Inclusive heavy flavor jet production with semi-inclusive jet functions: from proton to heavy-ion collisions

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Based on the work with Ivan Vitev arXiv:1811.07905

the 2019 Santa Fe Jets and Heavy Flavor workshop
at UCLA, January 28, 2019

Motivation

Jet production

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

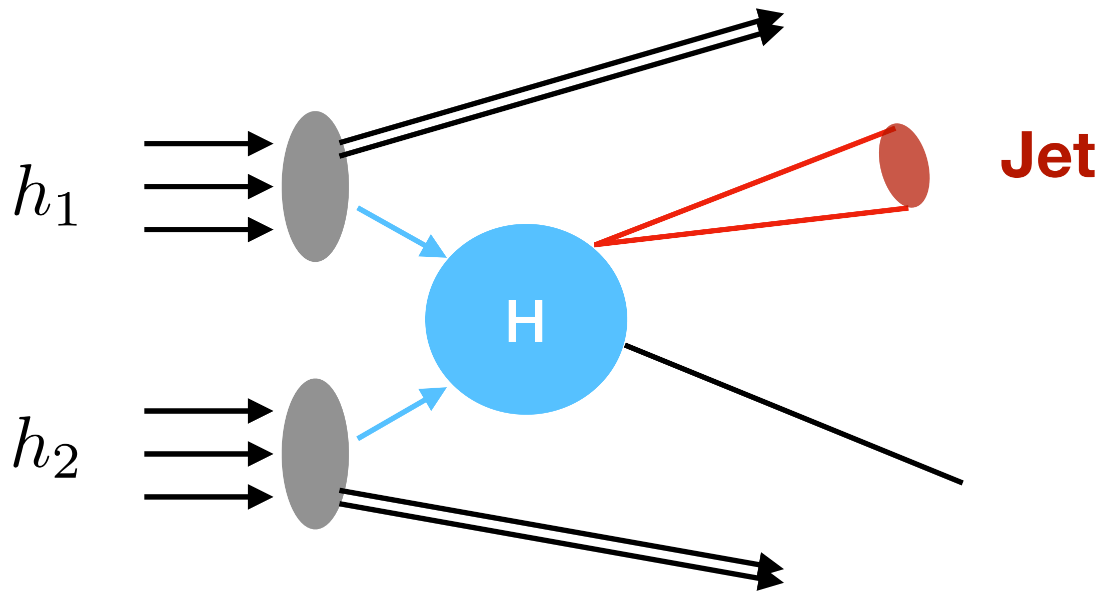
Heavy flavor jet

- is dominated by the quark initialed process compared to light jet
- experiences the full evolution of the hot and dense medium produced in ultra-relativistic heavy ion collisions
- seems to lose less energy; used to study the energy loss mechanisms in QCD medium

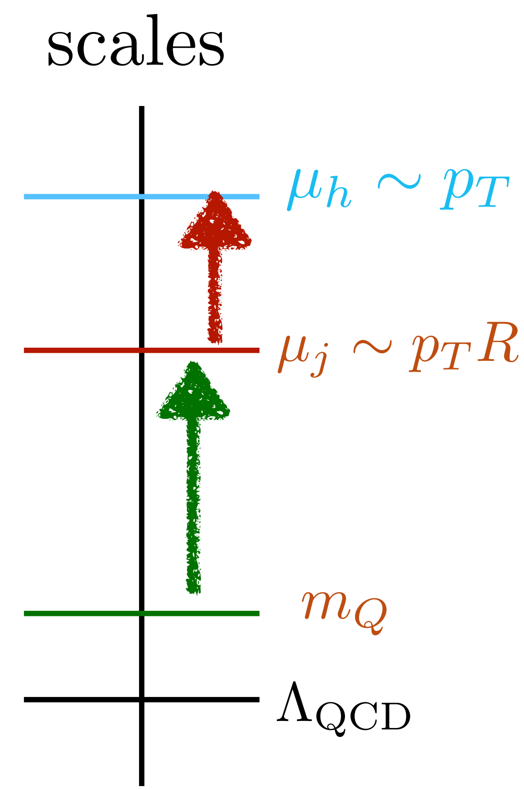
This talk is about the inclusive heavy flavor jet production

In p+p collisions

Inclusive jet Production



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



Aversa et al 1990
J¨ager 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

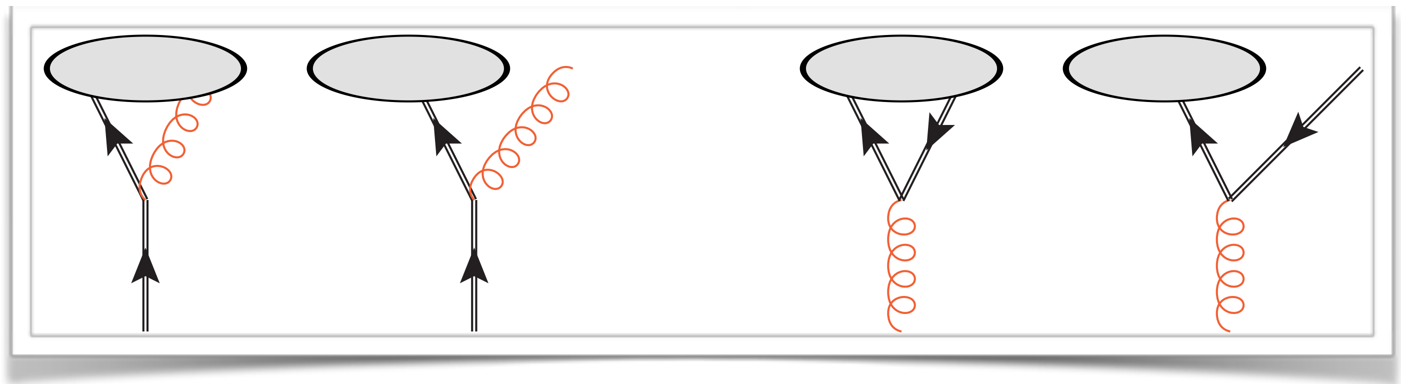
Aversa et al 1989, Jager et al 2002

Semi-inclusive jet function

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

heavy flavor jet: Dai et al 2018

Inclusive jet Production



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

Using SCET with finite quark mass

Leibovich, Ligeti, Wise 2003

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

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

Dai, Kim, Leibovich 2018

finite when m~0

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

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

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

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

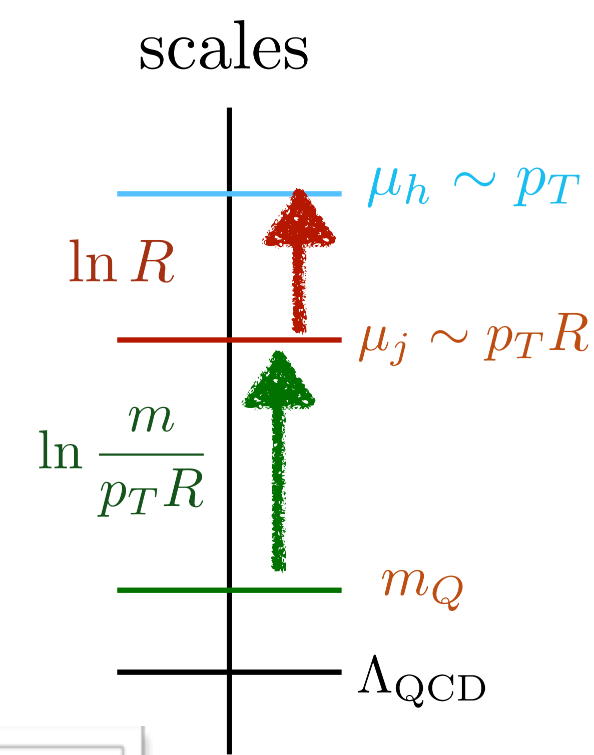
Resummation

The SiJFs Evolve according to DGLAP-like equations

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

P_{ij} is the usual Altarelli-Parisi splitting function

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



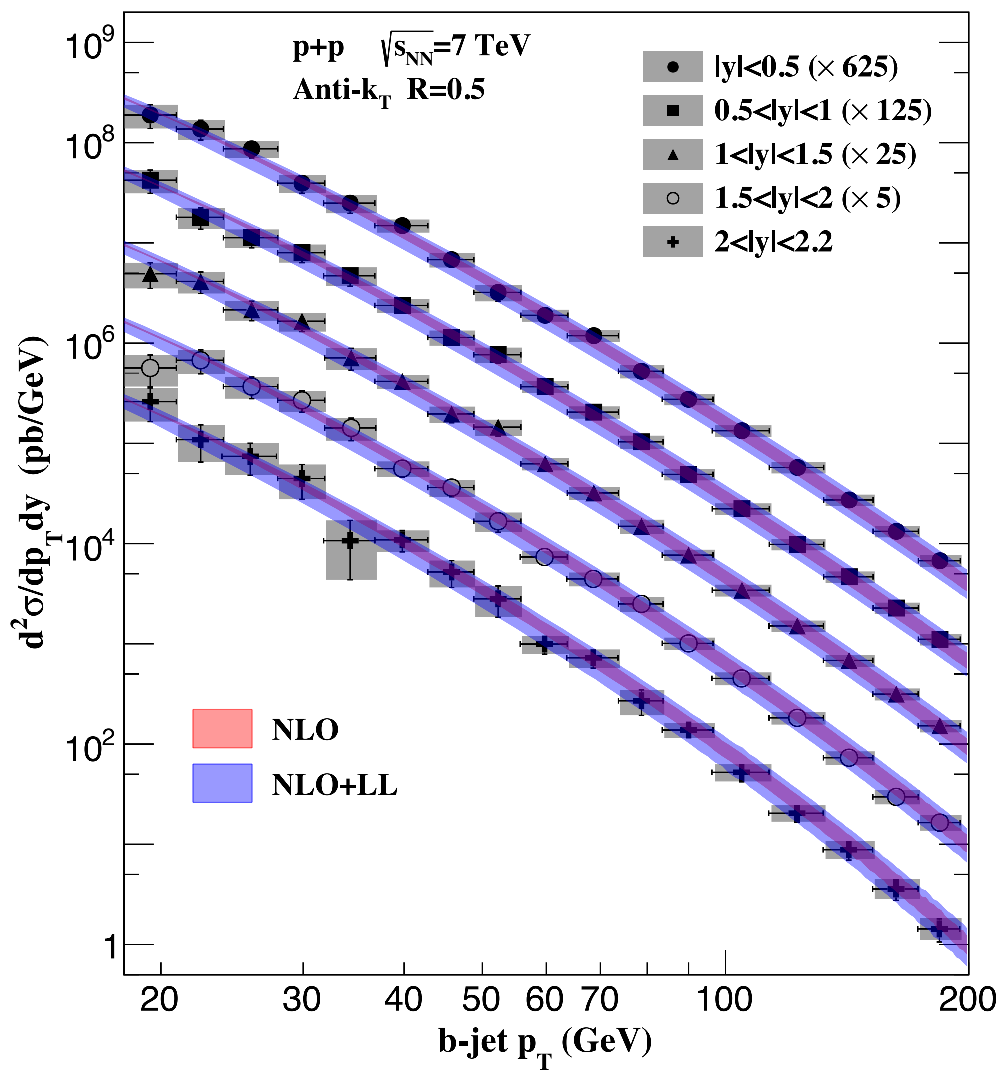
$$\mathcal{M}^{\rm in-jet}_{g\to Q\bar{Q}}(p_T R, m) = 2\sum_{l=g,Q}\bar{K}_{l/g}(p_T R, m, \mu_F)\bar{D}_{Q/l}(m,\mu_F)$$

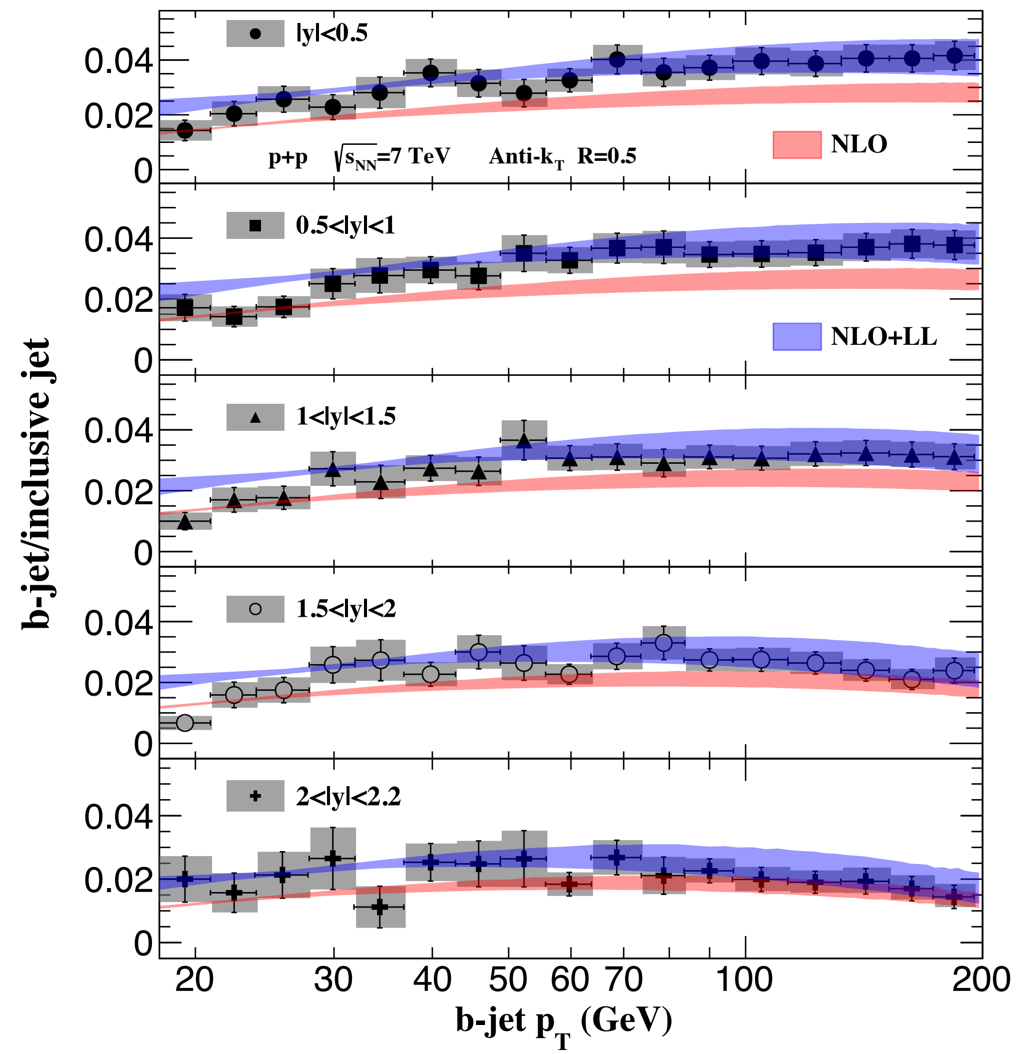
the integrated perturbative kernel at the jet typical scale

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

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

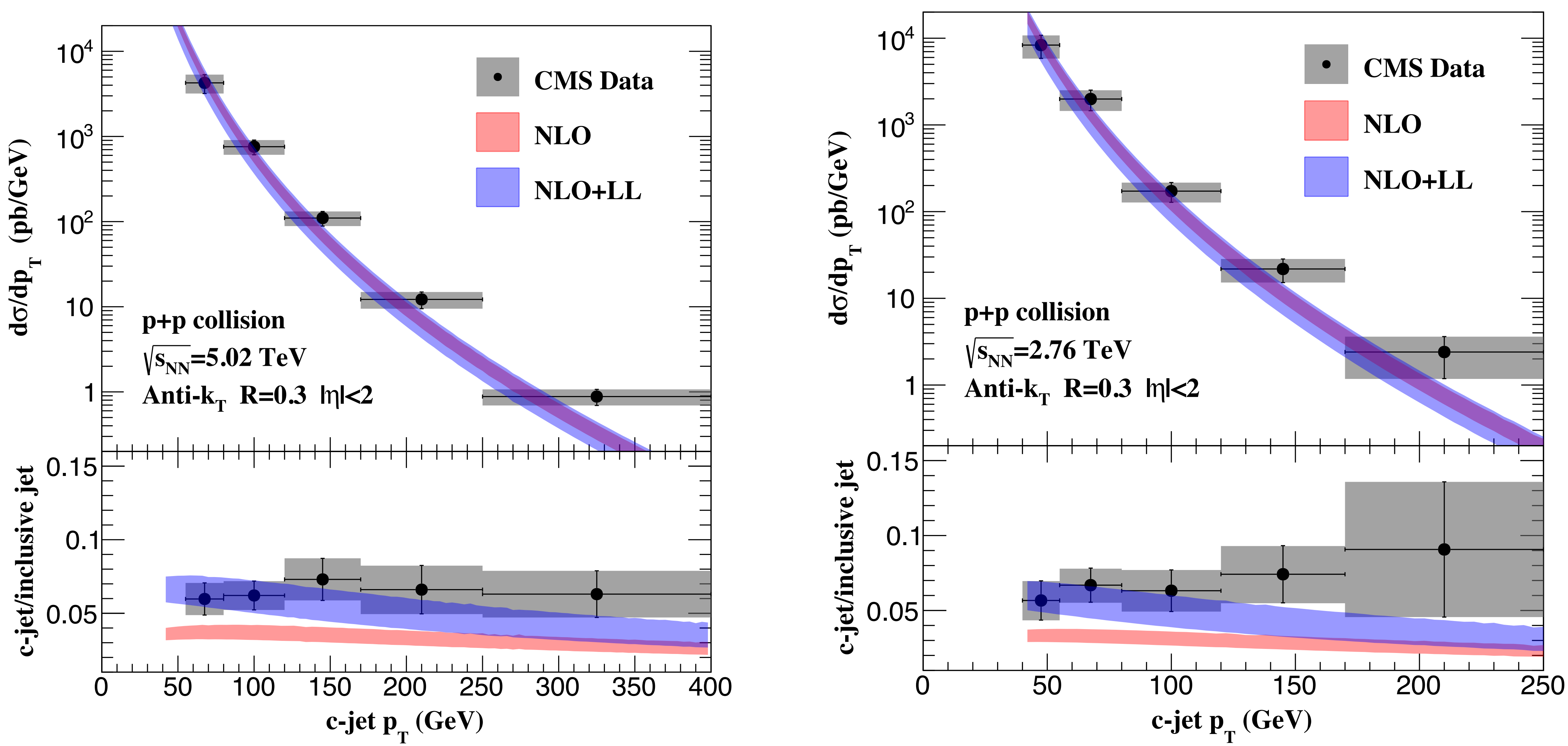
b-jet in pp collisions





- 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

c-jet in pp collisions



- the lnR resummation changes the c-jet cross section by about 10%
- but with larger theoretical uncertainties
- the NLO+LL c-jet fractions agree better with CMS measurements

In p+A collisions

Corrections in P-A collisions

Assume the factorization works in heavy ion collisions:

replaced by Nuclear PDFs

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

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 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

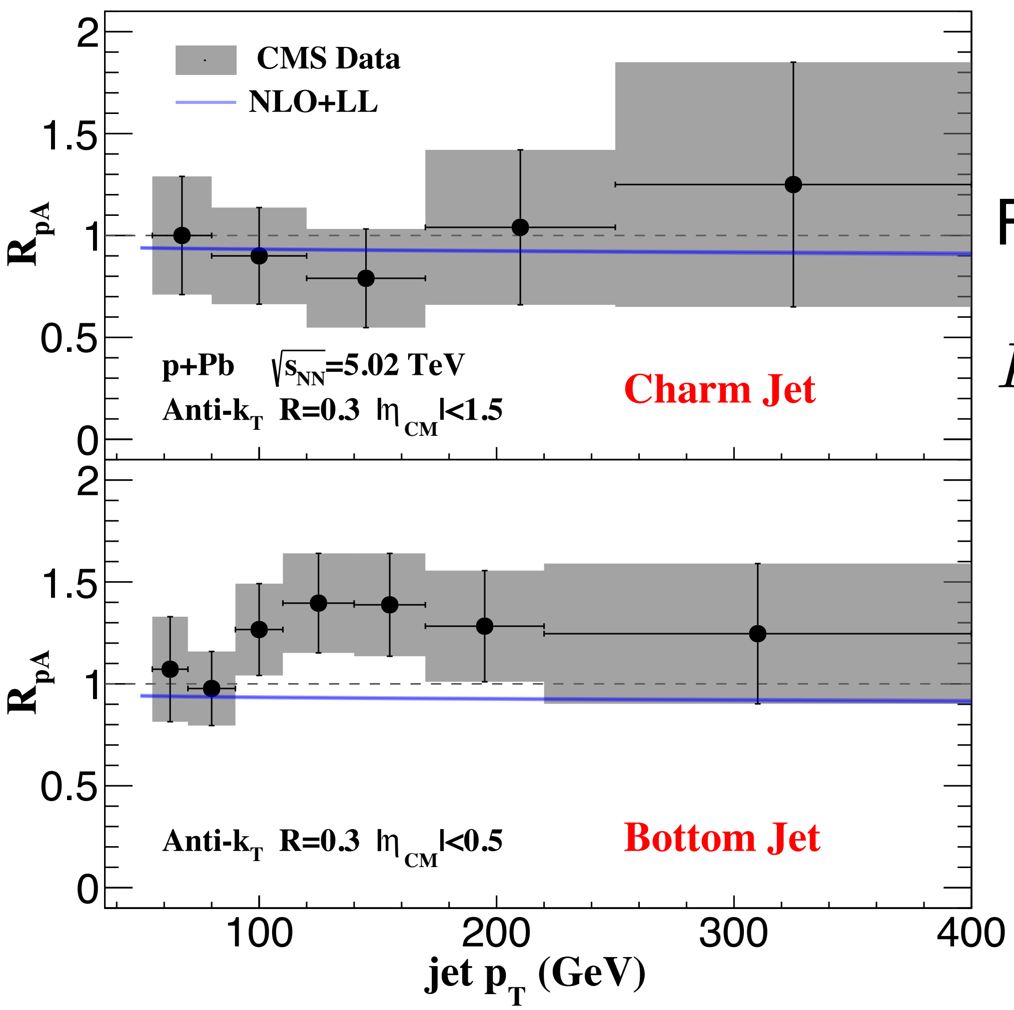
$$f_{q/A}(x,\mu) \to f_{q/A}\left(\frac{x}{1-\epsilon_q},\mu\right), \qquad f_{g/A}(x,\mu) \to f_{g/A}\left(\frac{x}{1-\epsilon_g},\mu\right).$$

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

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

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

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

Predictions:
- very 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

In A+A collisions

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encode the effects when the jet evolving in the QCD medium

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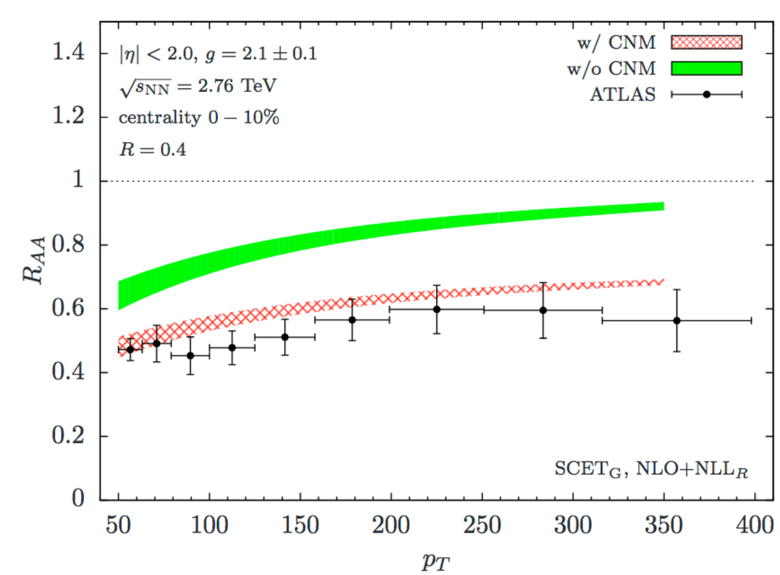
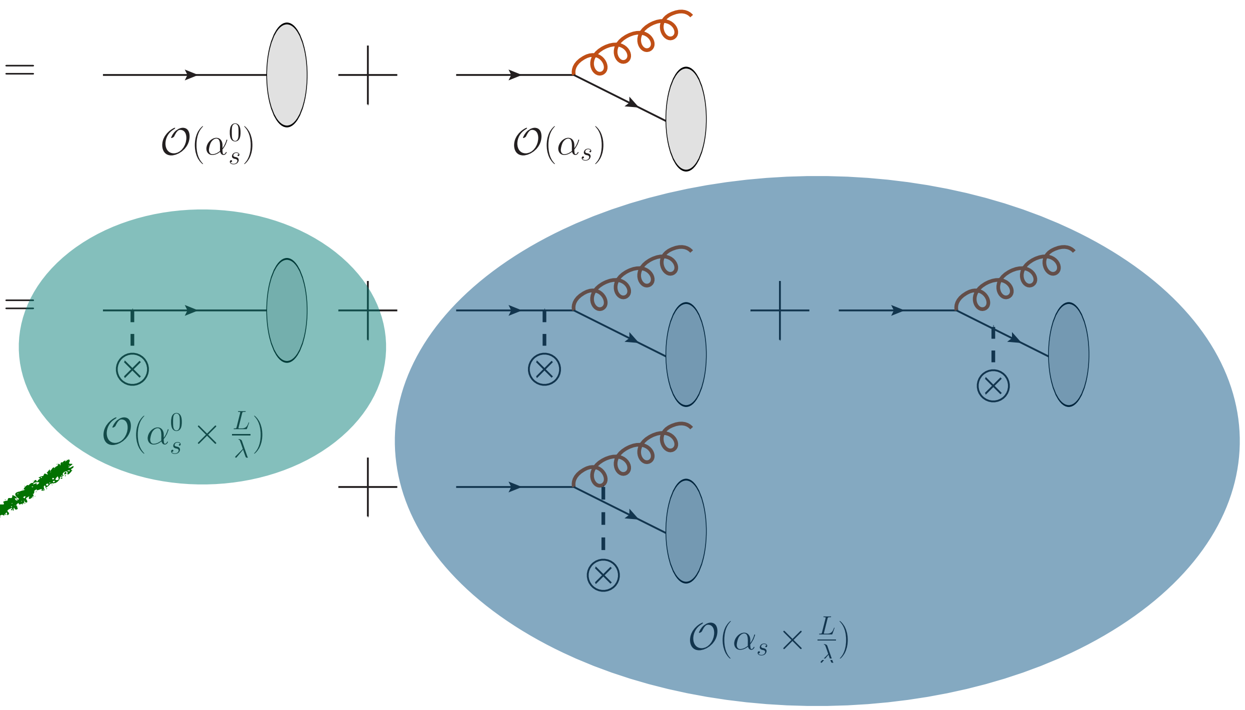
for light jet see the work Kang, Ringer and Vitev 2017



Jet functions in QCD medium

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

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



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

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

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

Corrections in QCD medium

$$J_{J_Q/i}^{\mathrm{med},(0)}(z, p_T, \delta p_T^i) = z\delta_{iQ}\left[\delta\left(1 - z - \frac{\delta p_T^i}{p_T + \delta p_T^i}\right) - \delta(1-z)\right]$$

The transverse momentum shift was derived from a operator definition

Neufeld, Vitev, Xing, 2014

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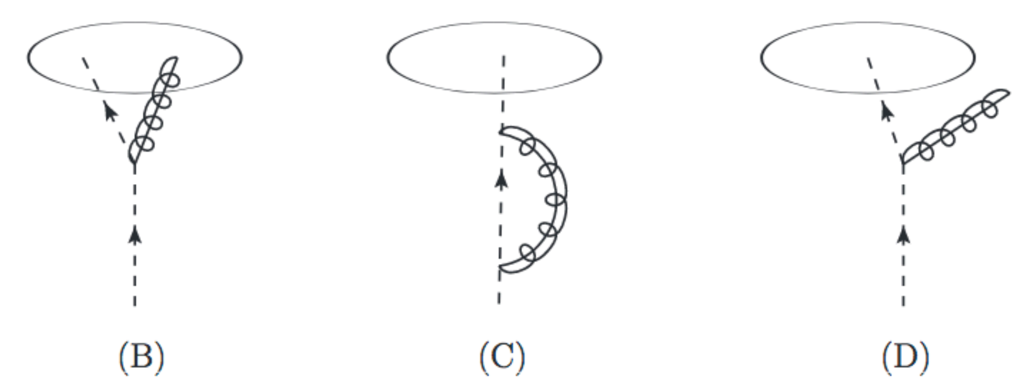
Medium corrections to the NLO jet function are written in terms of integrals over splitting functions.

for example

$$Q \to J_Q \qquad \begin{aligned} B &= \delta(1-z)\int_0^1 dx \int_0^{x(1-x)p_T R} dq_\perp P^{\mathrm{med}}_{QQ}(z, m, q_\perp) \\ C &= -\delta(1-z)\int_0^1 dx \int_0^{\mu} dq_\perp P^{\mathrm{med}}_{QQ}(z, m, q_\perp) \end{aligned}$$



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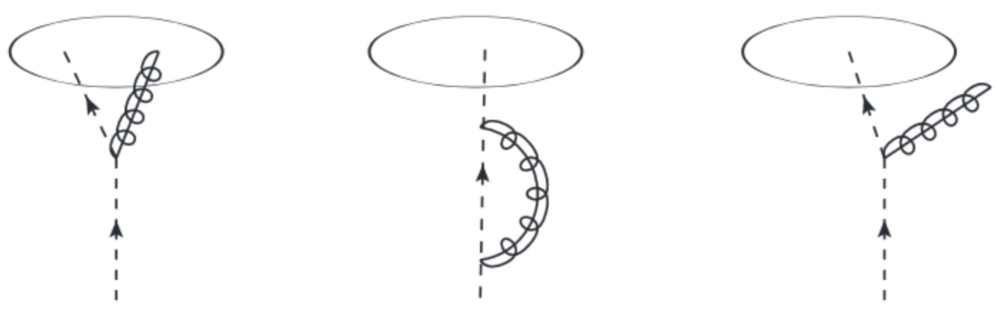

After summing over all diagrams

$$J_{J_Q/Q}^{\mathrm{med},(1)}(z, p_T R, m, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P_{QQ}^{\mathrm{med}}(z, m, q_\perp)\right]_+$$

$$J_{J_s/g}^{\mathrm{med},(1)}(z, p_T R, m, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P_{Qg}^{\mathrm{med}}(z, m, q_\perp)\right]_+ + \int_{z(1-z)p_T R}^{\mu} dq_\perp P_{Qg}^{\mathrm{med}}(z, m, q_\perp)$$

Kang, Ringer, Vitev, 2017

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

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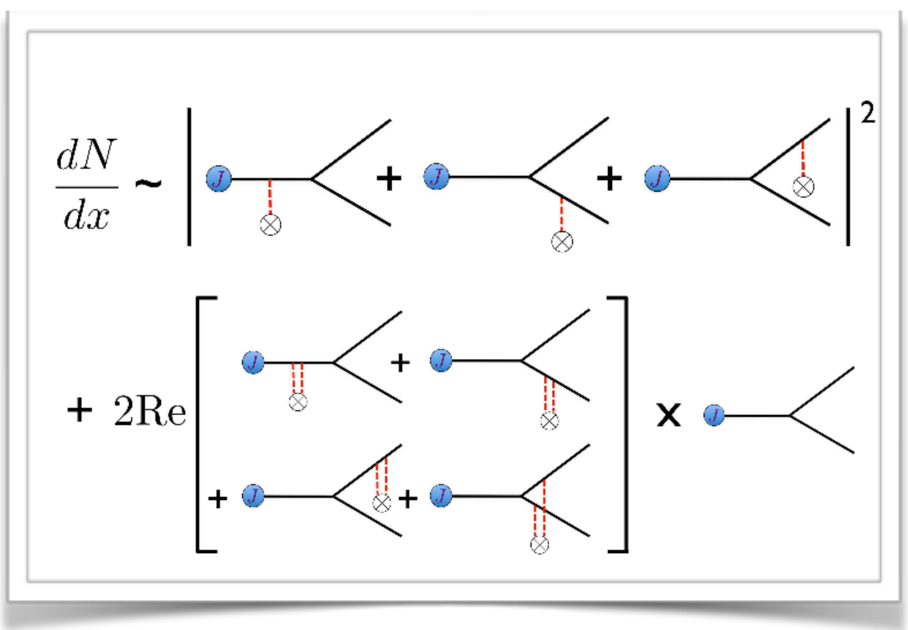

Massless partons: Ovanesyan and Vitev 2011

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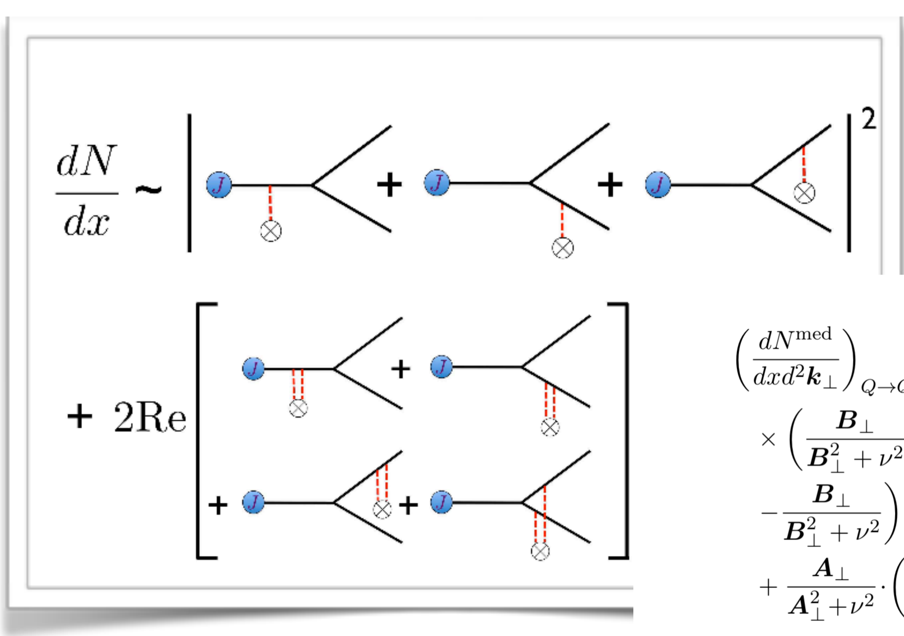

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$$\left(\frac{dN^{\rm med}}{dx d^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2} C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\boldsymbol{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm med}}{d^2\boldsymbol{q}_\perp} \left\{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

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

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

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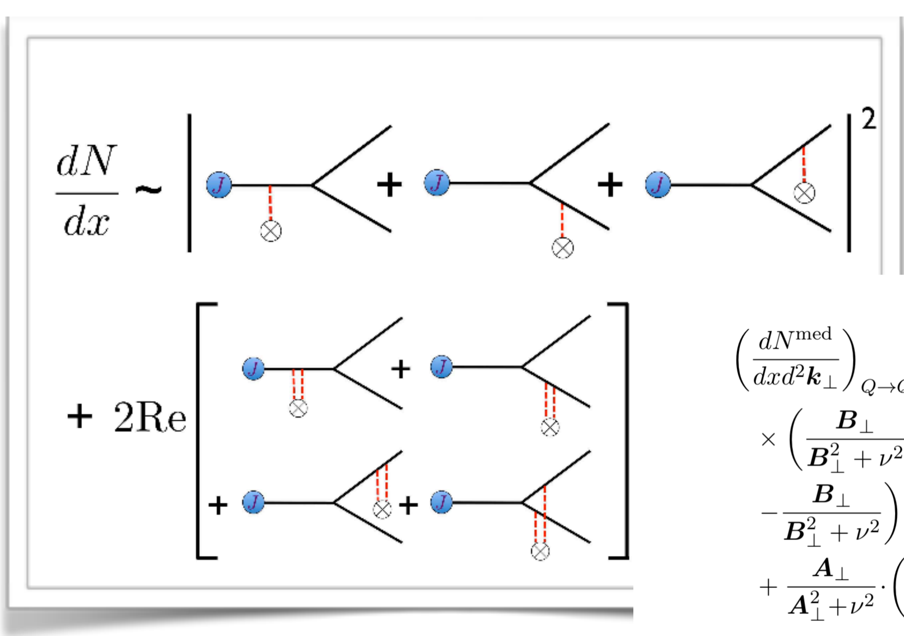

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\times\left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}-\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}-\frac{\boldsymbol{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]) \\
+\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])\Bigg] \\
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\end{aligned}$$

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\nu &= x\,m & &(Q\to Qg)\,, \\
\nu &= (1-x)\,m & &(Q\to gQ)\,, \\
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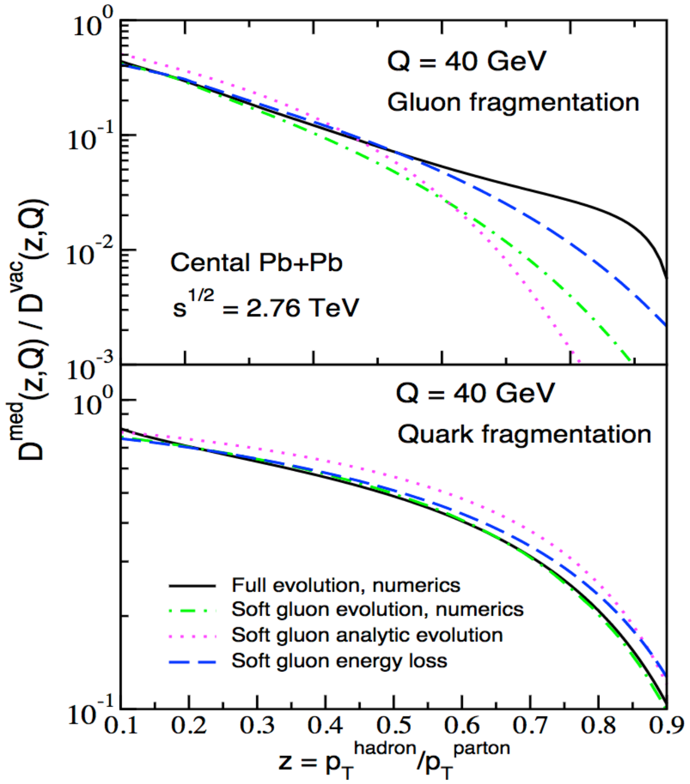
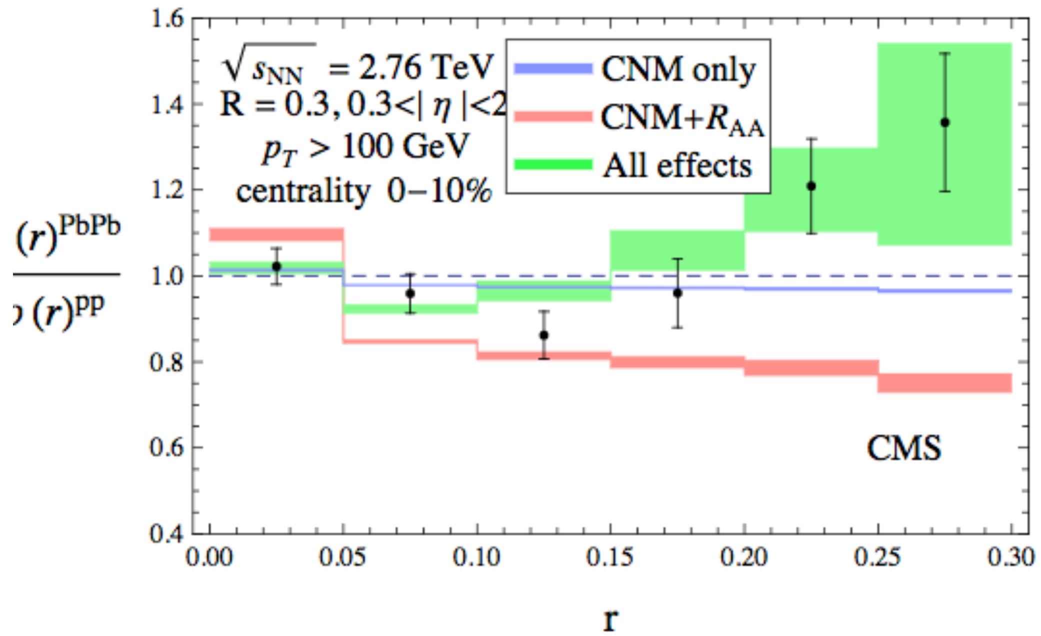
Applications

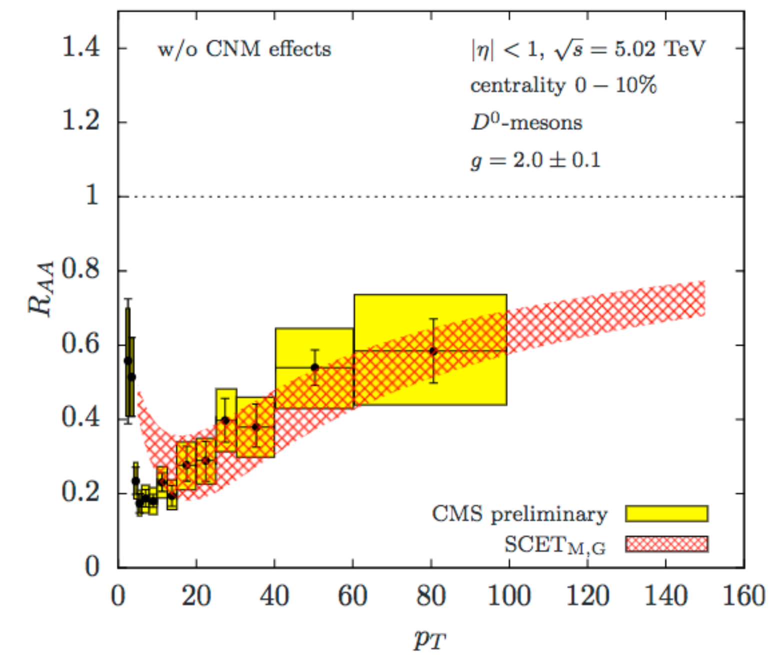


Modification of fragmentation functions for gluon and quark Kang et al 2014



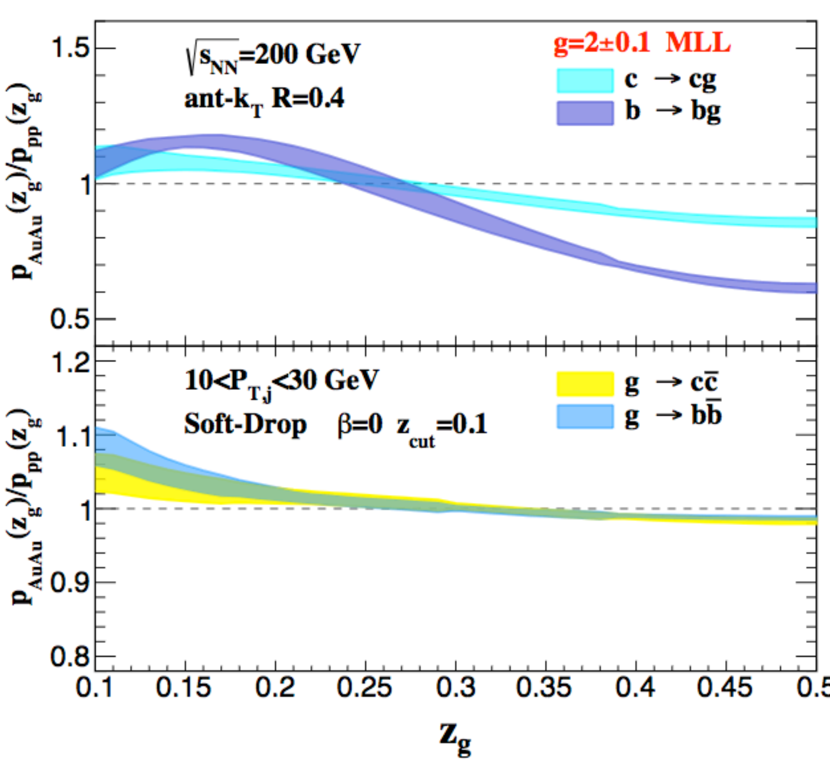
Modification of jet shape

Chien et al 2015



Nuclear modification factor RAA for D0 meson (massive)

Kang et al 2016

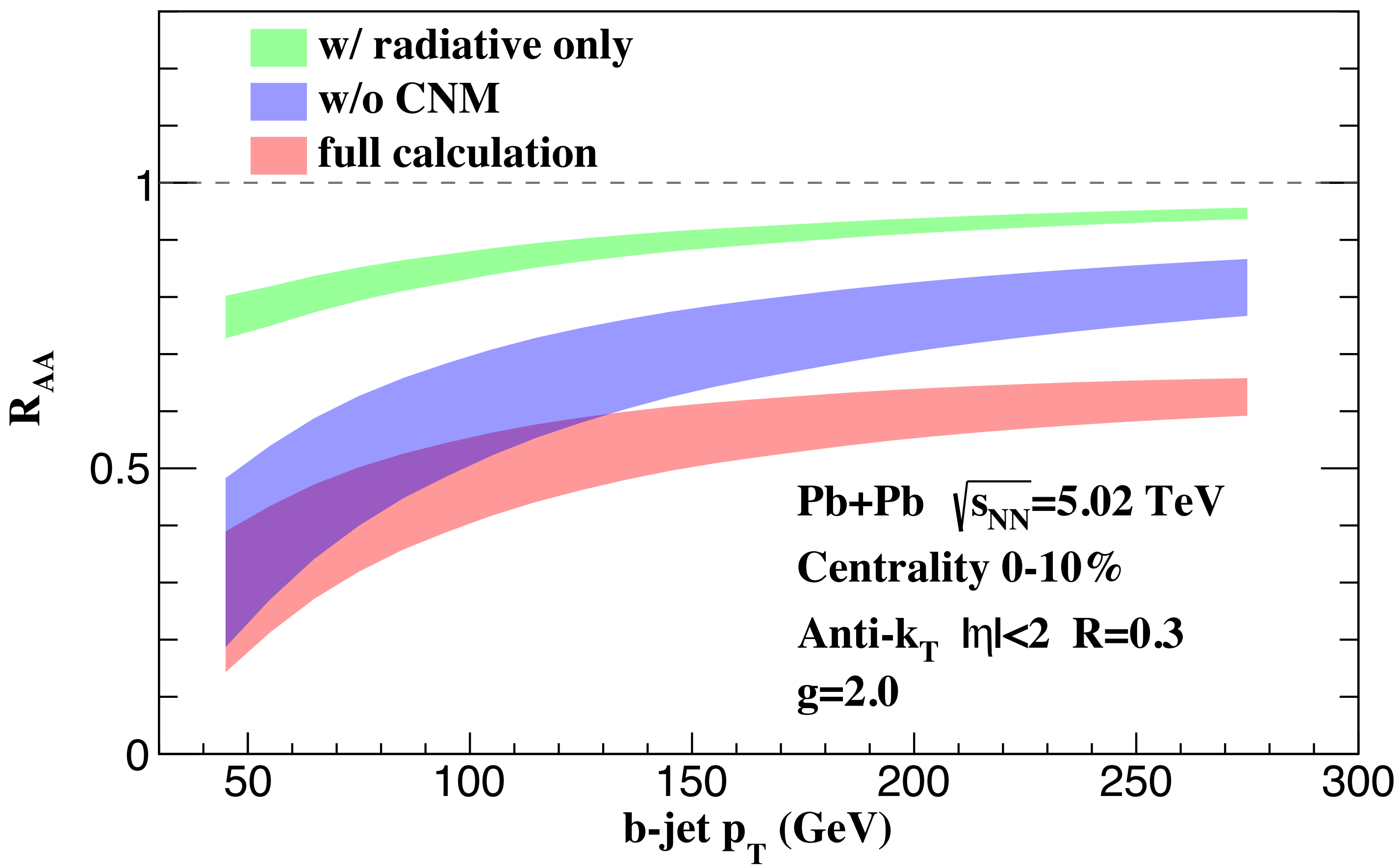


modifications of the jet splitting functions

HTL, Vitev 2018

Many other applications ……

RAA in A-A collisions

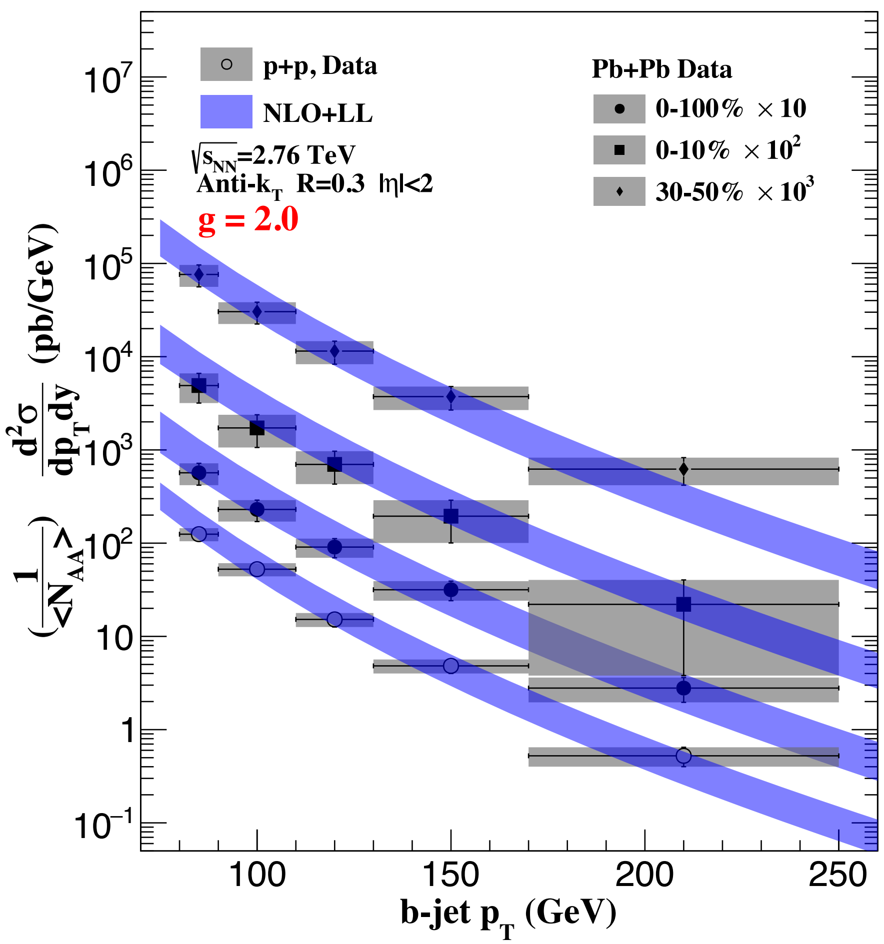


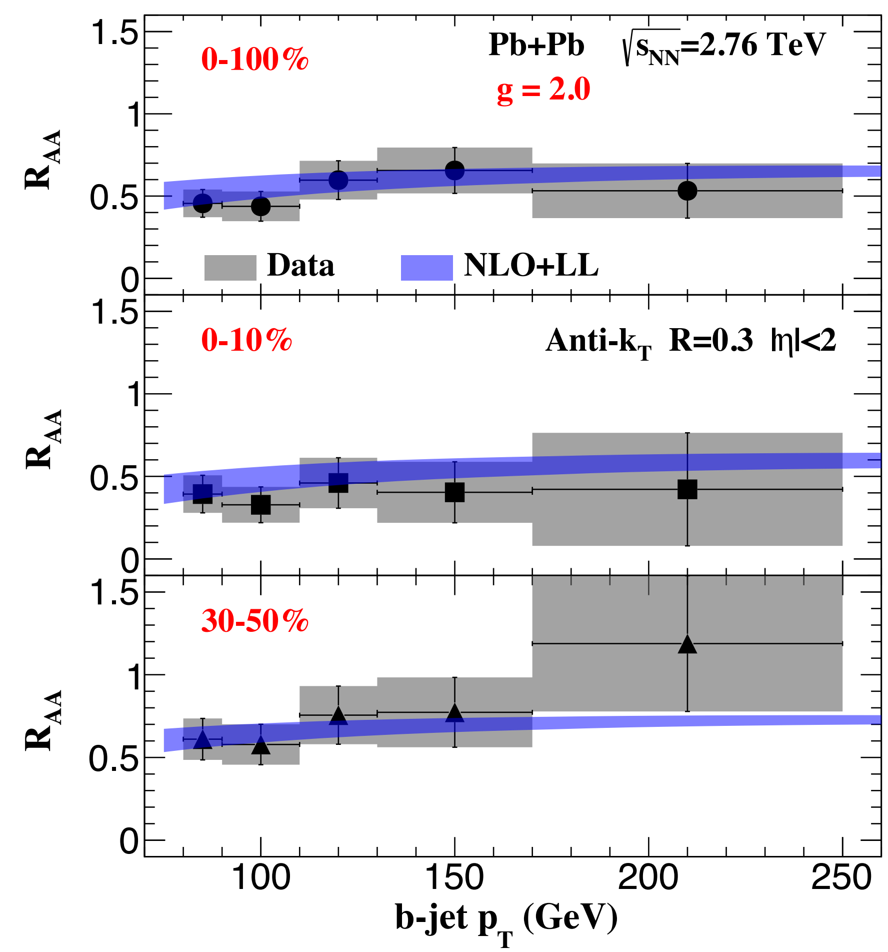
CNM = cold nuclear matter effect

- compared to light jet the radiative corrections are noticeably smaller
- collisional energy loss is more important when the jet transverse momentum is small.
- the CNM are more important in the high energy regime

Even though the b-jet modification is found to be qualitatively consistent with that of inclusive jets from measurements with the same collision energy, the underlying physics might be different.

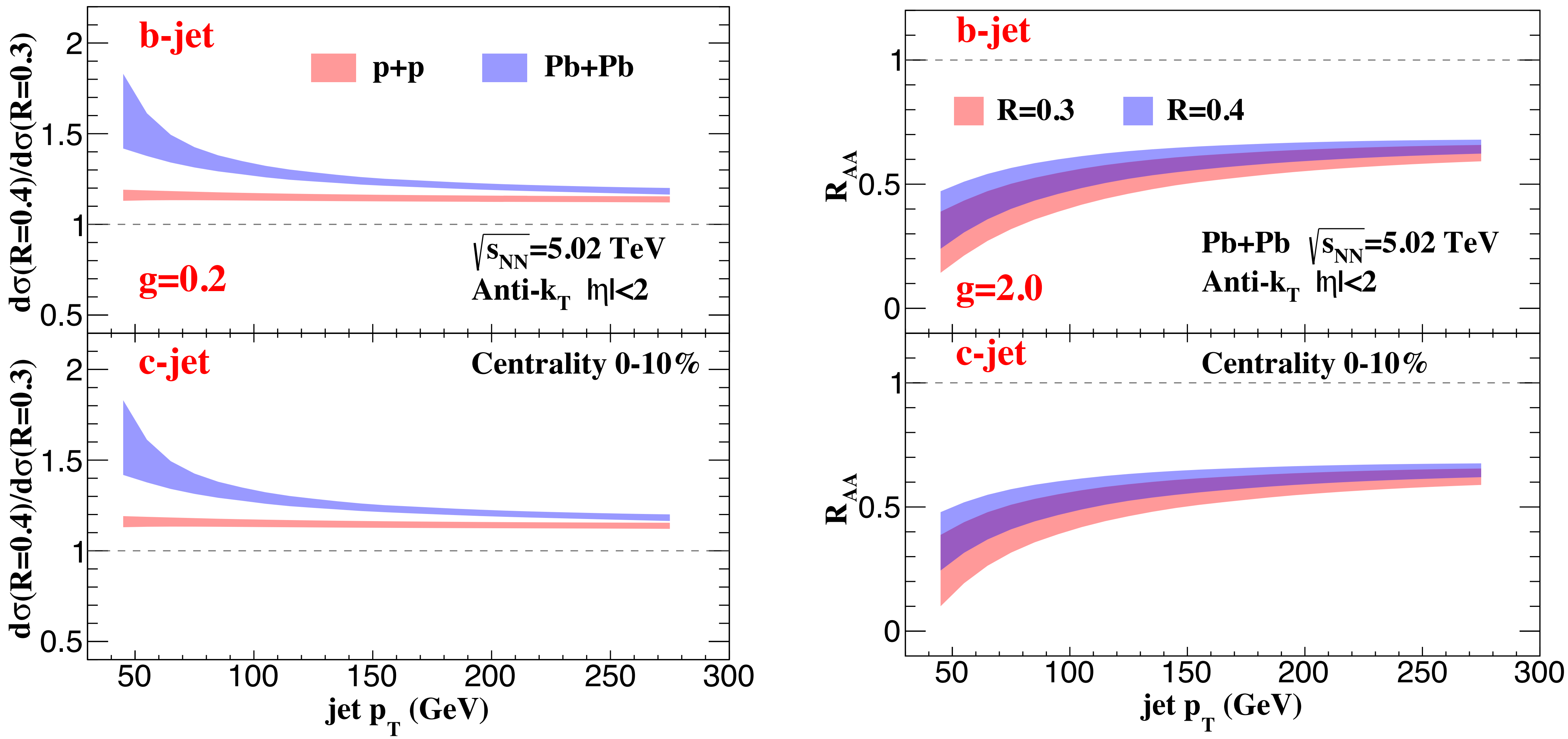
b-jet in A-A collisions





- 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.

b-jet and c-jet in A-A collisions



- not depend on jet pT in p+p collisions.
- small dependence on jet pT in Pb+Pb collisions
- the smaller radius jet tends to dissipate more energy in the medium
- no significant difference between the c-jet and b-jet due to the high transverse momentum

Conclusions and outlook

- we presented a formalism to study heavy flavor jet production in hadronic and heavy-ion collisions
- we presented the calculation of heavy flavor jets in pA and AA collisions using the heavy flavor semi-inclusive jet functions technique
- for inclusive c-jet and b-jet production we found very good agreement between data and theory.
- RAA has smaller centrality dependence and R dependence for heavy flavor jet

- further investigate heavy flavor-tagged jet substructure observables
- implement higher orders-in-opacity corrections in the medium
- study the kinematic domain where mass effects on the heavy flavor jet production and propagation in a dense are important

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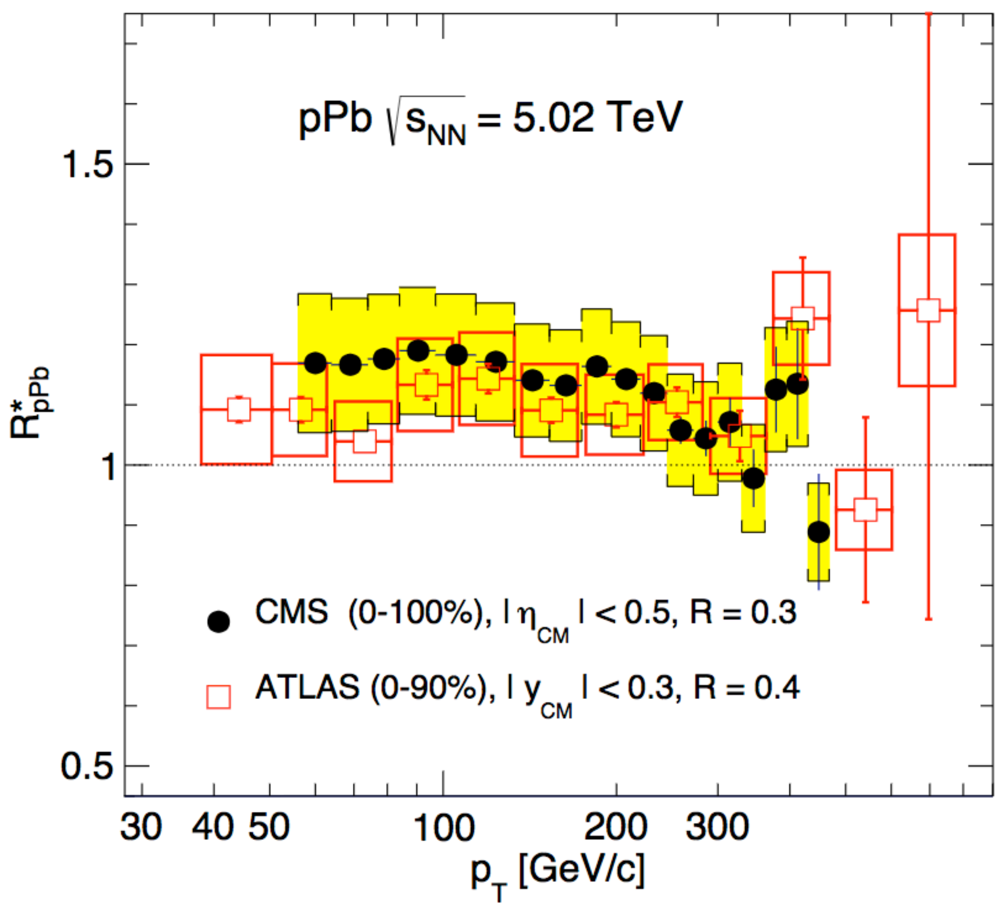
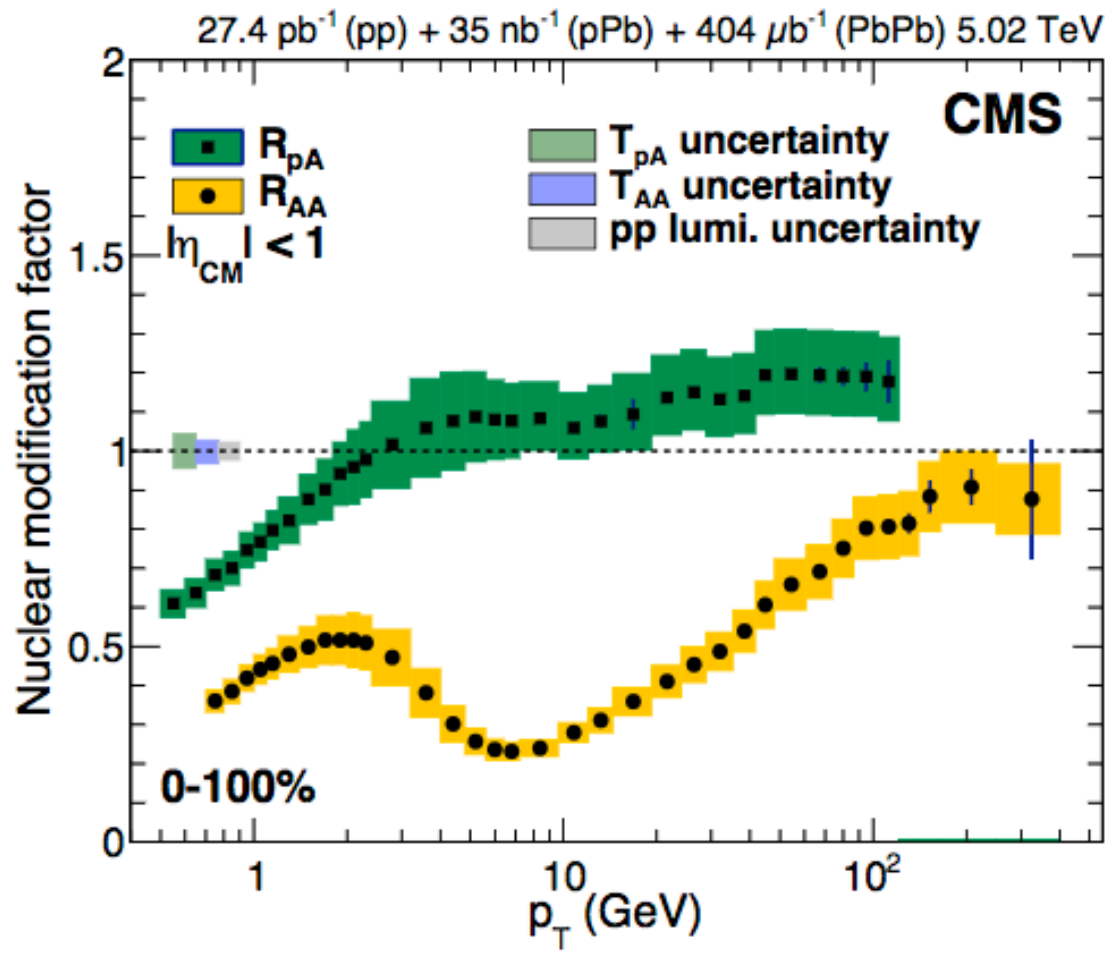
Thank you !

back up

RpA light jet



arXiv: 1601.02001



arXiv:1611.01664

RAA light jet