b-jet production in heavy-ion collisions

Los Alamos NATIONAL LABORATORY EST.1943

Haitao Li

Based on the work arXiv:1801.00008, arXiv:1811.07905 in collaboration with Ivan Vitev

QCD evolution 2019
Argonne National Laboratory

Outline

- Introduction
- Inclusive b-jet production
- b-jet substructures
- conclusion

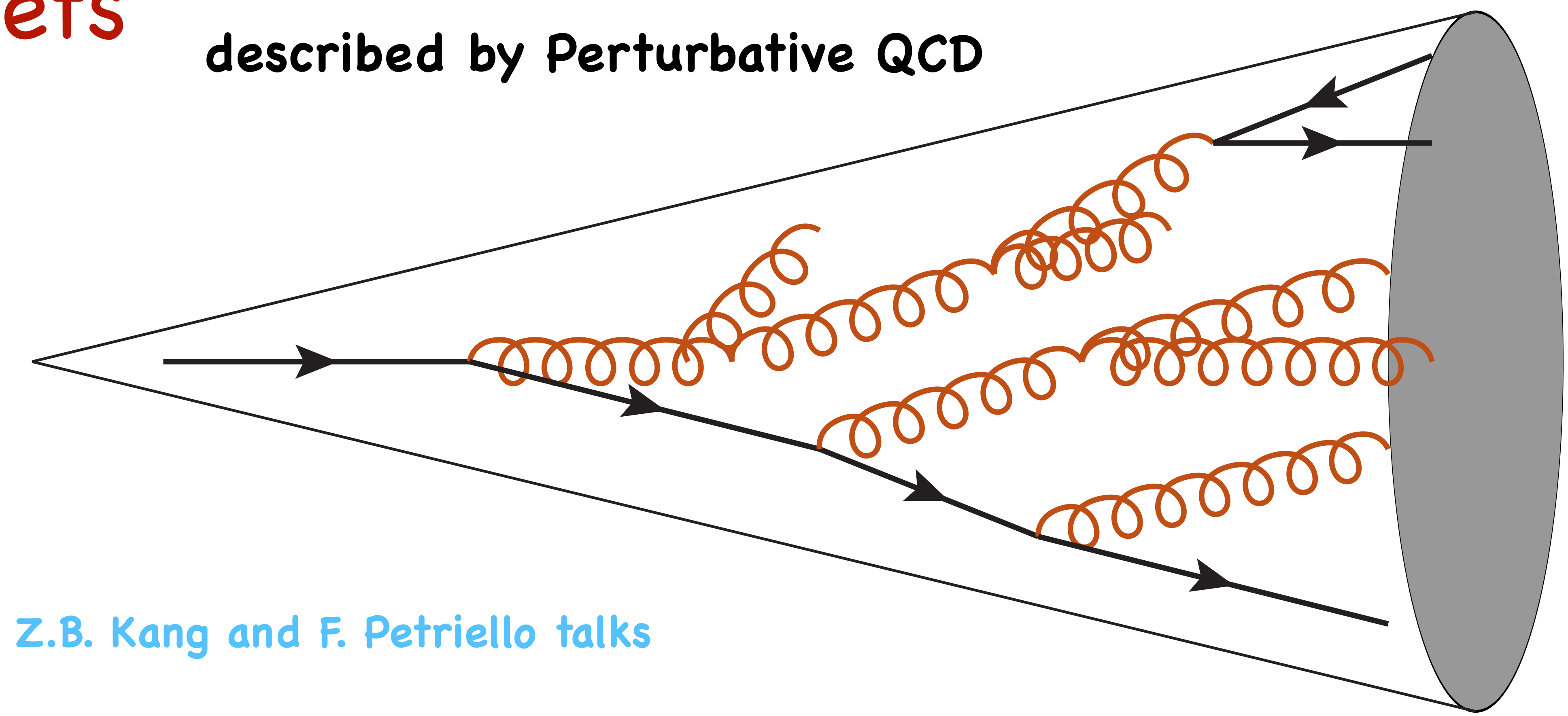
1. Introduction

Jet

Jets

Infrared-safe

described by Perturbative QCD



see Z.B. Kang and F. Petriello talks

The study of jets has been used to test perturbative QCD, to probe proton structure and to search for New Physics

Jet can also interact with QGP in heavy-ion collisions

Jet properties:

Where do jets come from, quark, gluon or decaying product of other particles?

Motivation of jet studies

Jet production

- is characterized by large cross sections and has been measured with unprecedented precision in comparison to other high energy processes
- reveals the fundamental thermodynamic and transport properties of the QGP in A+A collisions

Heavy flavor jet

- A b-jet is a jet containing one or more b-hadrons
- not necessary to be initiated by a heavy quark
- but it is dominated by the quark initialed process compared to light jet
- experiences the full evolution of the hot and dense medium
- seems to lose less energy; used to study the energy loss mechanisms in QCD medium

b-jet in heavy ion collisions

Inclusive b-jet

Huang, Kang, Vitev 2013 — **energy loss approach**

Senzel, Uphoff,. Xu, Greiner, 2016 — **modifying the vacuum shower (BAMPS)**

b-jet + photon (b hadron) production

Huang, Kang, Vitev, Xing, 2016 — **enhance the prompt b-jets via photon or b hadron tagging**

back-to-back b-jets production

Dai, Zhang, Zhang, Wang, 2018 — **transverse momentum balance and angular distribution**

Kang, Reiten, Vitev, Yoon, 2018 — **dijet invariant mass for light and heavy flavors**

b-jet in heavy ion collisions

Inclusive b-jet

Huang, Kang, Vitev 2013 — energy loss approach

Senzel, Uphoff,. Xu, Greiner, 2016 — modifying the vacuum shower (BAMPS)

b-jet + photon (b hadron) production

Huang, Kang, Vitev, Xing, 2016 — enhance the prompt b-jets via photon or b hadron tagging

back-to-back b-jets production

Dai, Zhang, Zhang, Wang, 2018 — transverse momentum balance and angular distribution

Kang, Reiten, Vitev, Yoon, 2018 — dijet invariant mass for light and heavy flavors

b-jet substructure

HTL, Vitev, 2018 — soft-drop groomed momentum sharing distribution

HTL, Vitev, 2018 — the inclusive b-jet production

b-jet in heavy ion collisions

Based on Monte Carlo Event Generators

Inclusive b-jet

Huang, Kang, Vitev 2013 — energy loss approach

Senzel, Uphoff, Xu, Greiner, 2016 — modifying the vacuum shower (BAMPS)

b-jet + photon (b hadron) production

Huang, Kang, Vitev, Xing, 2016 — enhance the prompt b-jets via photon or b hadron tagging

back-to-back b-jets production

Dai, Zhang, Zhang, Wang, 2018 — transverse momentum balance and angular distribution

Kang, Reiten, Vitev, Yoon, 2018 — dijet invariant mass for light and heavy flavors

b-jet substructure

HTL, Vitev, 2018 — soft-drop groomed momentum sharing distribution

HTL, Vitev, 2018 — the inclusive b-jet production

b-jet in heavy ion collisions

Inclusive b-jet

Huang, Kang, Vitev 2013 — energy loss approach

Senzel, Uphoff, Xu, Greiner, 2016 — modifying the vacuum shower (BAMPS)

b-jet + photon (b hadron) production

Huang, Kang, Vitev, Xing, 2016 — enhance the prompt b-jets via photon or b hadron tagging

back-to-back b-jets production

Dai, Zhang, Zhang, Wang, 2018 — transverse momentum balance and angular distribution

Kang, Reiten, Vitev, Yoon, 2018 — dijet invariant mass for light and heavy flavors

b-jet substructure

HTL, Vitev, 2018 — soft-drop groomed momentum sharing distribution

HTL, Vitev, 2018 — the inclusive b-jet production

Based on Monte Carlo Event Generators

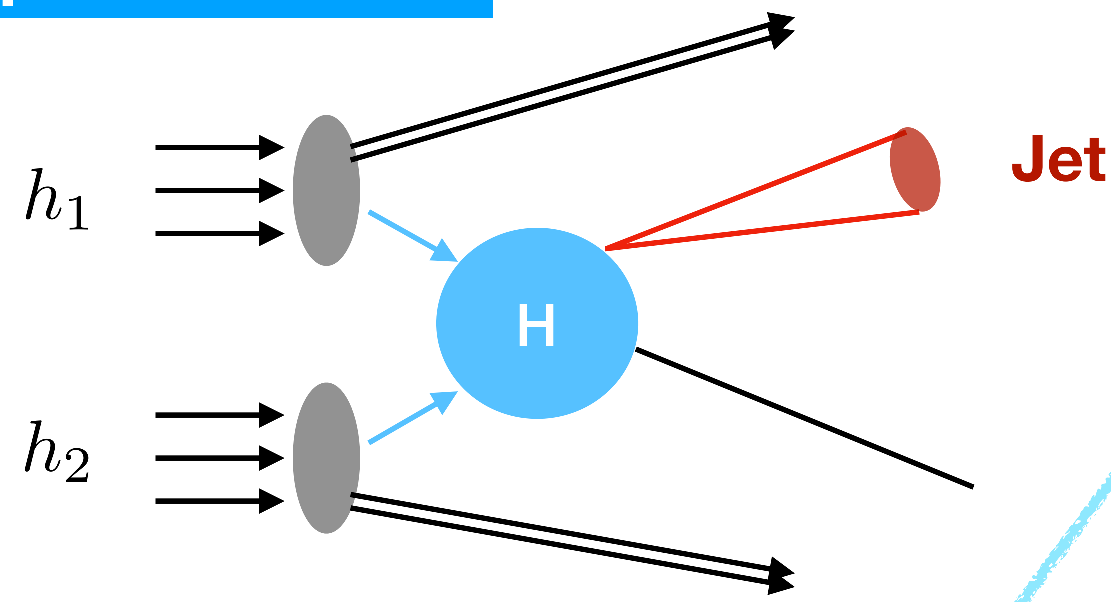
$SCET_G$

2. inclusive b jet production

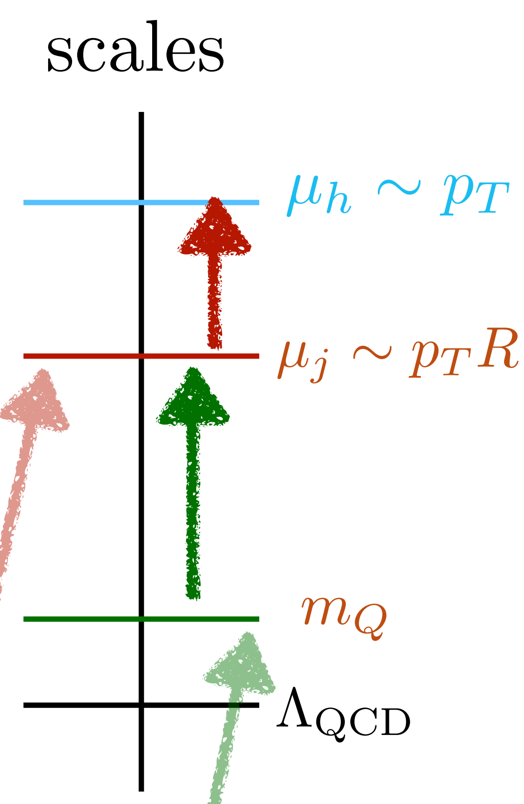
HTL, Vitev arXiv: 1811.03348

Inclusive jet Production

In p+p collisions



$$h_1 + h_2 \to \text{Jet} + X$$



Aversa et al 1990
Jager et al 2004
Mukherjee et al 2012
Kaufmann et al 2016
....

$$\frac{d\sigma_{pp\to J+X}}{dp_T\, d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^1 \frac{dx_a}{x_a} f_a(x_a,\mu)\int_{x_b^{\min}}^1 \frac{dx_b}{x_b} f_b(x_b,\mu) \times \int_{z_{\min}}^1 \frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab\to c}(\hat{s}, p_T/z_c, \hat{\eta}, \mu)}{dv\, dz} J_{J/c}(z_c, w_J \tan(R'/2), m_Q, \mu)$$

Hard scattering kernel

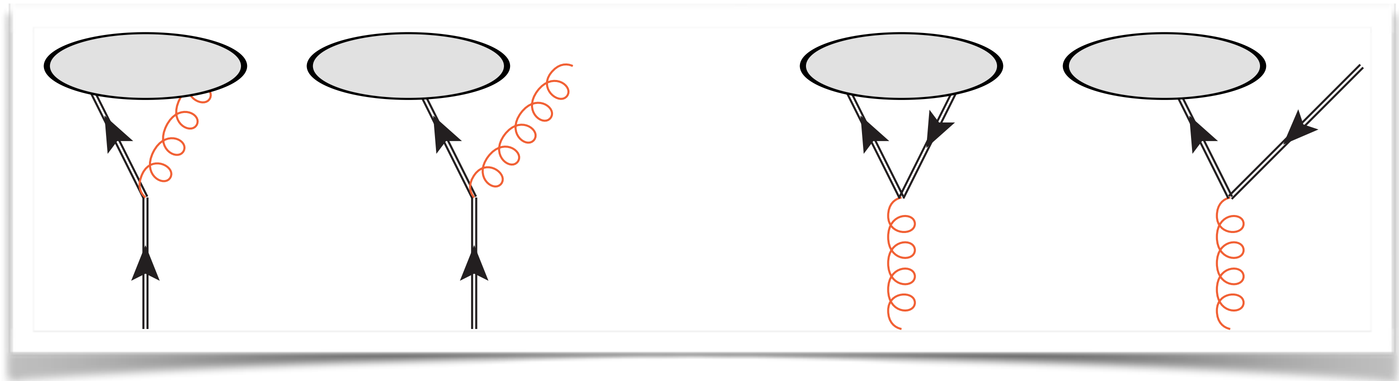
Aversa et al 1989, Jager et al 2002

Semi-inclusive jet function

light jet: Kang et al 2016, Dai et al 2016

heavy flavor jet: Dai et al 2018

SiJFs



$Q \to J_Q$ $\qquad$ $g \to J_Q$

Using SCET with finite quark mass

Leibovich, Ligeti, Wise 2003

$$J_{J_Q/Q}(z=\omega_J/\omega,\omega_J,m,\mu) = \frac{z}{2N_c}\mathrm{Tr}\left[\frac{\bar{\not n}}{2}\langle 0|\delta\left(\omega-\bar n\cdot\mathcal{P}\right)\chi_n^Q(0)|J_Q X\rangle\langle J_Q X|\bar\chi_n^Q(0)|0\rangle\right]$$

$$J_{J_Q/g}(z=\omega_J/\omega,\omega_J,m,\mu) = -\frac{z\,\omega}{2(N_c^2-1)}\langle 0|\delta\left(\omega-\bar n\cdot\mathcal{P}\right)\mathcal{B}_{n\perp\mu}(0)|J_Q X\rangle\langle J_Q X|\mathcal{B}^{\mu}_{n\perp}(0)|0\rangle$$

finite when m~0

Dai, Kim, Leibovich 2018

$$J_{J_Q/Q}(z,p_T R,m,\mu) = \delta(1-z) + \frac{\alpha_s C_F}{2\pi}\Bigg\{\delta(1-z)\left[f\left(\frac{m^2}{p_T^2R^2}\right)+g\left(\frac{m^2}{p_T^2R^2}\right)\right] + \left(\frac{1+z^2}{1-z}\right)_+\ln\frac{\mu^2}{z^2p_T^2R^2+m^2} - \left(2\frac{1+z^2}{1-z}\ln(1-z)+1-z\right)_+ - \left(\frac{2z}{1-z}\right)_+\frac{m^2}{z^2p_T^2R^2+m^2}\Bigg\}$$

include $\ln\frac{m^2}{p_T^2R^2}$

$J_s = J_Q + J_{\bar Q}$

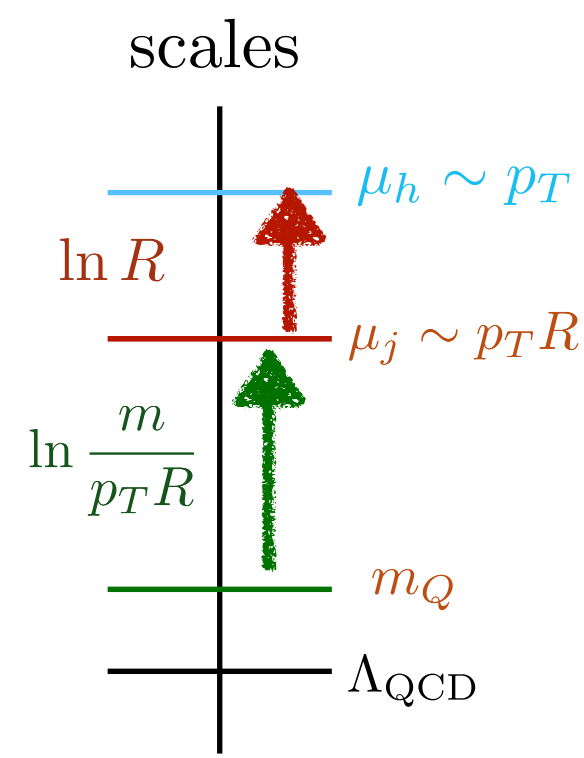
$$J_{J_s/g}(z,p_T R,m,\mu) = \delta(1-z)\mathcal{M}^{\text{in-jet}}_{g\to Q\bar Q}(p_T R,m) + \frac{\alpha_s}{2\pi}\Bigg\{(z^2+(1-z)^2) \times\ln\frac{\mu^2}{z^2(1-z^2)p_T^2R^2+m^2} - 2z(1-z)\frac{z^2(1-z)^2p_T^2R^2}{z^2(1-z)^2p_T^2R^2+m^2}\Bigg\}$$

Resummation

Using SCET with finite quark mass   Leibovich, Ligeti, Wise 2003

$$J_{J_Q/Q}(z=\omega_J/\omega,\omega_J,m,\mu) = \frac{z}{2N_c}\mathrm{Tr}\left[\frac{\bar{\not n}}{2}\langle 0|\delta\left(\omega-\bar{n}\cdot\mathcal{P}\right)\chi_n^Q(0)|J_Q X\rangle\langle J_Q X|\bar{\chi}_n^Q(0)|0\rangle\right]$$

$$J_{J_Q/g}(z=\omega_J/\omega,\omega_J,m,\mu) = -\frac{z\,\omega}{2(N_c^2-1)}\langle 0|\delta\left(\omega-\bar{n}\cdot\mathcal{P}\right)\mathcal{B}_{n\perp\mu}(0)|J_Q X\rangle\langle J_Q X|\mathcal{B}_{n\perp}^{\mu}(0)|0\rangle$$



The SiJFs Evolve according to DGLAP-like equations

$$\frac{d}{d\ln\mu^2}\begin{pmatrix} J_{J_Q/s}(x,\mu) \\ J_{J_s/g}(x,\mu)\end{pmatrix} = \frac{\alpha_s}{2\pi}\int_x^1\frac{dz}{z}\begin{pmatrix} P_{qq}(z) & 2P_{gq(z)} \\ P_{qg}(z) & P_{gg}(z)\end{pmatrix}\begin{pmatrix} J_{J_Q/s}(x/z,\mu) \\ J_{J_s/g}(x/z,\mu)\end{pmatrix}.$$

We use the Mellin moment space approach to solve this equation.

$$\mathcal{M}^{\rm in-jet}_{g\to Q\bar{Q}}(p_T R, m) = 2\sum_{l=g,Q}\bar{K}_{l/g}(p_T R, m, \mu_F)\bar{D}_{Q/l}(m,\mu_F)$$

the integrated perturbative kernel at the jet typical scale

the integrated parton fragmentation function from parton *l* to parton *Q*

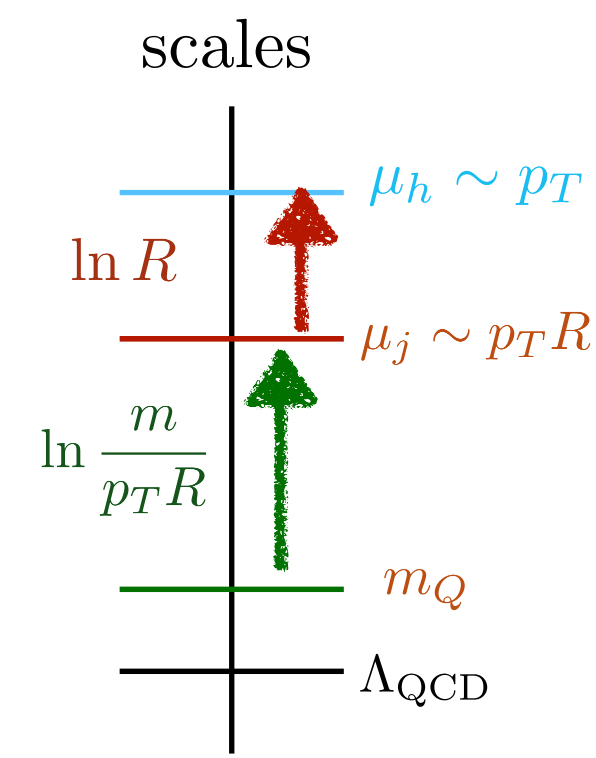
Bauer, Mereghetti 2013, Dai, Kim, Leibovich 2016, 2018

Resummation

Using SCET with finite quark mass **Leibovich, Ligeti, Wise 2003**

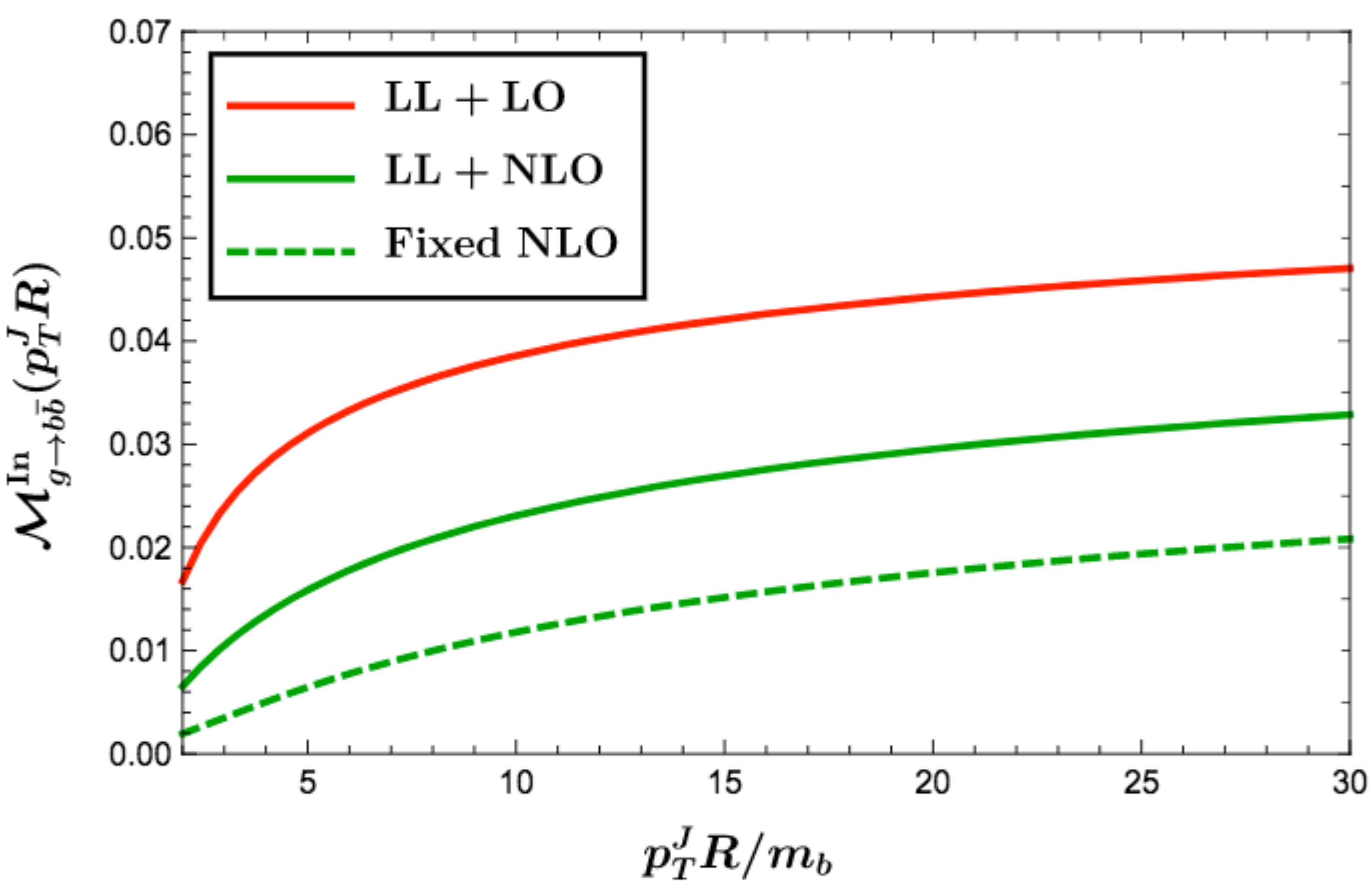
$$J_{J_Q/Q}(z=\omega_J/\omega,\omega_J,m,\mu) = \frac{z}{2N_c}\mathrm{Tr}\left[\frac{\bar{\not n}}{2}\langle 0|\delta\left(\omega-\bar n\cdot\mathcal{P}\right)\chi_n^Q(0)|J_Q X\rangle\langle J_Q X|\bar\chi_n^Q(0)|0\rangle\right]$$

$$J_{J_Q/g}(z=\omega_J/\omega,\omega_J,m,\mu) = -\frac{z\,\omega}{2(N_c^2-1)}\langle 0|\delta\left(\omega-\bar n\cdot\mathcal{P}\right)\mathcal{B}_{n\perp\mu}(0)|J_Q X\rangle\langle J_Q X|\mathcal{B}^{\mu}_{n\perp}(0)|0\rangle$$



The SiJFs Evolve according to DGLAP-like equations

$$\frac{d}{d\ln\mu^2}\Big(\ldots$$



We use … this equ…

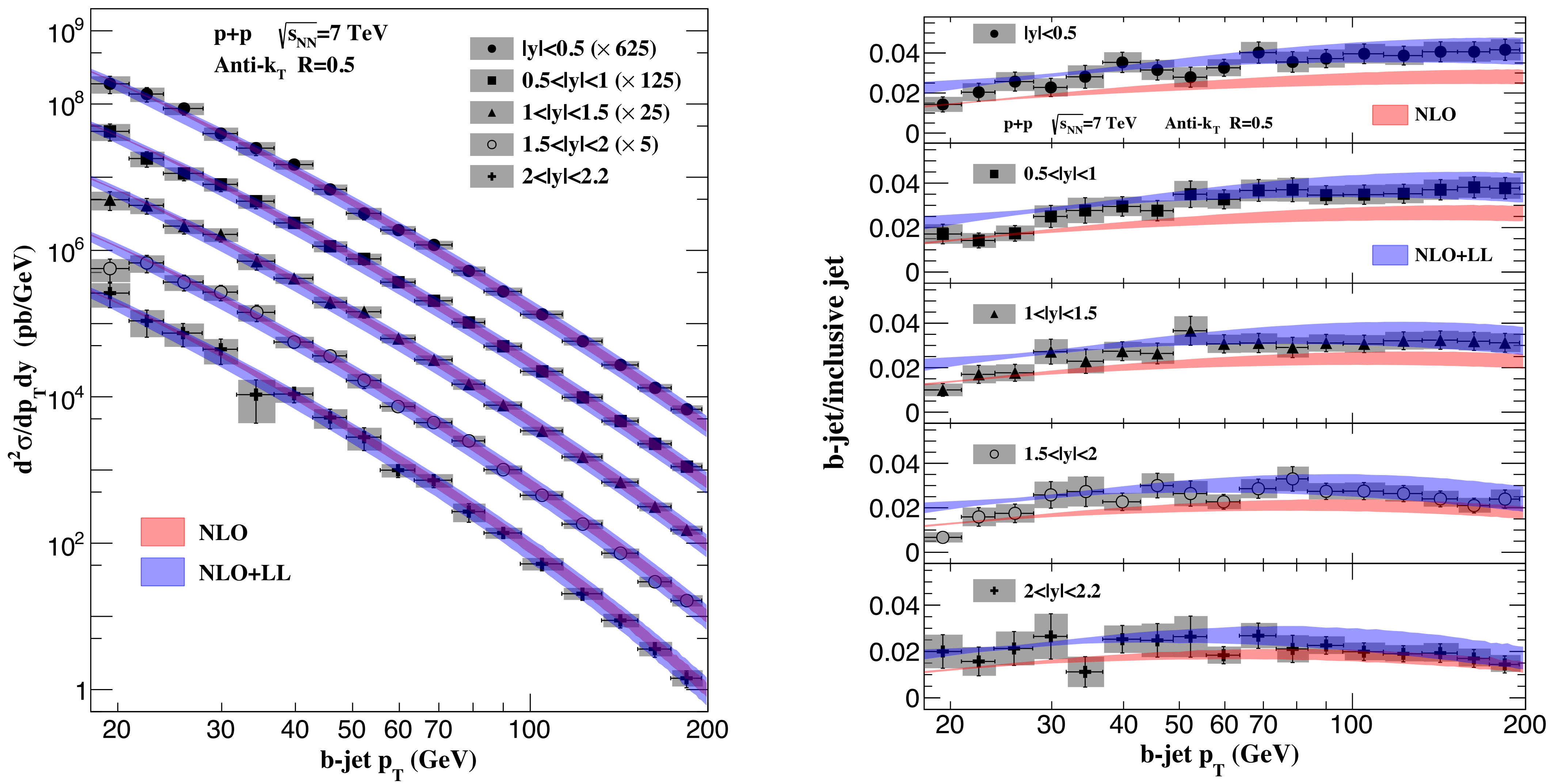
$\ldots_l(m,\mu_F)$

the inte… kernel …

…ragmentation to parton Q

Bauer, Mer…

b-jet in pp collisions



- data are consistent with the predictions
- for the ratio the difference between NLO+LL and NLO can be traced also to the differences in the inclusive jet cross section

Corrections in P-A collisions

In p+A collisions

Assume the factorization works in heavy ion collisions:

$$\frac{d\sigma_{pA\to J+X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^{1}\frac{dx_a}{x_a}f_a(x_a,\mu)\int_{x_b^{\min}}^{1}\frac{dx_b}{x_b}f_b(x_b,\mu)$$
$$\times\int_{z_{\min}}^{1}\frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab\to c}(\hat{s},p_T/z_c,\hat{\eta},\mu)}{dvdz}J_{J/c}(z_c,w_J\tan(R'/2),m_Q,\mu)$$

p-A collisions can be used to study the nuclear modifications at the initial state of the collisions, which is crucial for the interpretation of the A+A results

Corrections in P-A collisions

In p+A collisions

Assume the factorization works in heavy ion collisions:

modified for nuclear

$$\frac{d\sigma_{pA\to J+X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^1 \frac{dx_a}{x_a} f_a(x_a,\mu)\int_{x_b^{\min}}^1 \frac{dx_b}{x_b} f_b(x_b,\mu)$$
$$\times \int_{z_{\min}}^1 \frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab\to c}(\hat{s},p_T/z_c,\hat{\eta},\mu)}{dv dz} J_{J/c}(z_c, w_J \tan(R'/2), m_Q, \mu)$$

p-A collisions can be used to study the nuclear modifications at the initial state of the collisions, which is crucial for the interpretation of the A+A results

Corrections in P-A collisions

In p+A collisions

Assume the factorization works in heavy ion collisions:

modified for nuclear

$$\frac{d\sigma_{pA\to J+X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^{1}\frac{dx_a}{x_a} f_a(x_a,\mu)\int_{x_b^{\min}}^{1}\frac{dx_b}{x_b} f_b(x_b,\mu) \times \int_{z_{\min}}^{1}\frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab\to c}(\hat{s},p_T/z_c,\hat{\eta},\mu)}{dvdz} J_{J/c}(z_c, w_J\tan(R'/2), m_Q, \mu)$$

the short-distance hard part remains the same

p-A collisions can be used to study the nuclear modifications at the initial state of the collisions, which is crucial for the interpretation of the A+A results

Corrections in P-A collisions

In p+A collisions

Assume the factorization works in heavy ion collisions:

modified for nuclear

$$\frac{d\sigma_{pA\to J+X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^{1}\frac{dx_a}{x_a}f_a(x_a,\mu)\int_{x_b^{\min}}^{1}\frac{dx_b}{x_b}f_b(x_b,\mu) \times \int_{z_{\min}}^{1}\frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab\to c}(\hat{s},p_T/z_c,\hat{\eta},\mu)}{dvdz}J_{J/c}(z_c,w_J\tan(R'/2),m_Q,\mu)$$

the short-distance hard part remains the same

Not changed

p-A collisions can be used to study the nuclear modifications at the initial state of the collisions, which is crucial for the interpretation of the A+A results

Nuclear Effects from initial state

There are many studies about the global fits of nuclear parton distributions (nPDFs) , such as nCTEQ collaboration

nPDFs for a nucleus with atomic mass A and Z protons:

$$f_{a/A}(x,\mu) \to \frac{Z}{A} f_{a/p} + \frac{A-Z}{A} f_{a/n}(x)$$

As the parton from the proton undergoes multiple scattering in the nucleus before the hard collisions. They are implemented as shifts in the lightcone momentum fraction of the incident parton in the PDFs Kang, Vitev, Xing 2014, 2015

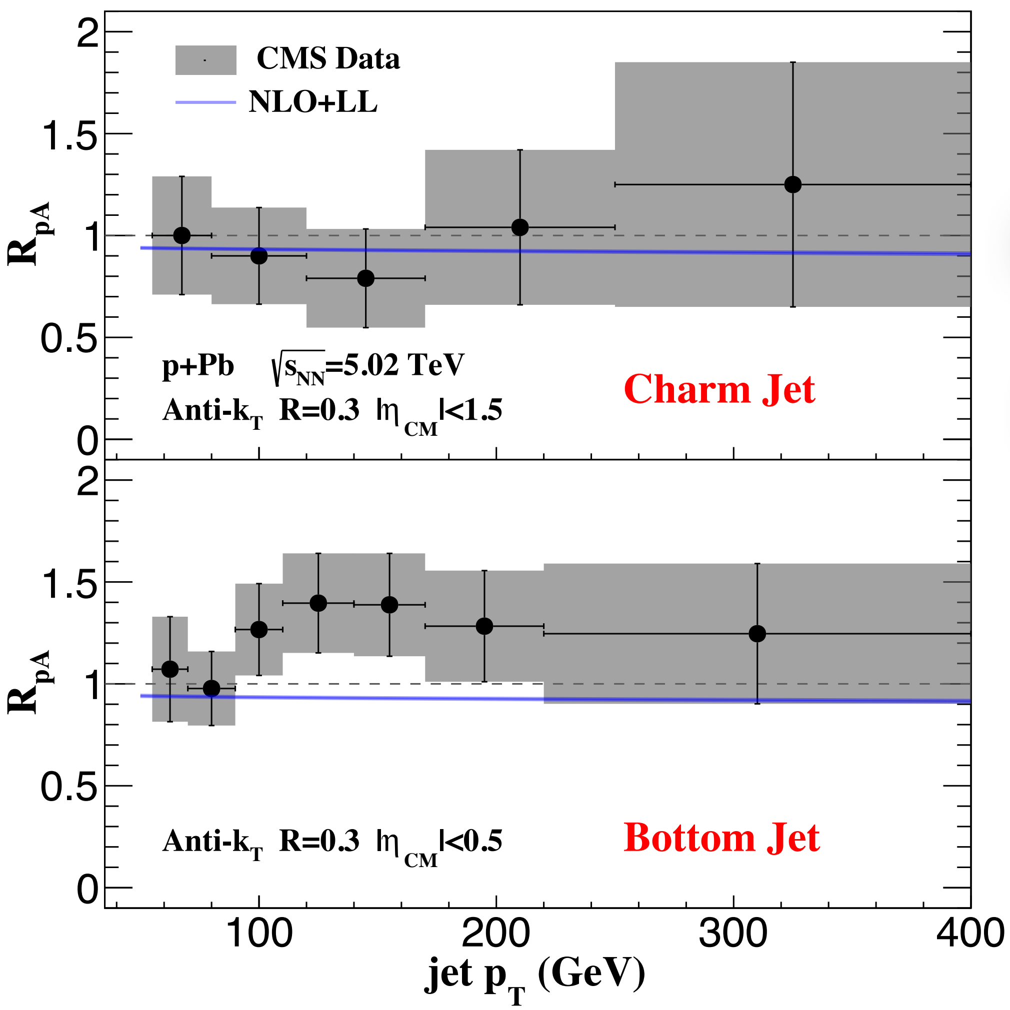
$$f_{q/A}(x,\mu) \to f_{q/A}\left(\frac{x}{1-\epsilon_q},\mu\right), \qquad f_{g/A}(x,\mu) \to f_{g/A}\left(\frac{x}{1-\epsilon_g},\mu\right).$$

for light jet: Kang, Ringer, Vitev 2017

At the high transverse momenta, only cold nuclear matter energy loss effects might play a role

RAA in p-A collisions

In p-A collisions, there is only initial-state cold nuclear matter energy loss



Fitting a constant to this measurements

$$R_{pA} = 0.92 \pm 0.07(\text{stat}) \pm 0.11(\text{syst})$$

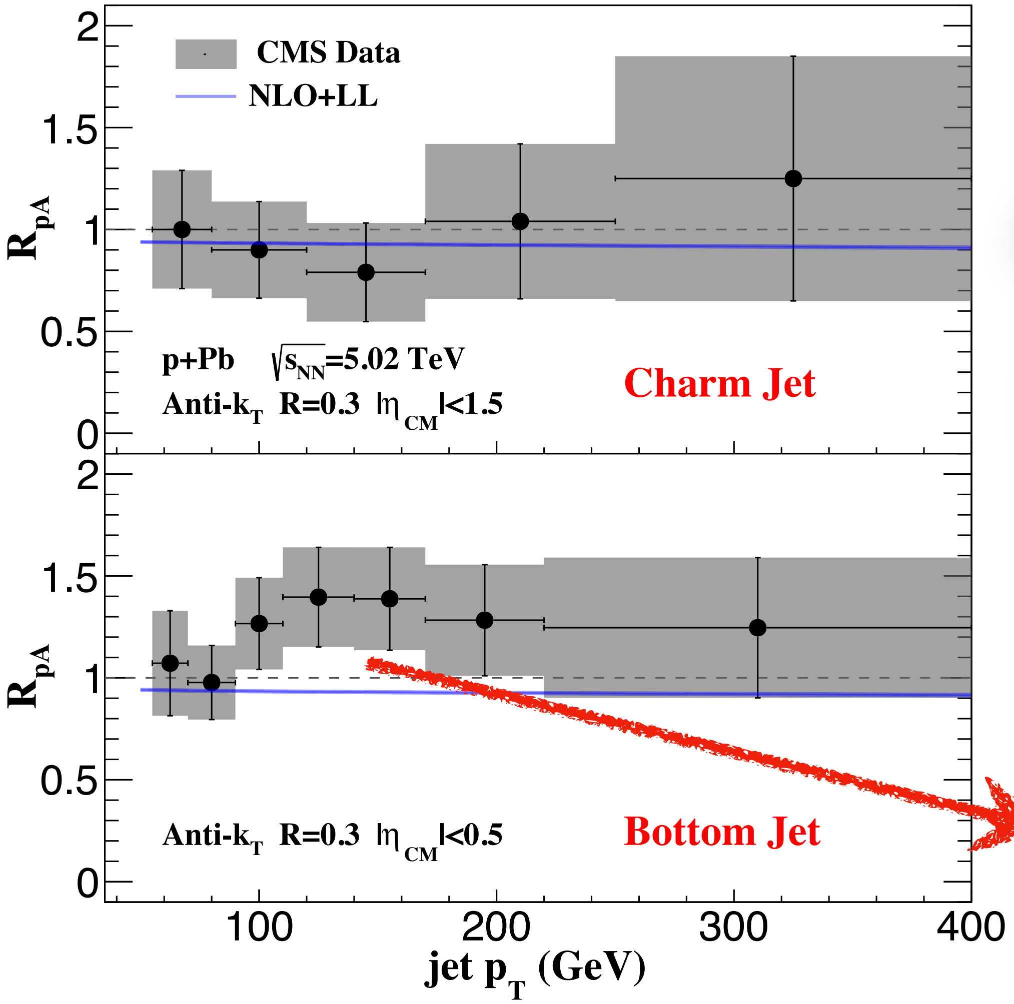
$$R_{pA}^{\text{PYTHIA}} = 1.22 \pm 0.15(\text{stat} + \text{syst}) \pm 0.27(\text{syst PYTHIA})$$

Measurements:
- large uncertainty
- not enough to exclude the cold nuclear matter effects

Predictions:
- vary little with jet transverse momentum and scale variation
- there is not an obvious difference between c-jet and b-jet
- in Pb+Pb collisions the effects will be amplified

RAA in p-A collisions

In p-A collisions, there is only initial-state cold nuclear matter energy loss



Fitting a constant to this measurements

$$R_{pA} = 0.92 \pm 0.07(\mathrm{stat}) \pm 0.11(\mathrm{syst})$$

$$R_{pA}^{\mathrm{PYTHIA}} = 1.22 \pm 0.15(\mathrm{stat+syst}) \pm 0.27(\mathrm{syst\ PYTHIA})$$

Measurements:
- large uncertainty
- not enough to exclude the cold nuclear matter effects

Naively speaking: $\mathrm{Pb+Pb}: \quad \underbrace{(1 \pm \epsilon)}_{\mathrm{Pb}}\underbrace{(1 \pm \epsilon)}_{\mathrm{Pb}}$

Predictions:
- vary little with jet transverse momentum and scale variation
- there is not an obvious difference between c-jet and b-jet
- in Pb+Pb collisions the effects will be amplified

Corrections in A-A collisions

In A+A collisions

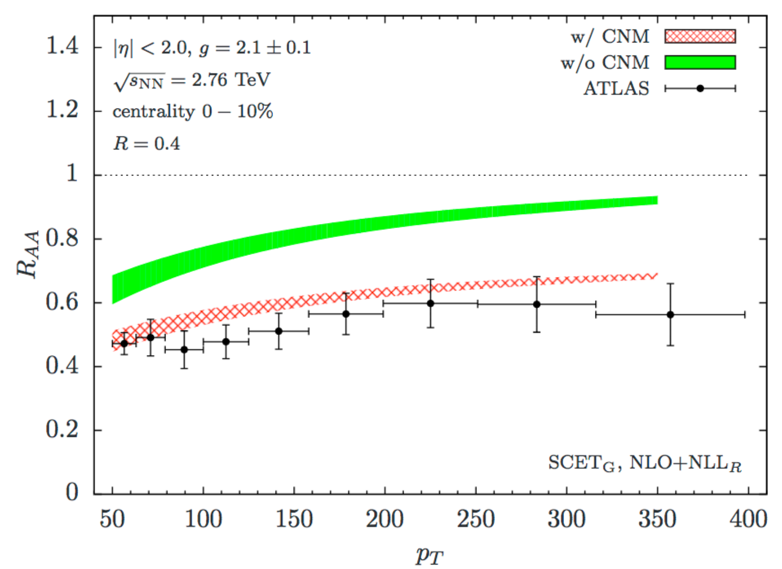
modified for nuclear

$$\frac{d\sigma_{AA\to J+X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^{1}\frac{dx_a}{x_a} f_a(x_a,\mu)\int_{x_b^{\min}}^{1}\frac{dx_b}{x_b} f_b(x_b,\mu) \times \int_{z_{\min}}^{1}\frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab\to c}(\hat{s},p_T/z_c,\hat{\eta},\mu)}{dvdz} J_{J/c}(z_c, w_J\tan(R'/2), m_Q,\mu)$$

the short-distance hard part remains the same

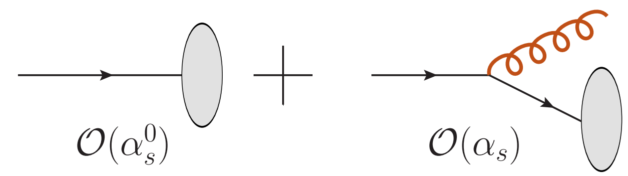
encode the effects when the jet evolving in the QCD medium

for light jet see the work Kang, Ringer and Vitev 2017

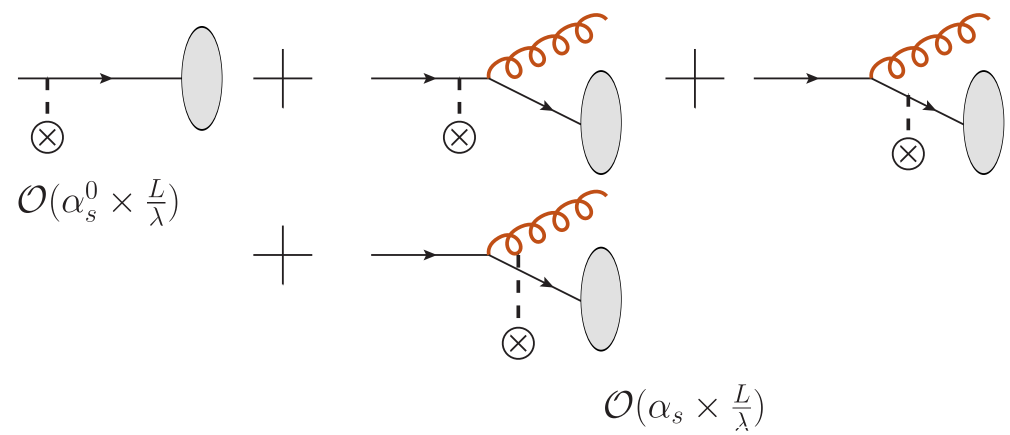


Jet functions in QCD medium

Vacuum jet function: $J^{\mathrm{vac}}_{J_b/b} =$



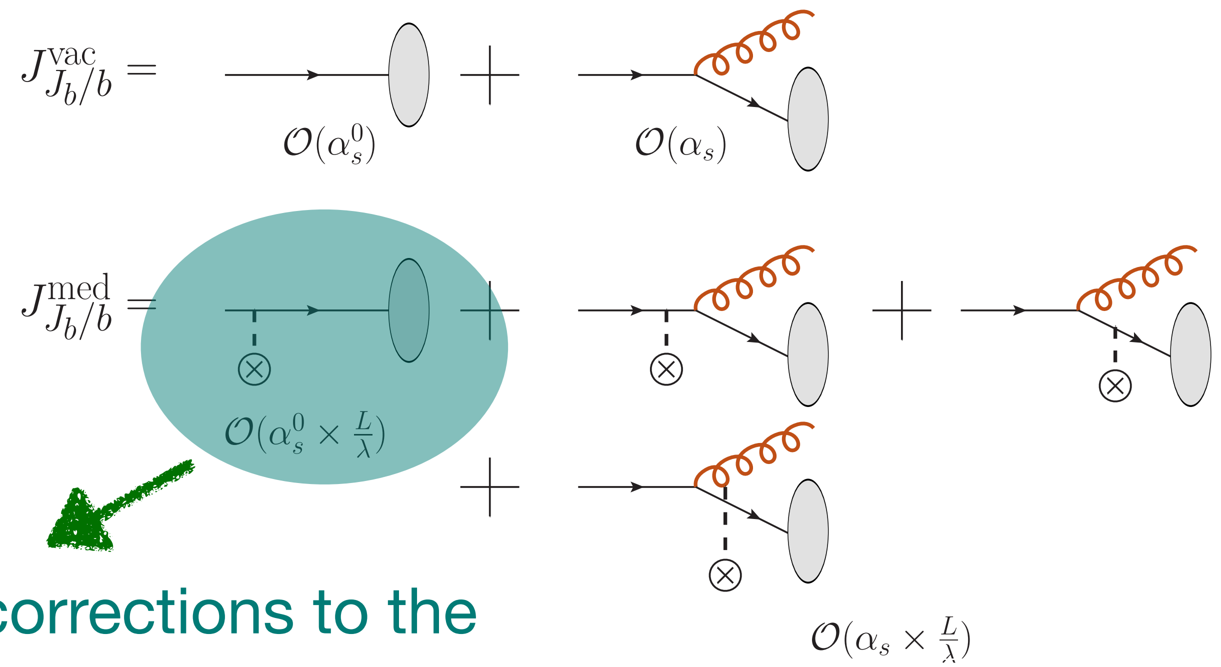
Medium corrections: $J^{\mathrm{med}}_{J_b/b} =$



Jet functions in QCD medium

Vacuum jet function:

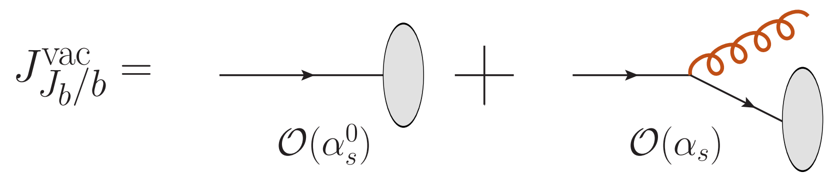
Medium corrections:

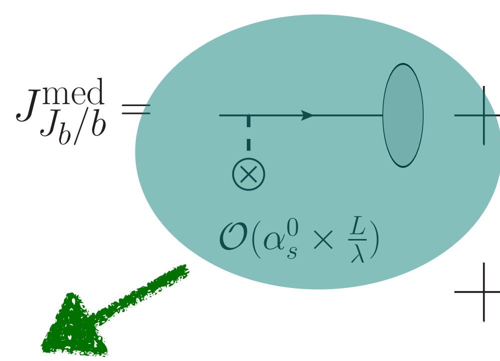


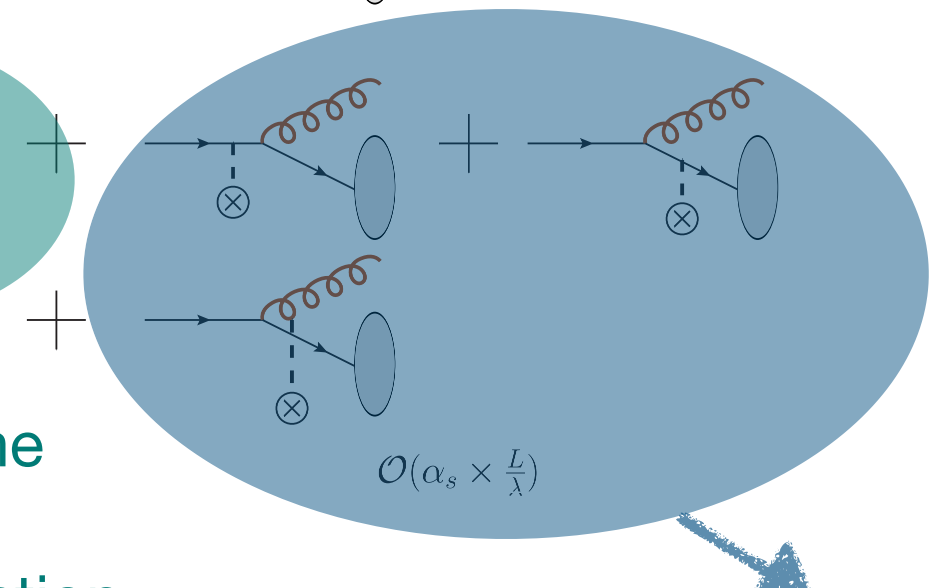
- Medium induced corrections to the LO jet function.
- Only in-medium jet energy dissipation due collisional interactions is allowed.

refers to the higher-twist corrections which generate a direct transfer of energy between the jet and the medium

Jet functions in QCD medium

Vacuum jet function: 

Medium corrections: 



- Medium induced corrections to the LO jet function.
- Only in-medium jet energy dissipation due collisional interactions is allowed.

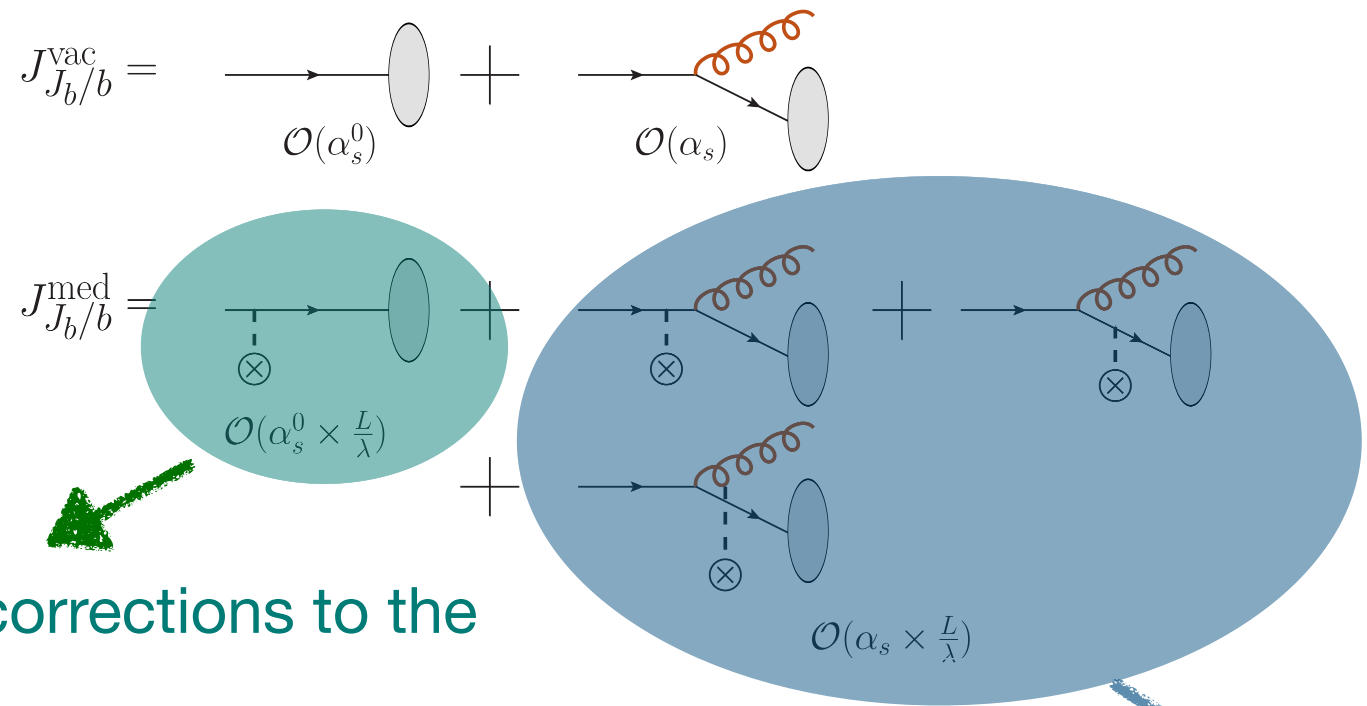
refers to the higher-twist corrections which generate a direct transfer of energy between the jet and the medium

- **Medium induced corrections to the NLO jet function**
- **Vacuum radiation along with corrections from the medium-induced parton shower**

Jet functions in QCD medium

Vacuum jet function:

Medium corrections:



- Medium induced corrections to the LO jet function.
- Only in-medium jet energy dissipation due collisional interactions is allowed.

- **Medium induced corrections to the NLO jet function**
- **Vacuum radiation along with corrections from the medium-induced parton shower**

refers to the higher-twist corrections which generate a direct transfer of energy between the jet and the medium

$$J^{\rm med}_{J_Q/i} = J^{{\rm med},(0)}_{J_Q/i} + J^{{\rm med},(1)}_{J_Q/i}$$

Collisional + radiational energy loss

Medium induced splitting

The medium induced splitting functions were derived from the framework of SCET with Glauber gluons up to the first order of opacity.

$\mathrm{SCET_G}$ Using background field method, $A^\mu = A_c^\mu + A_s^\mu + A_G^\mu$

Then Feynman Rules with Glauber interaction can be derived

Idilbi and Majumder 2008, Ovanesyan and Vitev 2011 Kang, Ringer, Vitev 2016

Medium induced splitting

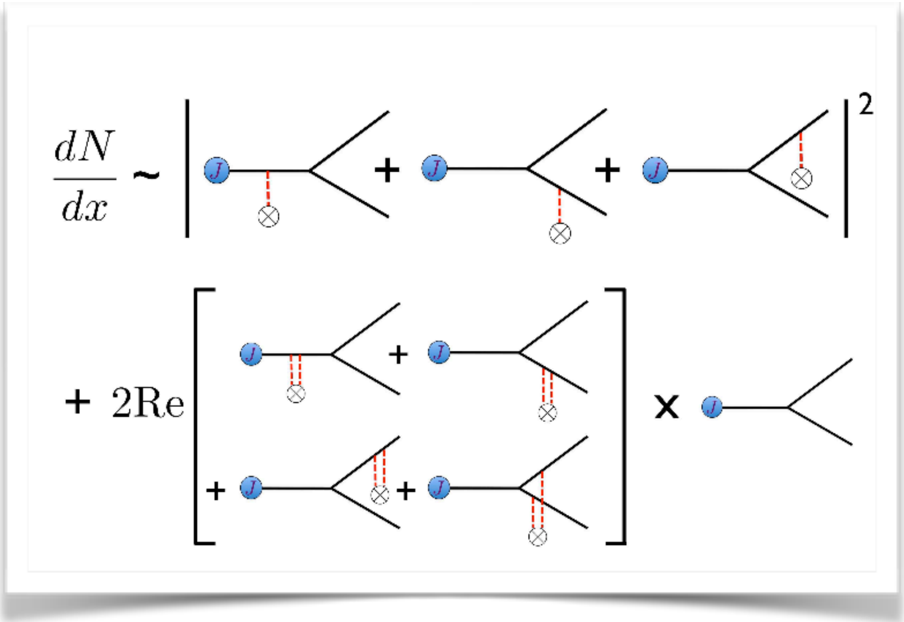
The medium induced splitting functions were derived from the framework of SCET with Glauber gluons up to the first order of opacity.

$\mathrm{SCET_G}$ Using background field method, $A^\mu = A^\mu_c + A^\mu_s + A^\mu_G$

Then Feynman Rules with Glauber interaction can be derived

Idilbi and Majumder 2008, Ovanesyan and Vitev 2011 Kang, Ringer, Vitev 2016

The splitting function are obtained by calculating the diagram:



Massless partons: Ovanesyan and Vitev 2011

Massive partons: Kang, Ringer, Vitev 2016

Medium induced splitting

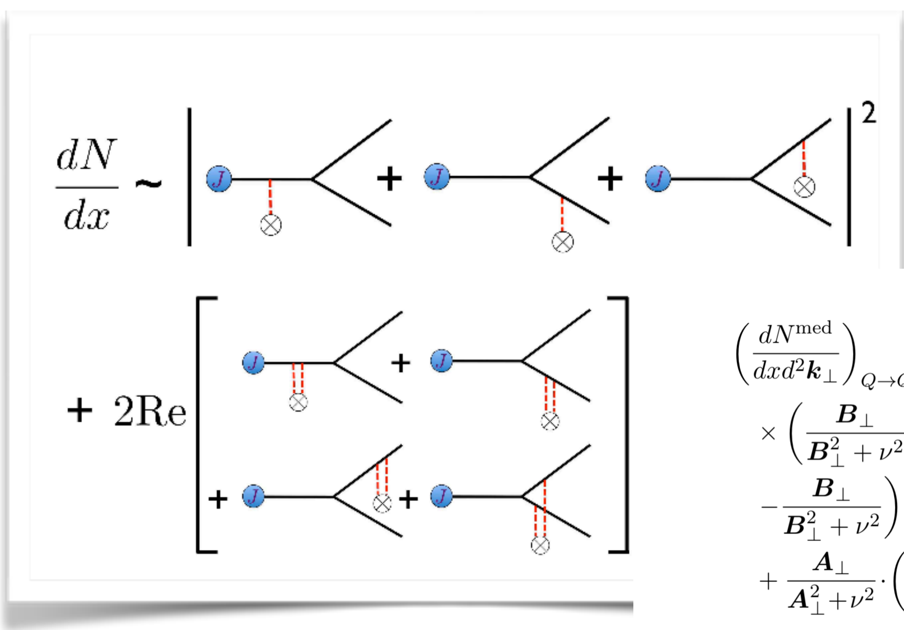
The medium induced splitting functions were derived from the framework of SCET with Glauber gluons up to the first order of opacity.

$\mathrm{SCET_G}$ Using background field method, $A^\mu = A^\mu_c + A^\mu_s + A^\mu_G$

Then Feynman Rules with Glauber interaction can be derived

Idilbi and Majumder 2008, Ovanesyan and Vitev 2011 Kang, Ringer, Vitev 2016

The splitting function are obtained by calculating the diagram:



Massless partons: Ovanesyan and Vitev 2011

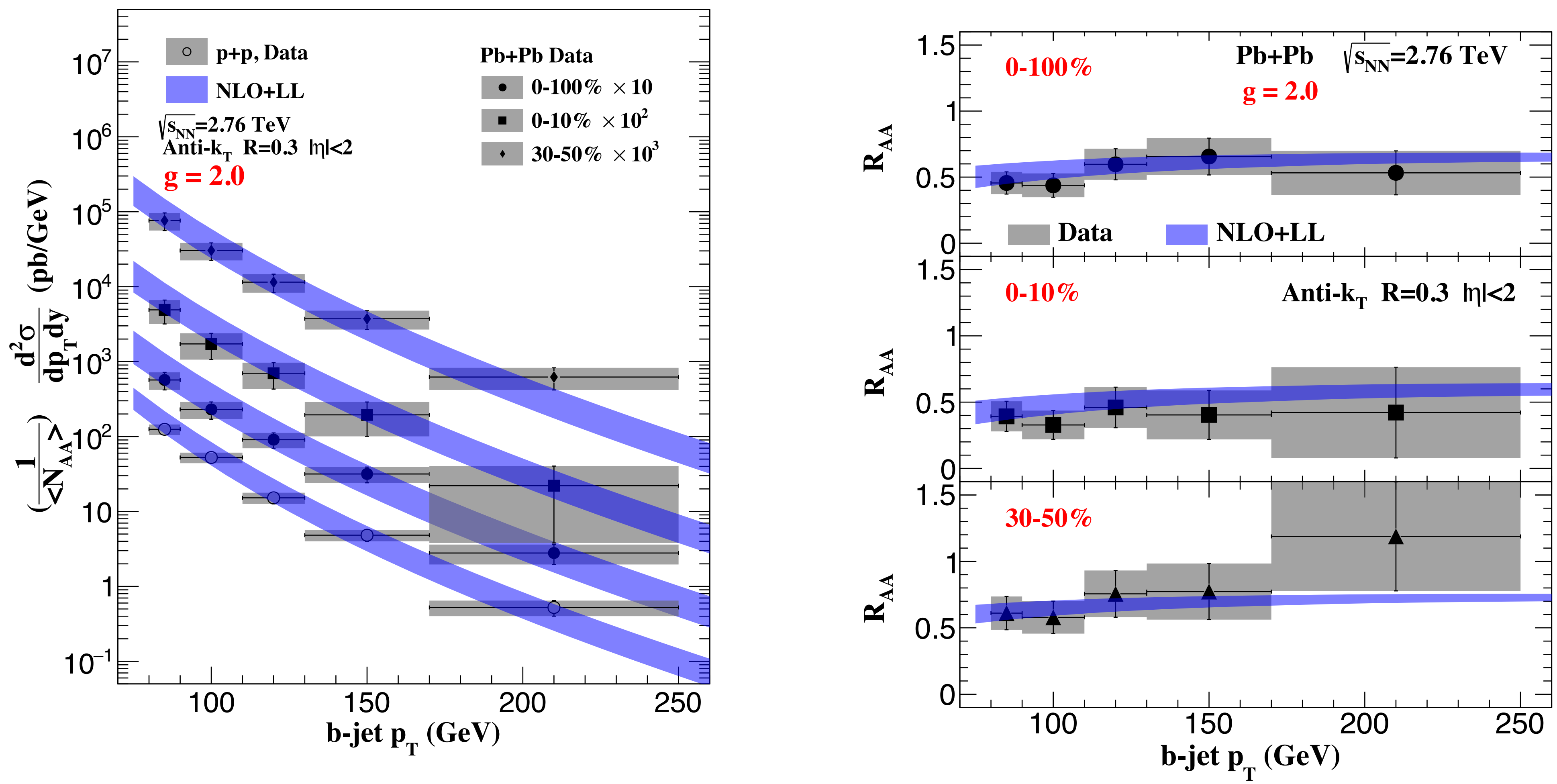
Massive partons: Kang, Ringer, Vitev 2016

$$\left(\frac{dN^{\rm med}}{dx d^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2} C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\boldsymbol{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm med}}{d^2\boldsymbol{q}_\perp} \left\{ \left(\frac{1+(1-x)^2}{x}\right) \left[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \right.\right.$$
$$\times \left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right.$$
$$\left. - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z]) + \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z])$$
$$+ \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right)(1-\cos[\Omega_4\Delta z]) - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2}(1-\cos[\Omega_5\Delta z])$$
$$\left. + \frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])\right]$$
$$\left. + x^3 m^2 \left[\frac{1}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{1}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{1}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \ldots\right]\right\}$$

$$\nu = x\,m \qquad (Q\to Qg)\,,$$
$$\nu = (1-x)\,m \qquad (Q\to gQ)\,,$$
$$\nu = m \qquad (g\to Q\bar{Q})\,,$$

$\boldsymbol{A}_\perp = \boldsymbol{k}_\perp,\ \boldsymbol{B}_\perp = \boldsymbol{k}_\perp + x\boldsymbol{q}_\perp,\ \boldsymbol{C}_\perp = \boldsymbol{k}_\perp - (1-x)\boldsymbol{q}_\perp,\ \boldsymbol{D}_\perp = \boldsymbol{k}_\perp - \boldsymbol{q}_\perp,$

b-jet in A-A collisions



- less dependence on the centrality when compared to the well-known light jet modification.
- the predictions agree very well with the data for both the inclusive cross sections and the nuclear modification factors.

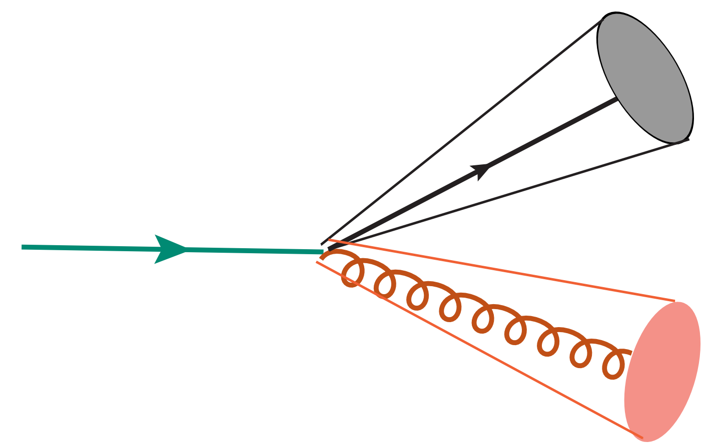
3. b-jet substructure

HTL, Vitev arXiv: 1801.00008

Soft-drop

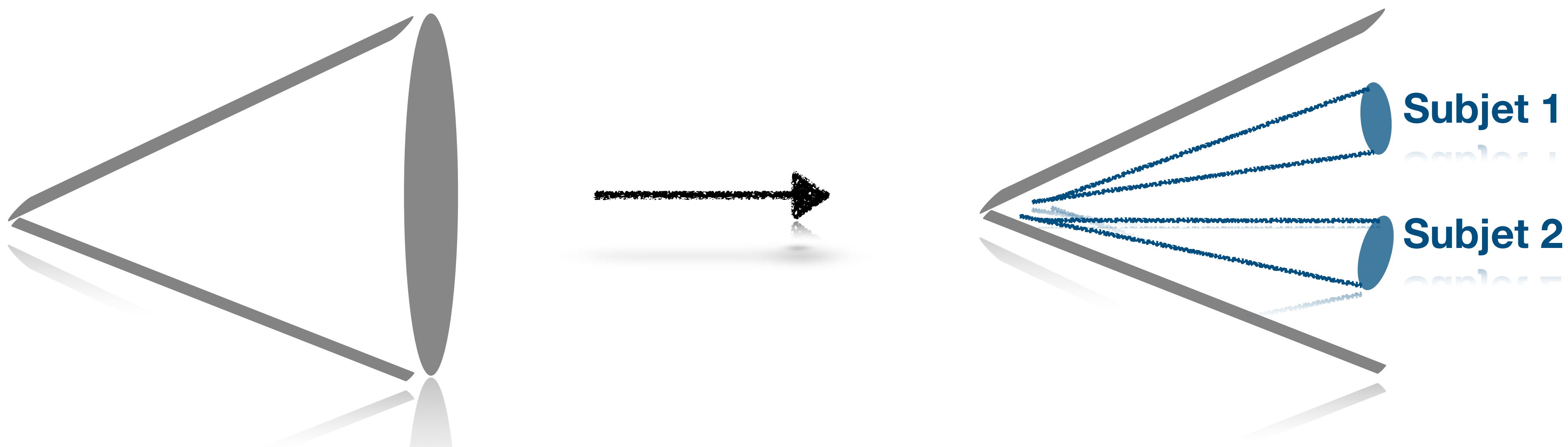
Defined as a two-prong substructure

- An early hard splitting will result in two partons with high transverse momentum.



One way to do this is to use Soft-Drop decluttering

$1 \to 2$ splitting process



Original jet with radius R_0

Undo last stage of C/A clustering

Define $z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$

If $z_g < z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$ redefine j to be the harder one, else we have the two-prong subjets

Resummed splitting kernels in the vacuum

Larkoski et al 2015

$\frac{dN_j^{FO}}{dz_g d\theta_g}$ is divergent when $\theta_g \to 0$ Collinear singularities

$\frac{dN_j^{F}}{dz_g}$ is not well-defined at any fixed perturbative order

but is well defined if we resum logs to all order

The MLL resummation for light jet to modified leading-logarithmic (MLL) accuracy,

$$\frac{dN_j^{\mathrm{vac,MLL}}}{dz_g d\theta_g} = \sum_i \left(\frac{dN^{\mathrm{vac}}}{dz_g d\theta_g}\right)_{j\to i\bar{i}} \underbrace{\exp\left[-\int_{\theta_g}^{1} d\theta \int_{z_{\mathrm{cut}}}^{1/2} dz \sum_i \left(\frac{dN^{\mathrm{vac}}}{dz d\theta}\right)_{j\to i\bar{i}}\right]}_{\text{Sudakov Factor}}$$

MLL includes running coupling effects and subleading terms in the splitting functions compared to LL resummation.

For $g \to b\bar{b}$, $g \to c\bar{c}$ the resumed distribution is

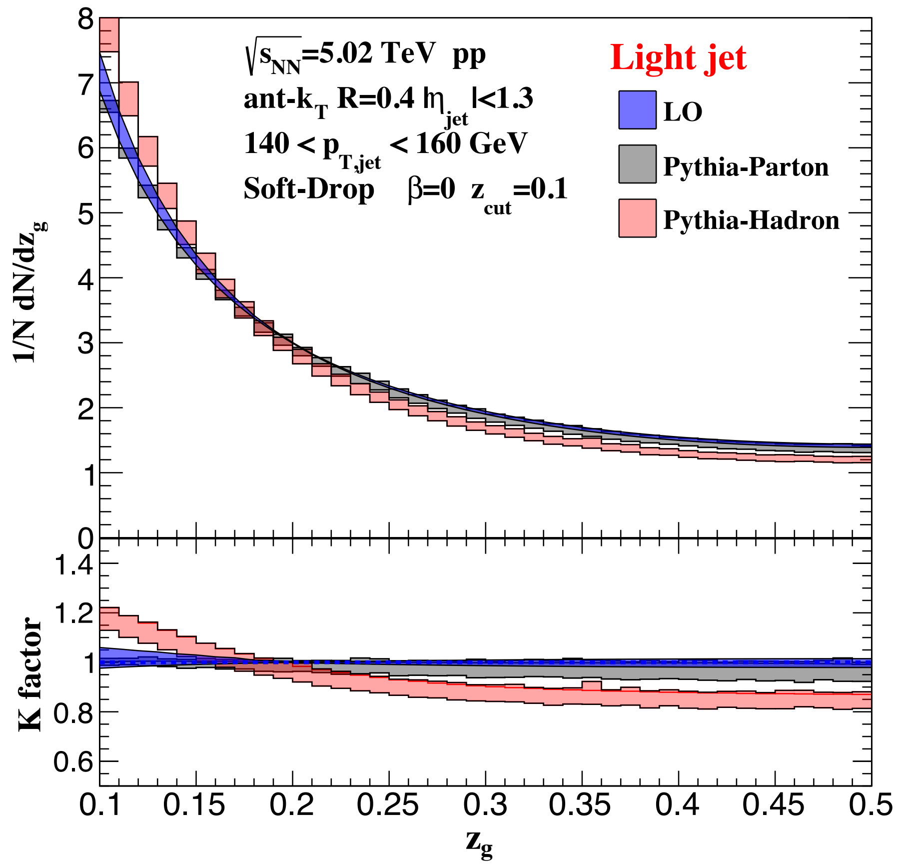
$$p(\theta_g, z_g)\big|_{g\to Q\bar{Q}} = \frac{\left(\frac{dN^{\mathrm{vac}}}{dz_g d\theta_g}\right)_{g\to Q\bar{Q}} \Sigma_g(\theta_g)}{\int_0^1 d\theta \int_{z_{\mathrm{cut}}}^{1/2} dz \left(\frac{dN^{\mathrm{vac}}}{dz d\theta}\right)_{g\to Q\bar{Q}} \Sigma_g(\theta)},$$

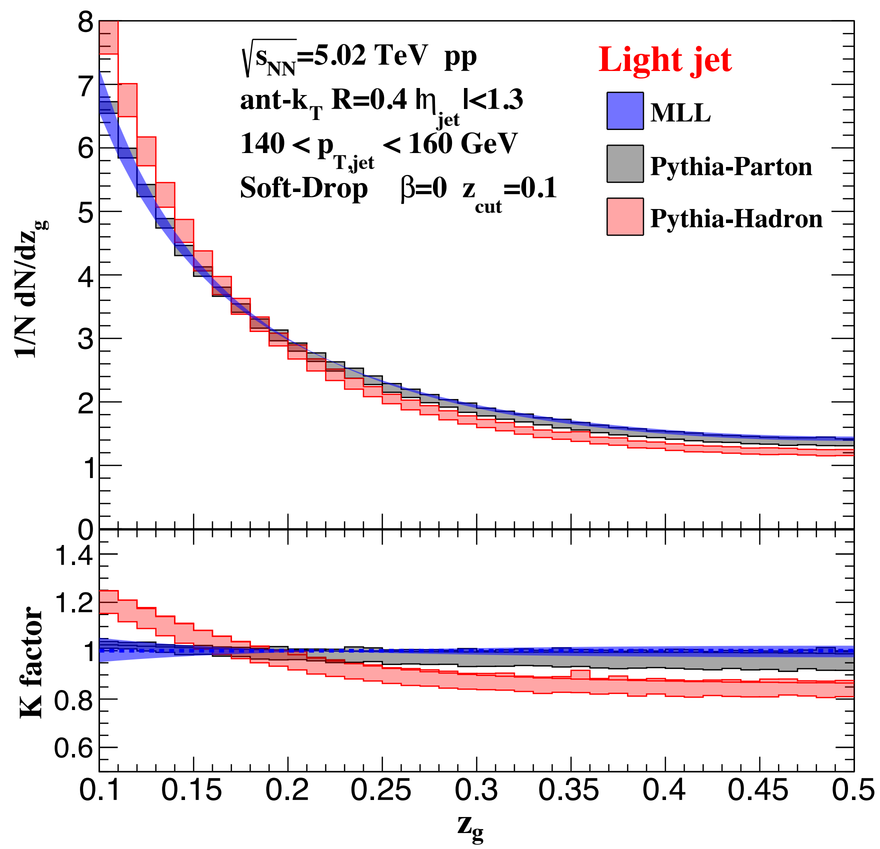
Exponentiate all the possible contributions for gluon evolution

Results for light jet

In pp collisions uncertainties are generated **by varying scales**

In heavy-ion collisions uncertainties are generated **by varying scales and coupling (between medium and jet)** independently.

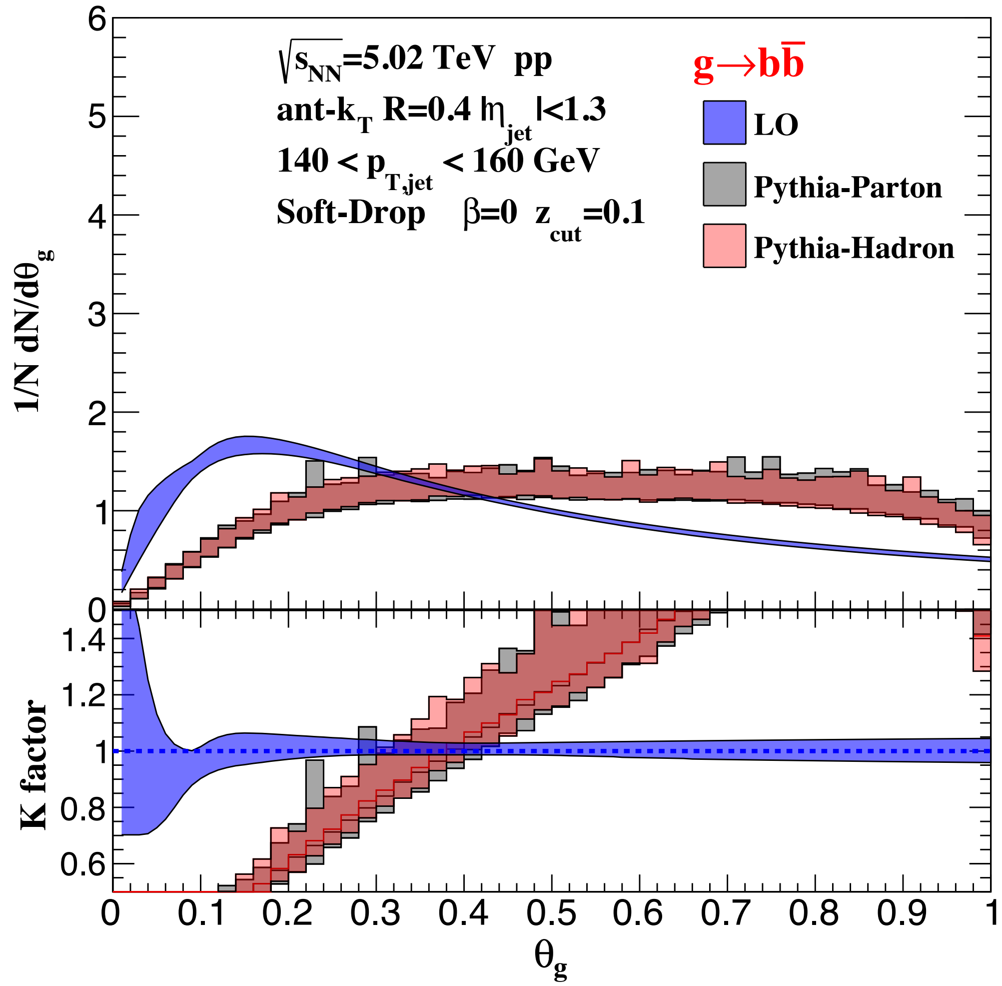


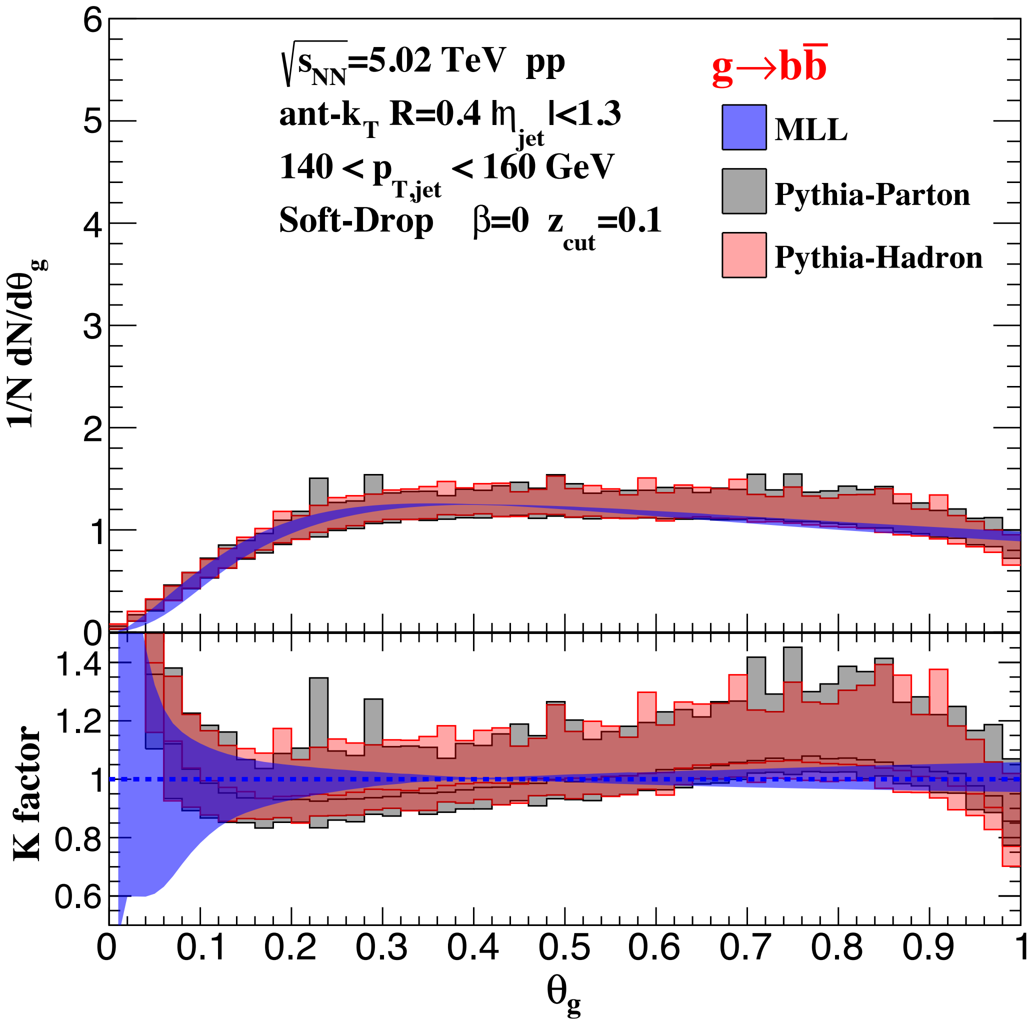


- MLL is slightly less steep than Pythia with hadronization
- Our results are consistent with the ones from literature

Results for heavy flavor tagged jet

LO and MLL predictions for b-tagged subjets

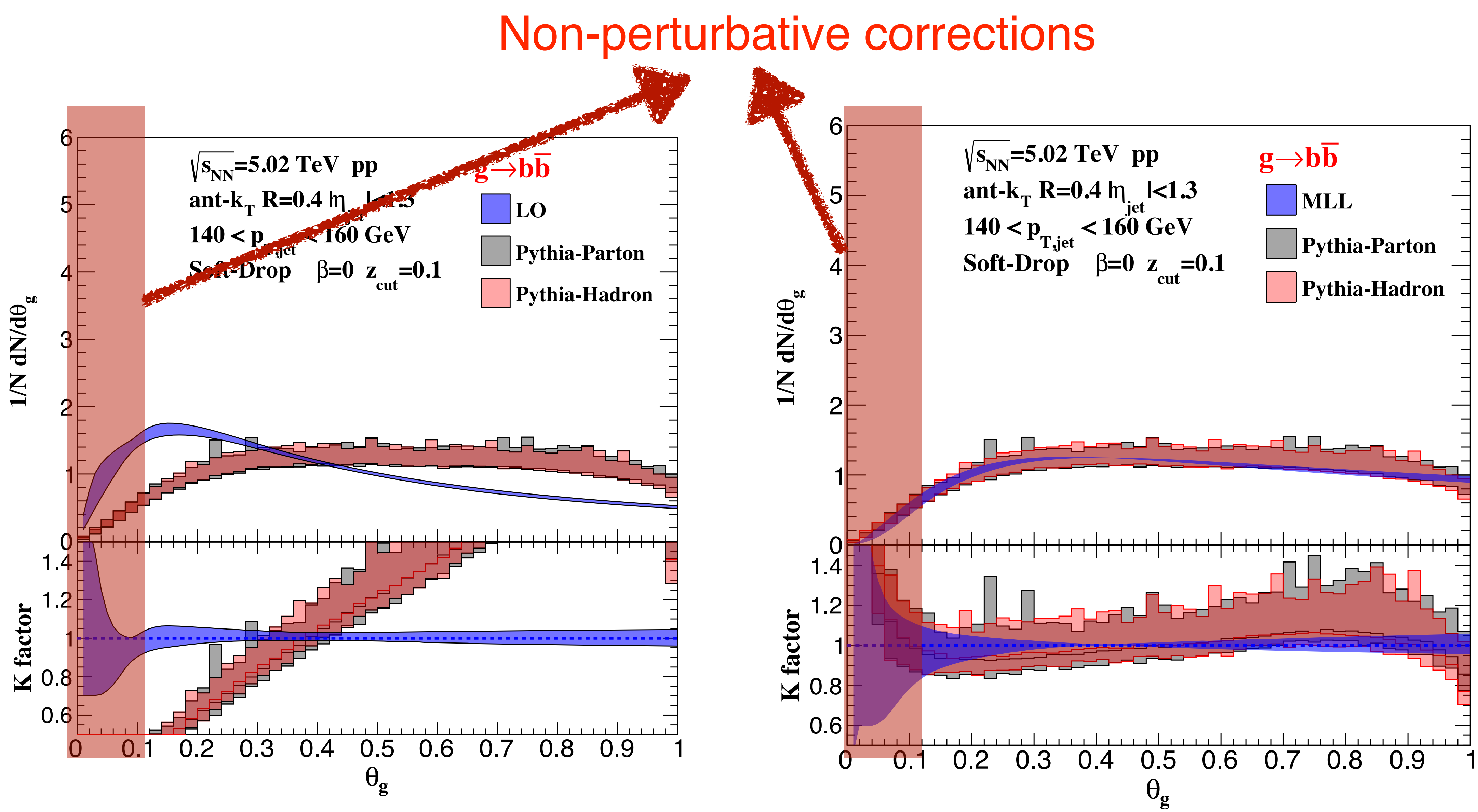




- Huge Sudakov suppression in the small angle region
- Dominated by wide-angle gluon splittings

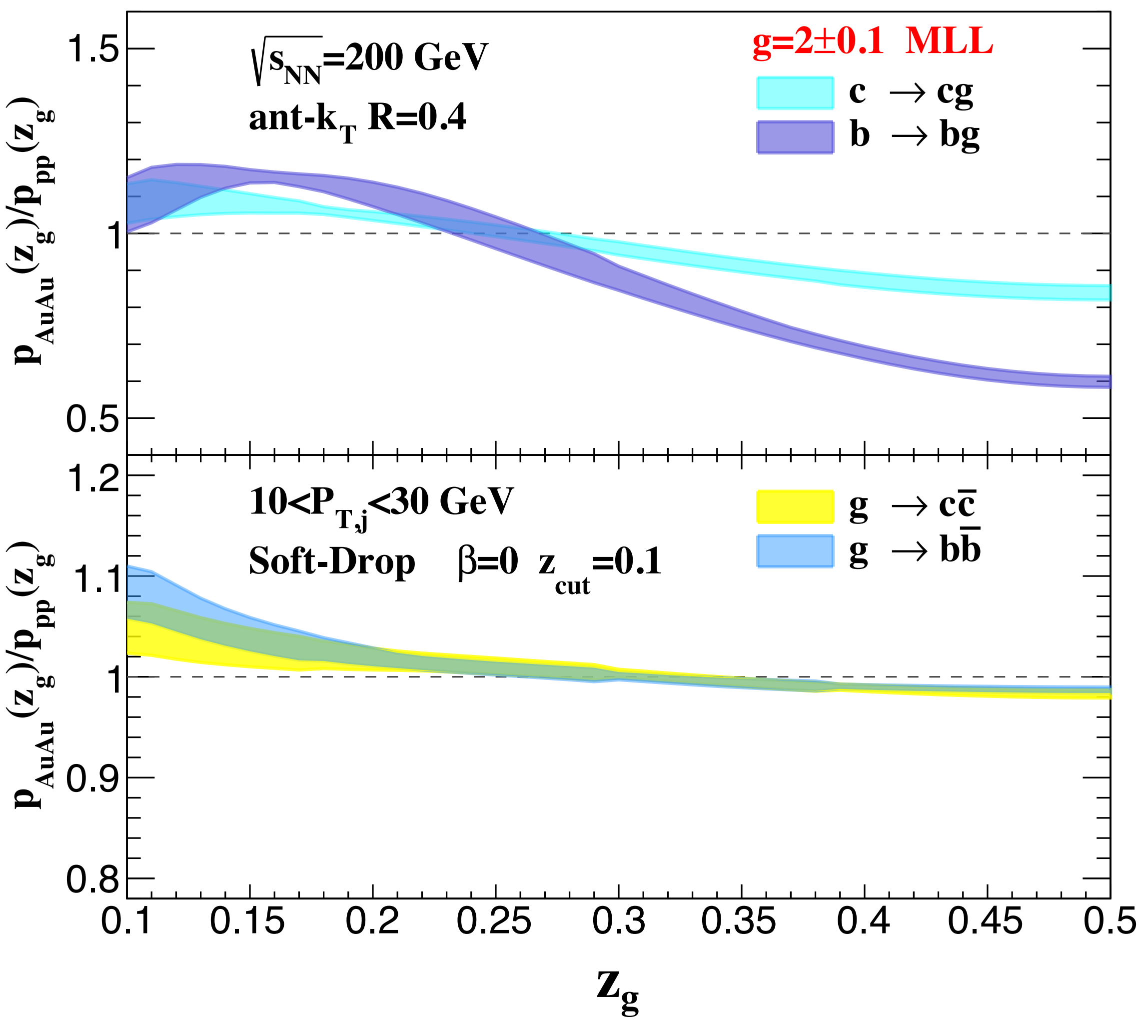
Results for heavy flavor tagged jet

LO and MLL predictions for b-tagged subjets

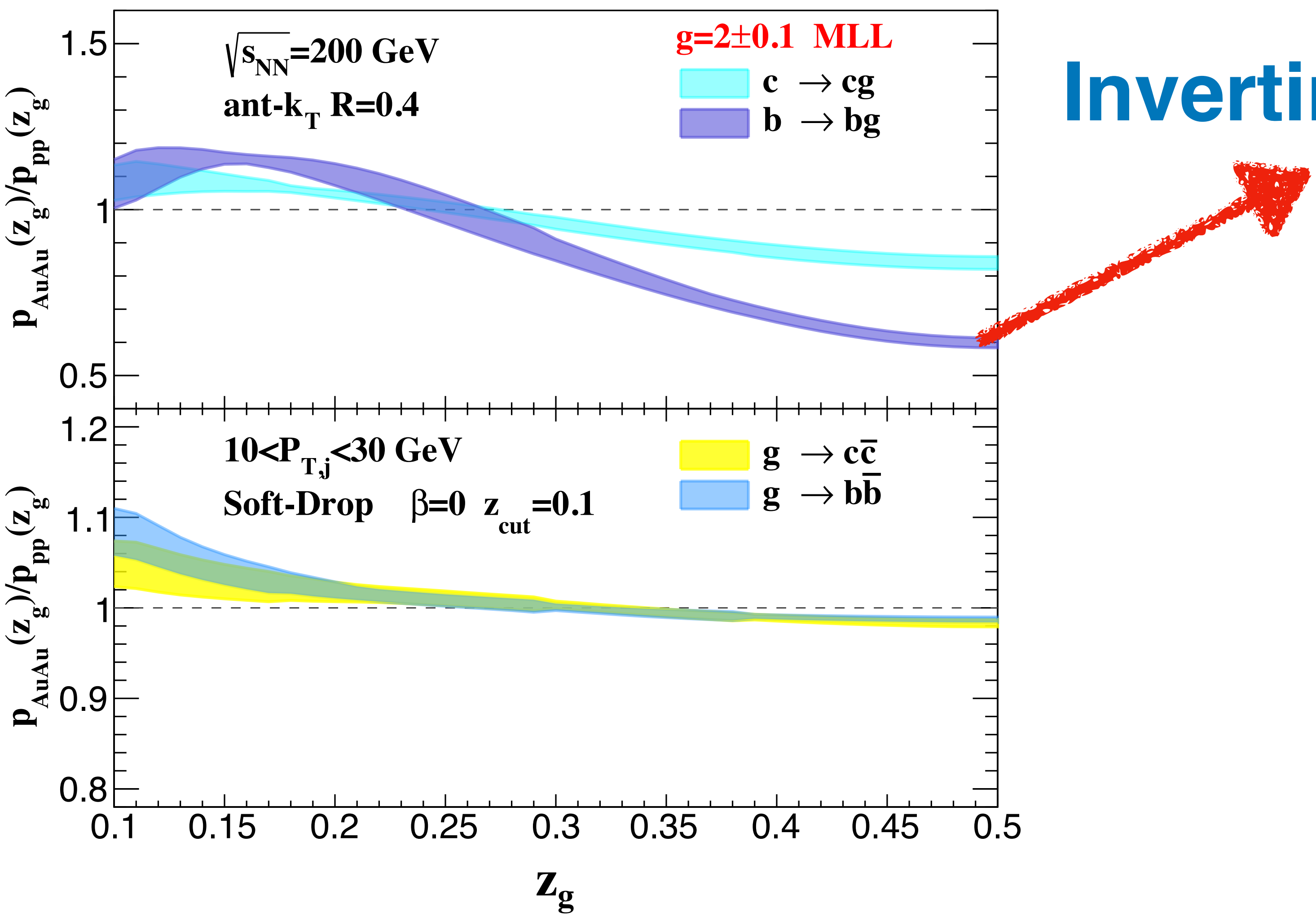


- Huge Sudakov suppression in the small angle region
- Dominated by wide-angle gluon splittings

Results for heavy flavor tagged jet

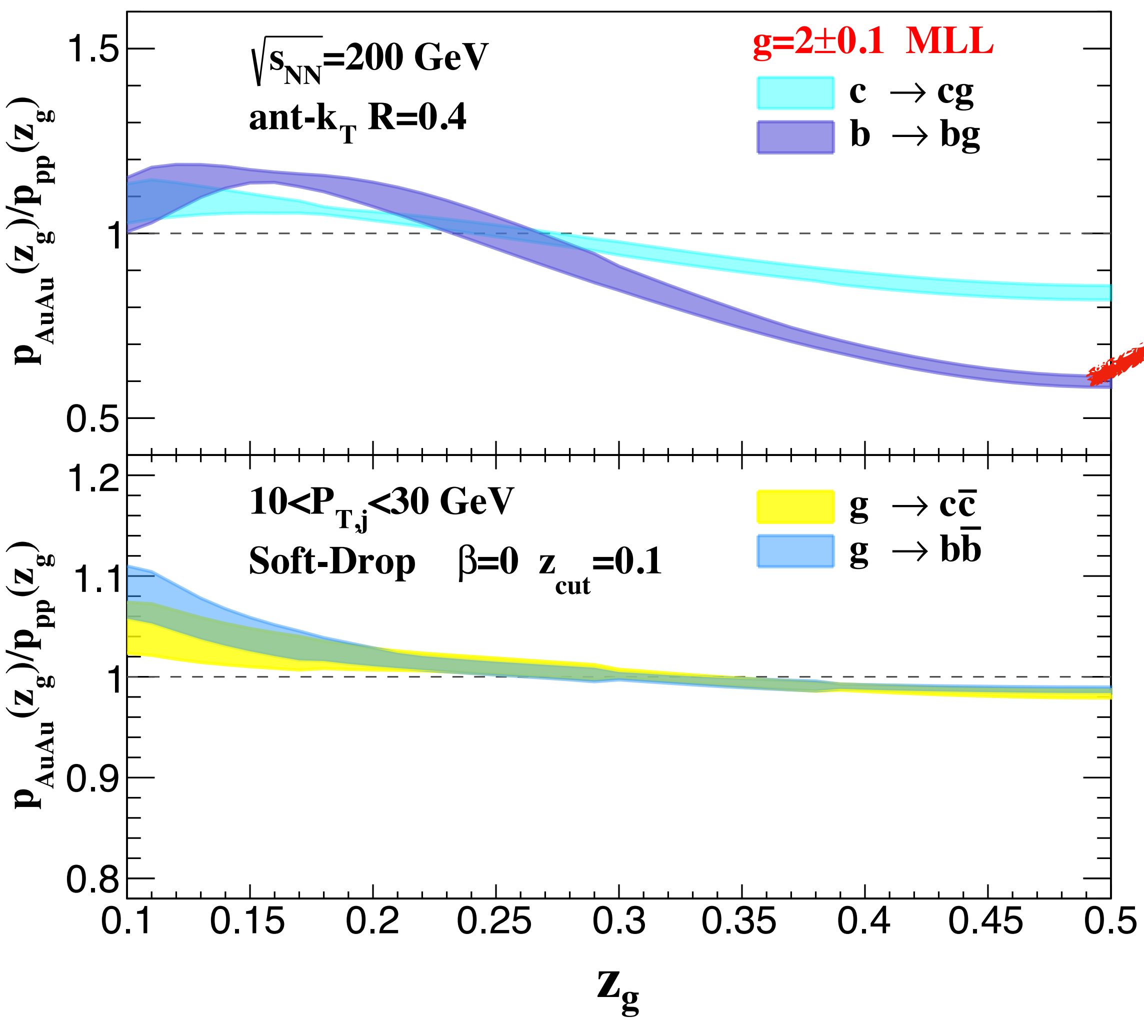


Results for heavy flavor tagged jet



Inverting the mass hierarchy in

Results for heavy flavor tagged jet



Inverting the mass hierarchy in

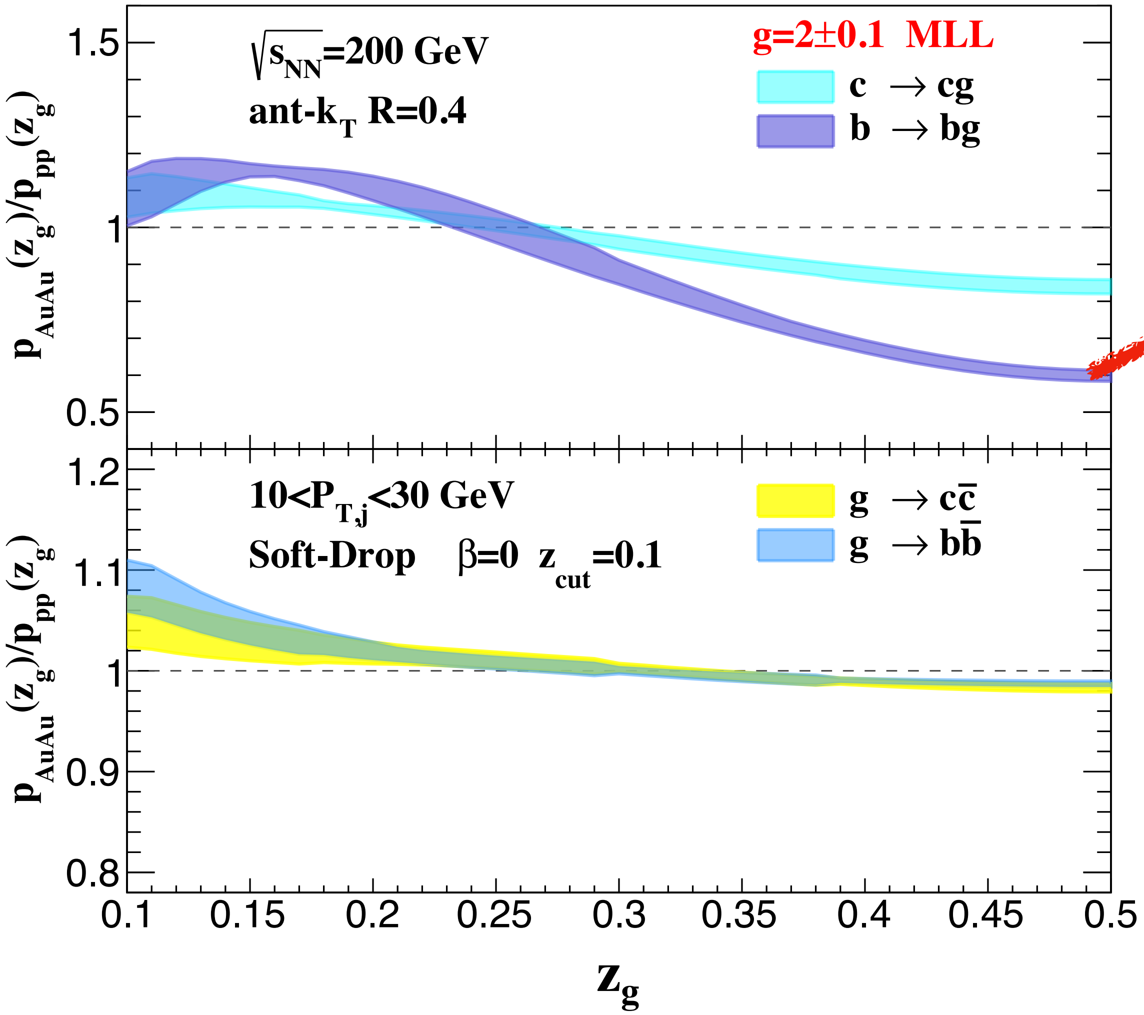
$$k_\perp \sim 2z(1-z)\Delta R_{12} p_T$$

Splitting function in the vacuum

$$\left(\frac{dN^{\rm vac}}{dz d^2\mathbf{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2}\frac{C_F}{\mathbf{k}_\perp^2 + z^2m^2}\left(\frac{1+(1-z)^2}{z} - \frac{2z(1-z)m^2}{\mathbf{k}_\perp^2+z^2m^2}\right)$$

$$\left(\frac{dN^{\rm vac}}{dz d^2\mathbf{k}_\perp}\right)_{g\to Q\bar{Q}} = \frac{\alpha_s}{2\pi^2}\frac{T_R}{\mathbf{k}_\perp^2 + m^2}\left(z^2+(1-z)^2 + \frac{2z(1-z)m^2}{\mathbf{k}_\perp^2+m^2}\right)$$

Results for heavy flavor tagged jet



Inverting the mass hierarchy in

$$k_\perp \sim 2z(1-z)\Delta R_{12} p_T$$

Splitting function in the vacuum

$$\left(\frac{dN^{\rm vac}}{dz d^2\mathbf{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2}\frac{C_F}{\mathbf{k}_\perp^2 + z^2 m^2}\left(\frac{1+(1-z)^2}{z} - \frac{2z(1-z)m^2}{\mathbf{k}_\perp^2 + z^2m^2}\right)$$

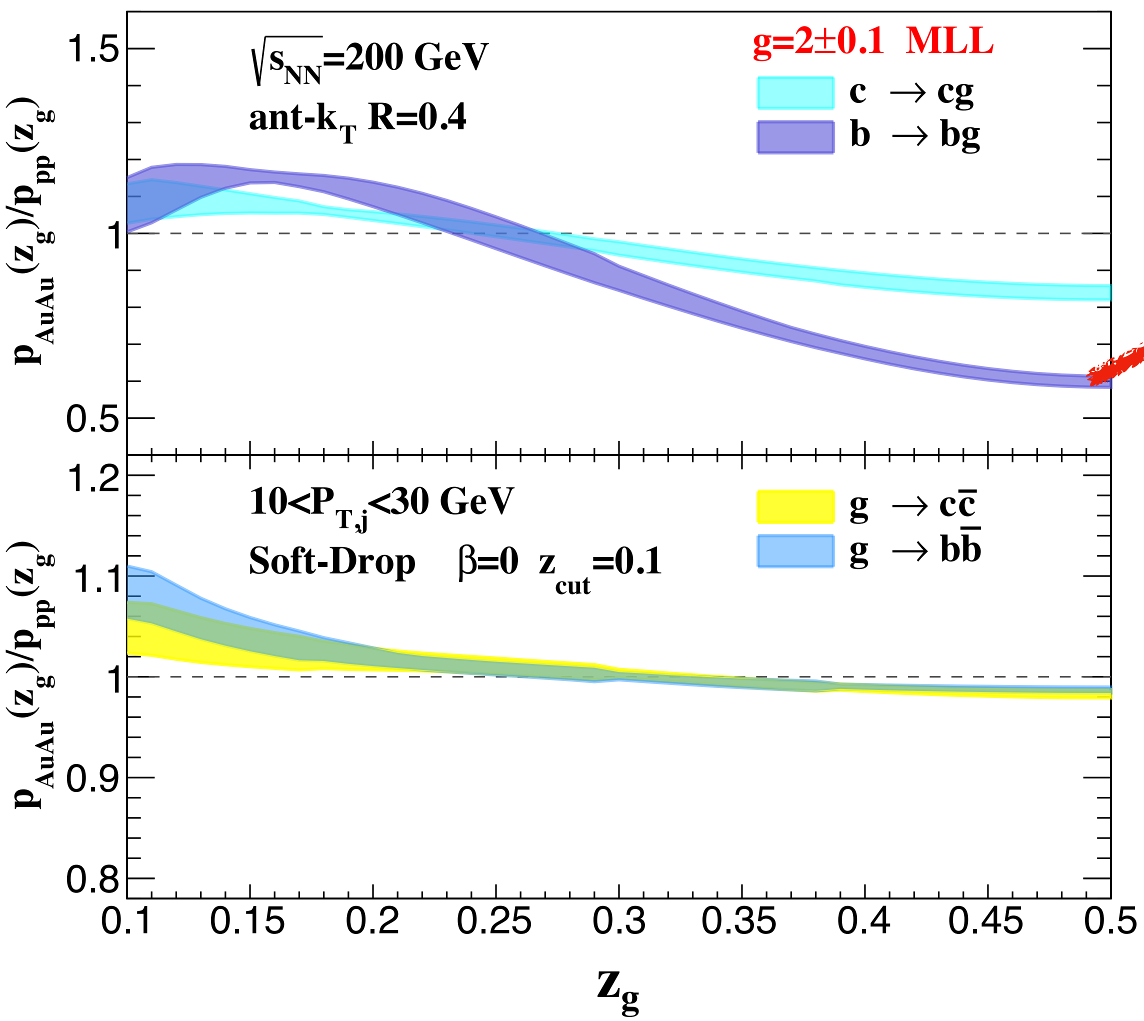
$$\left(\frac{dN^{\rm vac}}{dz d^2\mathbf{k}_\perp}\right)_{g\to Q\bar{Q}} = \frac{\alpha_s}{2\pi^2}\frac{T_R}{\mathbf{k}_\perp^2 + m^2}\left(z^2+(1-z)^2 + \frac{2z(1-z)m^2}{\mathbf{k}_\perp^2 + m^2}\right)$$

$$\mathbf{b \to bg}$$

$$\left(\frac{1}{k_\perp^2 + z^2m^2}\right) \times \left(\frac{1}{k_\perp^2 + z^2m^2}\right) \times c \quad \xrightarrow{k_\perp \to 0} \quad \frac{1}{z^4m^4} \times c$$

Predict stronger jet momentum sharing distribution modification than light jets

Results for heavy flavor tagged jet



Inverting the mass hierarchy in

$$k_\perp \sim 2z(1-z)\Delta R_{12} p_T$$

Splitting function in the vacuum

$$\left(\frac{dN^{\rm vac}}{dzd^2\mathbf{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2}\frac{C_F}{\mathbf{k}_\perp^2 + z^2m^2}\left(\frac{1+(1-z)^2}{z} - \frac{2z(1-z)m^2}{\mathbf{k}_\perp^2 + z^2m^2}\right)$$

$$\left(\frac{dN^{\rm vac}}{dzd^2\mathbf{k}_\perp}\right)_{g\to Q\bar{Q}} = \frac{\alpha_s}{2\pi^2}\frac{T_R}{\mathbf{k}_\perp^2 + m^2}\left(z^2+(1-z)^2 + \frac{2z(1-z)m^2}{\mathbf{k}_\perp^2 + m^2}\right)$$

$b \to bg$

$$\left(\frac{1}{k_\perp^2 + z^2m^2}\right)\times\left(\frac{1}{k_\perp^2 + z^2m^2}\right)\times c \xrightarrow{k_\perp \to 0} \frac{1}{z^4m^4}\times c$$

Predict stronger jet momentum sharing distribution modification than light jets

$g \to b\bar{b}$

$$\left(\frac{1}{k_\perp^2 + m^2}\right)\times\left(\frac{1}{k_\perp^2 + m^2}\right)\times c \xrightarrow{k_\perp \to 0} \frac{1}{m^4}\times c$$

Predict almost no jet momentum sharing distribution modification

4. Conclusion

- ☑ jet is a QCD observable, calculable in perturbative QCD
- ☑ heavy quarks have fundamentally different radiation patterns from light quarks
- ☑ present inclusive b-jet production from pp to AA collisions
- ☑ present soft drop groomed b-jet z_g substructure

4. Conclusion

- ☑ jet is a QCD observable, calculable in perturbative QCD
- ☑ heavy quarks have fundamentally different radiation patterns from light quarks
- ☑ present inclusive b-jet production from pp to AA collisions
- ☑ present soft drop groomed b-jet z_g substructure

Jet production can be related to TMD physics

4. Conclusion

- ☑ jet is a QCD observable, calculable in perturbative QCD
- ☑ heavy quarks have fundamentally different radiation patterns from light quarks
- ☑ present inclusive b-jet production from pp to AA collisions
- ☑ present soft drop groomed b-jet z_g substructure

Jet production can be related to TMD physics

Thank you !