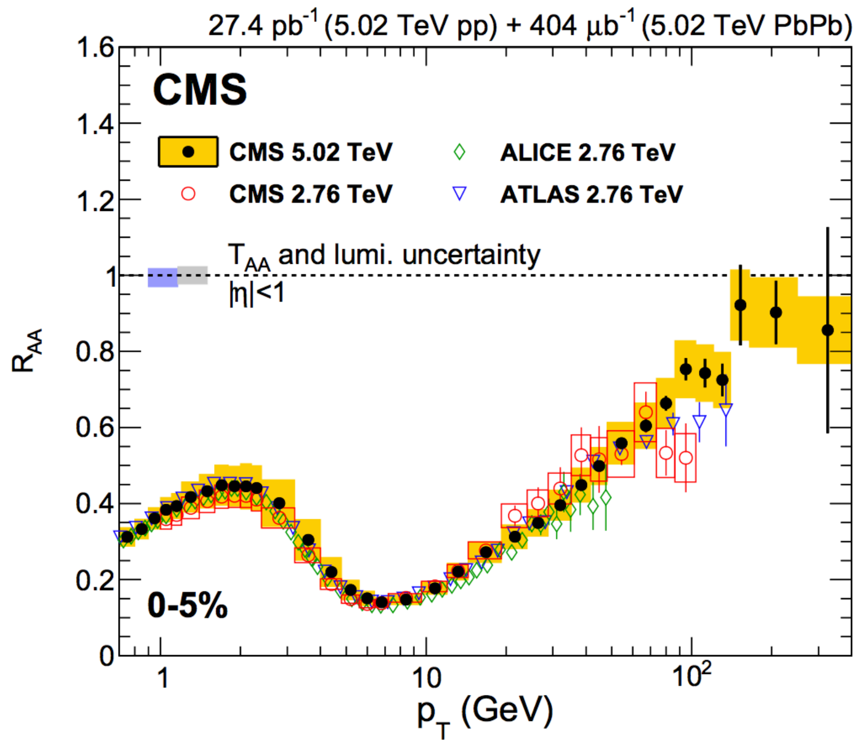


The jet radius dependence



Factorization and universality

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



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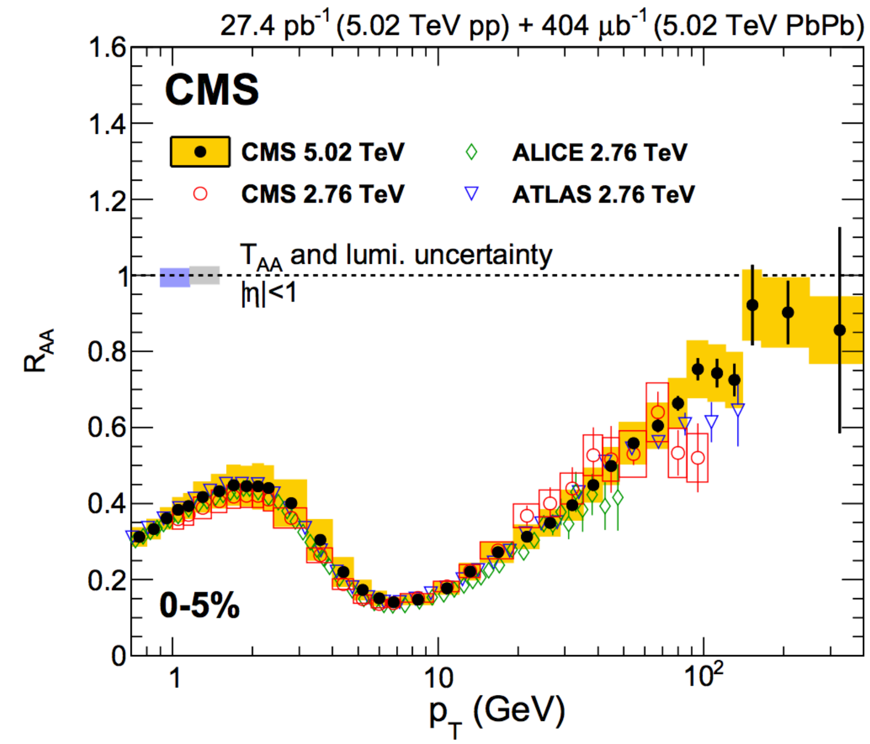
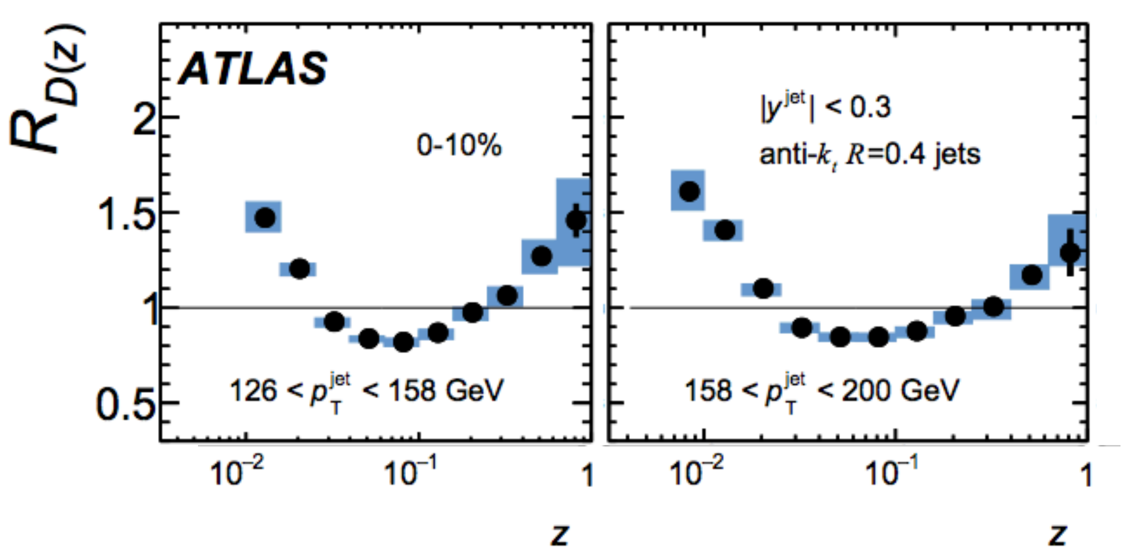
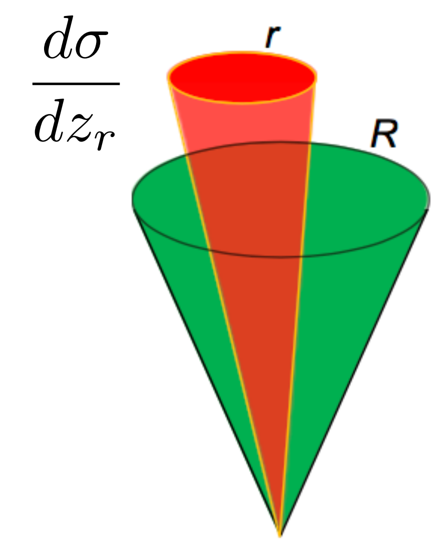


- Test universality using jet substructure observables
- Similar collinear factorization theorems

Hadrons and subjets inside jets

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





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
- Interplay with background subtraction techniques