Ivan Vitev

Jet and di-jet production in heavy-ion collisions

8^{th} Workshop of the APS Topical Group on Hadronic Physics
April 10 – 12, 2019, Denver, CO

Outline of the talk

Thanks to the organizers for the invitation

This talk is based on

- Motivation
- Light and heavy dijes and dijet mass modification
- Inclusive heavy flavor jet production from $SCET_G$
- Conclusions & future directions

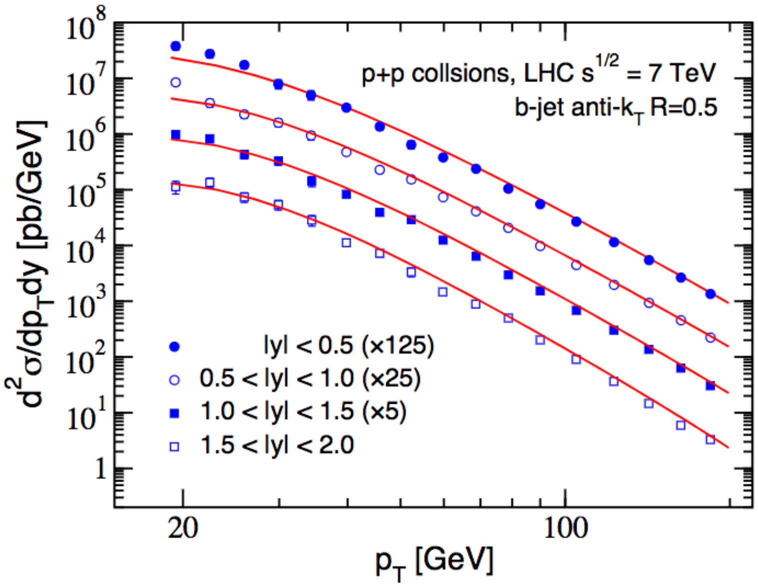
Light and heavy flavor dijet production and dijet mass modification in heavy ion collisions, Zhong-Bo Kang, Jared Reiten, Ivan Vitev, Boram Yoon, arXiv:1810.10007

Inclusive heavy flavor jet production with semi-inclusive jet functions: from proton to heavy-ion collisions, Hai Tao Li, Ivan Vitev, arXiv:1811.07905

A complete set of in-medium splitting functions to any order in opacity, Matt Sievert, Ivan Vitev, Boram Yoon, arXiv:1903.06169

Motivation

Jet production



- Is characterized by large cross sections and has been measured with unprecedented precision in comparison to other high energy processes
- Can reveal the fundamental thermodynamic and transport properties of the QGP in A+A collisions
- B-jets are useful to study the energy loss mechanisms in QCD medium as a function of parton mass

Even Heavy flavor jets have large cross sections

- Dijet measurements have emphasized the difference in the quenching effects between trigger and recoil jets. It is important to find new observables that amplify them
- Go beyond energy loss models and include higher order calculations and resummation. Has to be done for heavy flavor jets

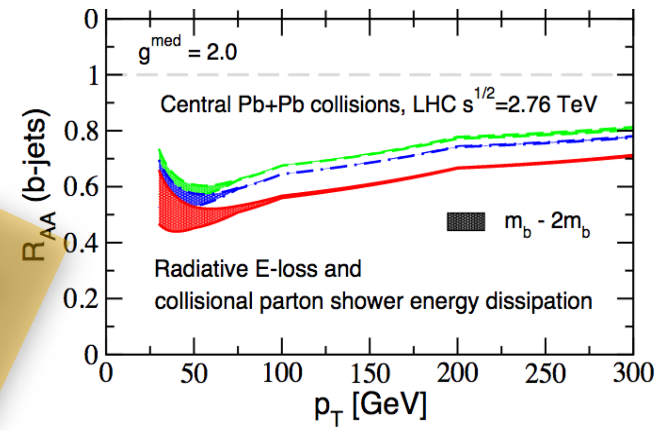
B-jets HI studies in the literature

Inclusive b-jet

Huang, Kang, Vitev 2013 — energy loss approach

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

Based on Monte Carlo Event Generators



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

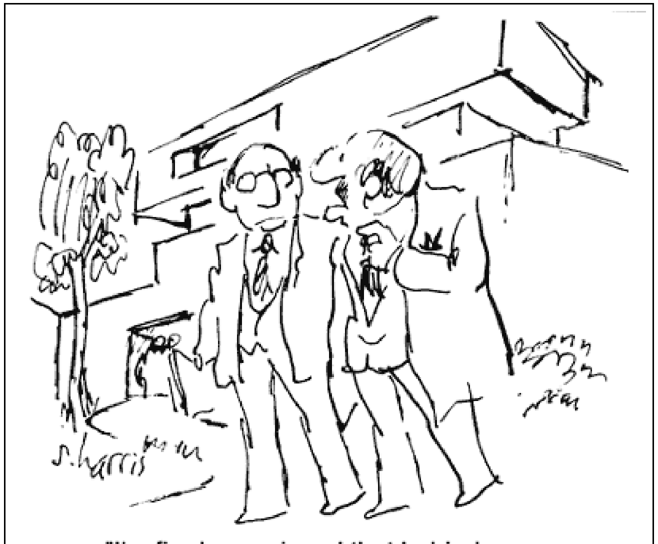
B-jet substructure

Haitao Li, Vitev, 2018 — soft-drop groomed momentum sharing distribution

Haitao Li, Vitev, 2018 — the inclusive b-jet production

SCETG

Invariant mass modification for light and heavy dijets

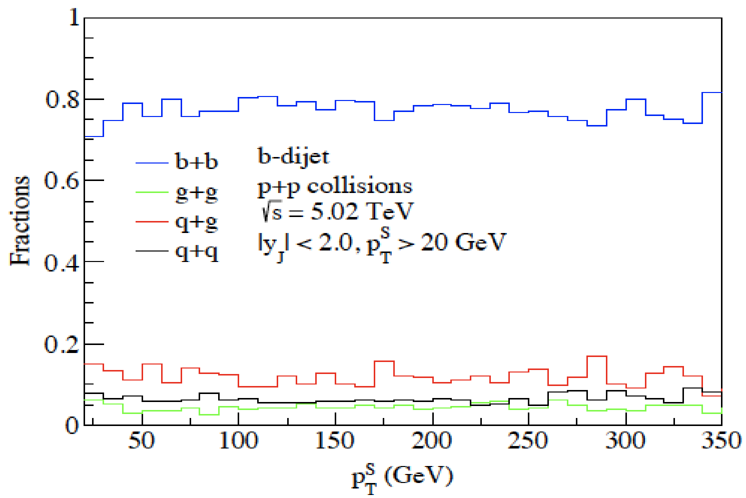


"I'm firmly convinced that behind every great man is a great computer."

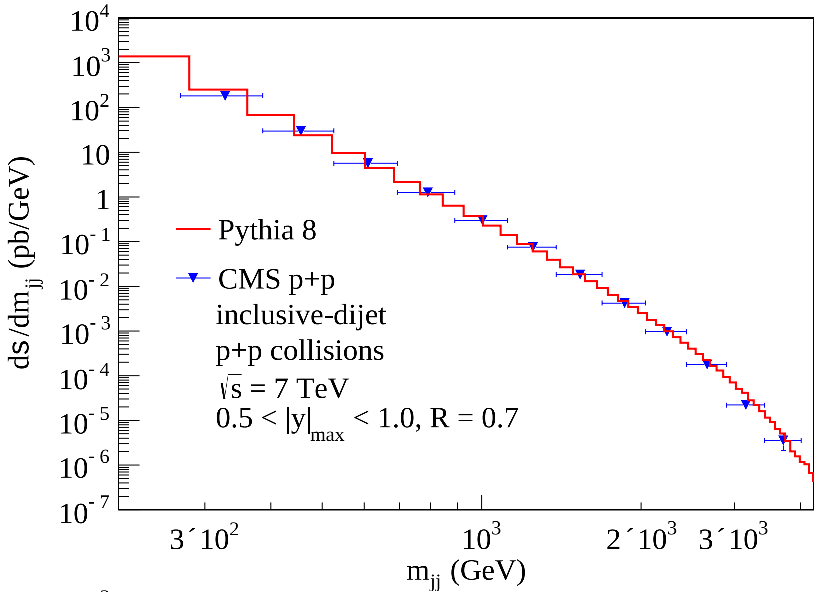
PYTHA baseline

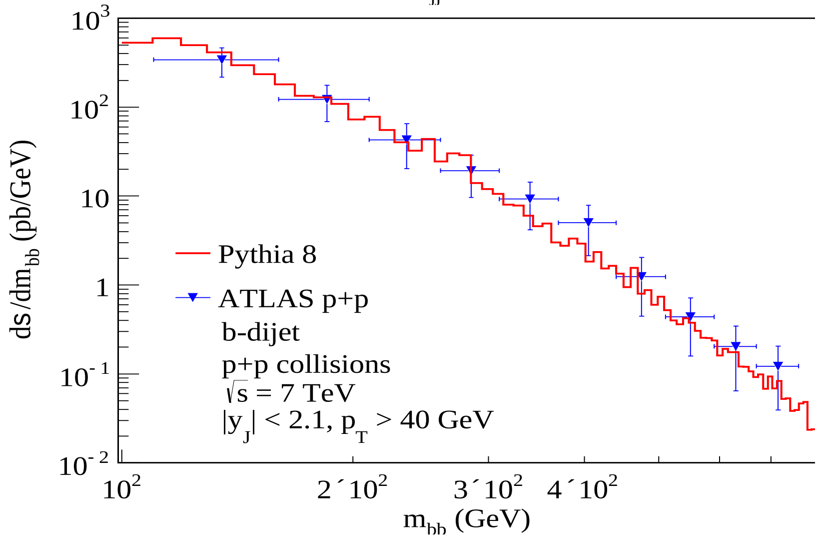
Kang, Reiten, Vitev, Yoon 2018

- Appears to do a reasonable job in describing light dijet production. There are some differences in describing the dibjet cross sections that will affect the dijet momentum imbalance
- We can also simulate all relevant partonic channels contributions to study in-medium modification



Dibjets can ensure up to 80% purity, i.e. b-jets originating from prompt b quarks. Help get a handle on flavor and mass effects on parton energy loss





Taking a closer look at the dijet mass

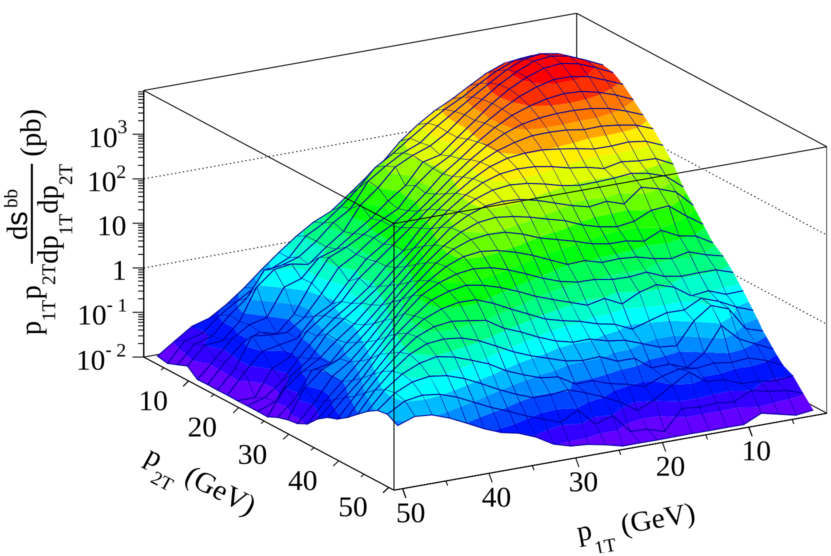
- Approximating the dijet cross section with individual jet pT, rapidity, mass and angular distributions (which we simulate from PYHIA)
- We have checked that aby difference are < 10%, also cancel in R_{AA} ratios

$$\frac{d\sigma}{dm_{12}} = \int dp_{1T} dp_{2T} \frac{d\sigma}{dp_{1T} dp_{2T}} \delta\left(m_{12} - \sqrt{\langle m_1^2 \rangle + \langle m_2^2 \rangle + 2 p_{1T} p_{2T} \langle \cosh(\Delta\eta) - \cos(\Delta\phi) \rangle} \right)$$

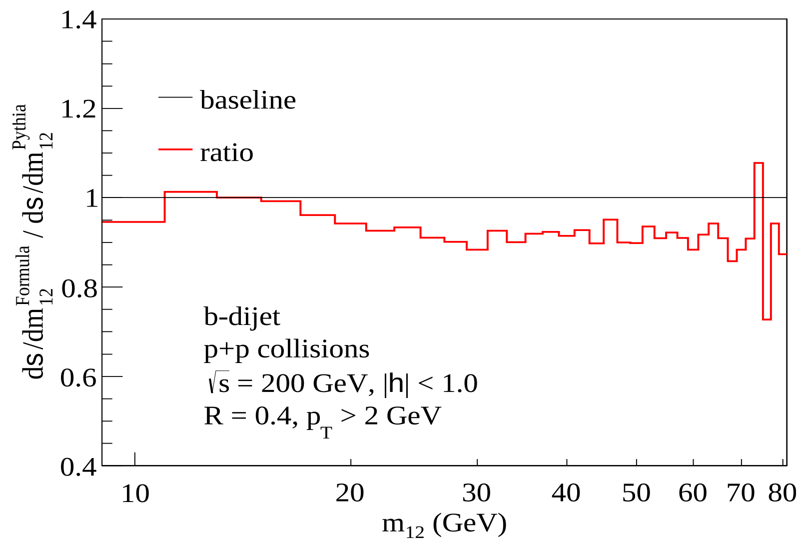
2-D nuclear modification factor needed

inclusive jet mass remains the same

angular information remains the same



2D distributions for inclusive dijets and Di-bjets



Differences very small

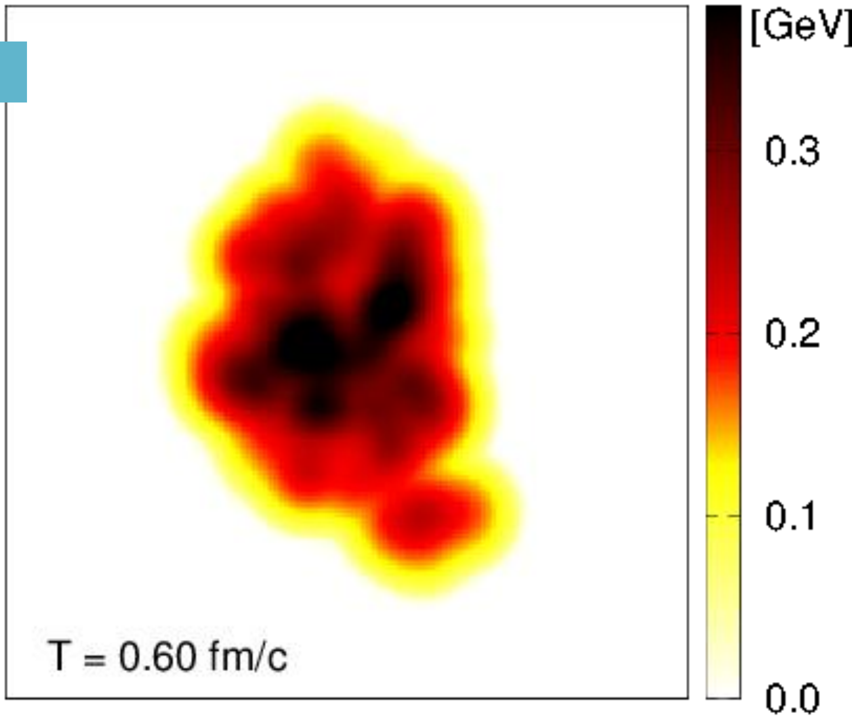
The energy loss calculation

- Soft gluon emission limit of the full splitting kernels for heavy quarks Kang, Ringer, Vitev, 2016
- Evaluated in viscous 2+1D hydro

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

- Quenched dijet cross sections

$$\frac{d\sigma^{AA}(|\mathbf{b}_\perp|)}{dp_{1T}dp_{2T}} = \int d^2\mathbf{s}_\perp T_A\left(\mathbf{s}_\perp - \frac{\mathbf{b}_\perp}{2}\right) T_A\left(\mathbf{s}_\perp + \frac{\mathbf{b}_\perp}{2}\right)$$
$$\times \sum_{q,g} \int_0^1 d\epsilon \frac{P^1_{q,g}(\epsilon; \mathbf{s}_\perp, |\mathbf{b}_\perp|)}{1 - f^{1\,\rm loss}_{q,g}(R; s_\perp, |\mathbf{b}_\perp|)\,\epsilon} \int_0^1 d\epsilon' \frac{P^2_{q,g}(\epsilon'; \mathbf{s}_\perp, |\mathbf{b}_\perp|)}{1 - f^{2\,\rm loss}_{q,g}(R; s_\perp, |\mathbf{b}_\perp|)\,\epsilon'}$$
$$\times \frac{d\sigma^{NN}_{q,g}\left(p_{1T}/[1 - f^{1\,\rm loss}_{q,g}(R; s_\perp, |\mathbf{b}_\perp|)\,\epsilon],\, p_{2T}/[1 - f^{2\,\rm loss}_{q,g}(R; s_\perp, |\mathbf{b}_\perp|)\,\epsilon']\right)}{dp_{1T}dp_{2T}}$$



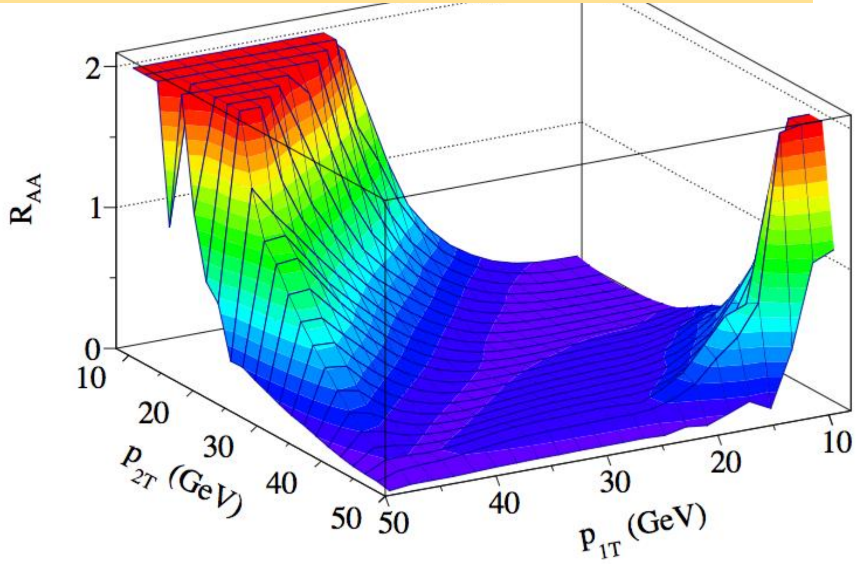
C. Shen et al, 2014

Results for the dijet suppression

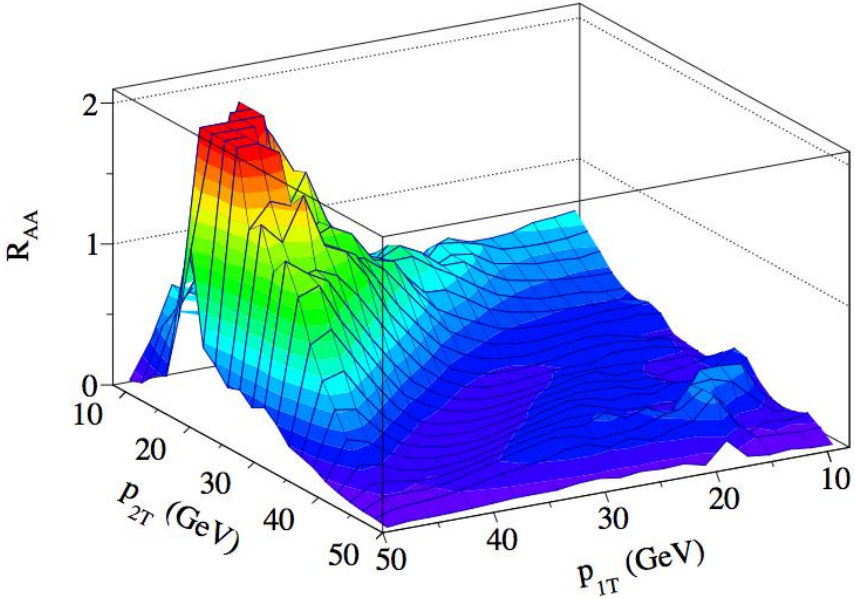
- All the information in this calculation is contained in the full 2D di-jet suppression pattern
- Examples here given for RHIC energies

Double differential dijet suppression pattern

$$R_{AA}(p_{1T}, p_{2T}, |\mathbf{b}_\perp|) = \frac{1}{\langle N_{\rm bin} \rangle} \frac{d\sigma^{AA}(|\mathbf{b}_\perp|)/dp_{1T}dp_{2T}}{d\sigma^{pp}/dp_{1T}dp_{2T}}$$



inclusive dijet



b dijet

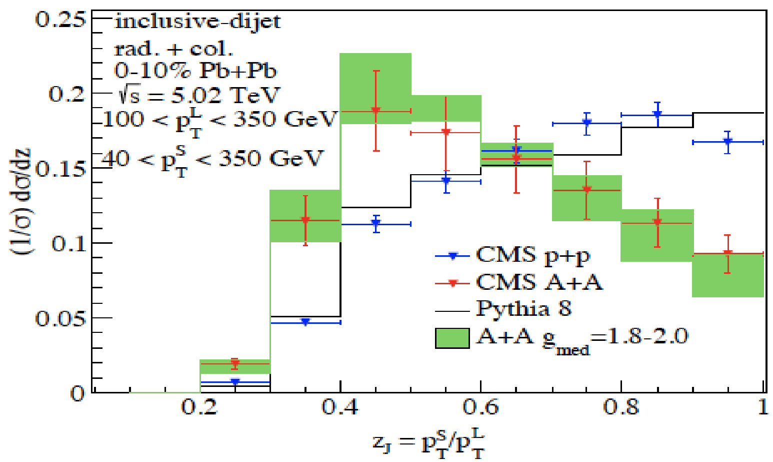
- The suppression is largest along the main diagonal; can get enhancement in asymmetric phase space . Arises form flavor bias (mostly) and geometric bias

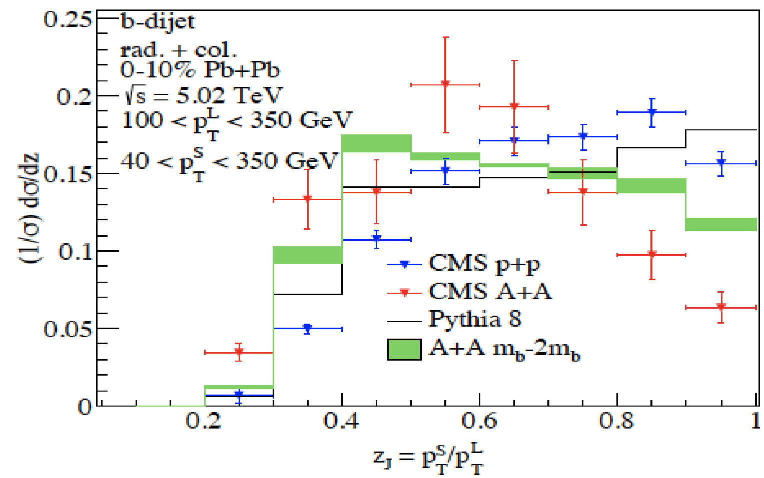
Inclusive dijet and b-dijet momentum imbalance

- Our brain is programmed to recognize patterns but the changes can be subtle
- A good example where quenching effects on jets subtract rather than add – LHC example

$$z_J = p_{2T}/p_{1T};$$

$$\frac{d\sigma}{dz_J} = \int dp_{1T}dp_{2T}\frac{d\sigma}{dp_{1T}dp_{2T}}\delta\left(z_J - \frac{p_{2T}}{p_{1T}}\right)$$





PYTHIA does not do a great job on the b-dijet baseline. In such cases the physics is captured by the mean imbalance shift. It is subtle – of order 10%

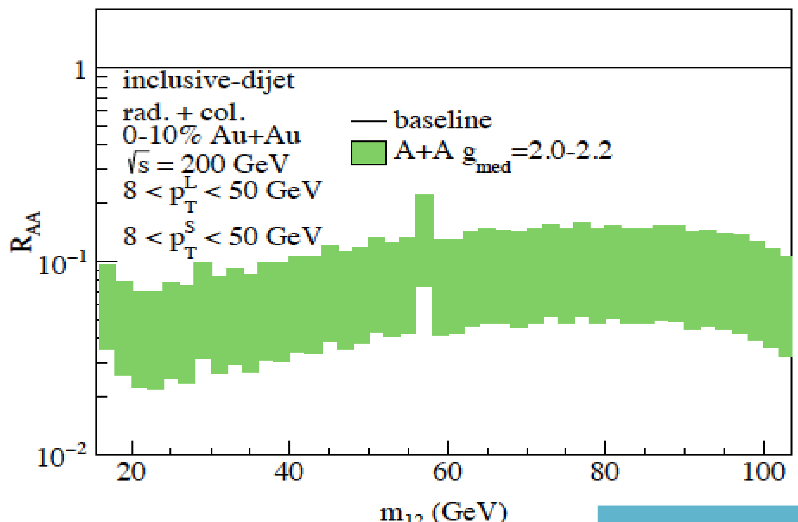
Kinematics	dijet flavor	$\langle z_J\rangle_{pp}$	$\langle z_J\rangle_{AA}$	$\Delta\langle z_J\rangle$
CMS [25]	b-tagged	0.661 ± 0.003	0.601 ± 0.023	0.060 ± 0.025
Experiment	inclusive	0.669 ± 0.002	0.617 ± 0.027	0.052 ± 0.024
LHC	b-tagged	0.685	0.626 ± 0.013	0.059 ± 0.013
theory	inclusive	0.701	0.605 ± 0.022	0.096 ± 0.022
sPHENIX	b-tagged	0.730	0.665 ± 0.012	0.065 ± 0.012
theory	inclusive	0.743	0.643 ± 0.005	0.100 ± 0.005

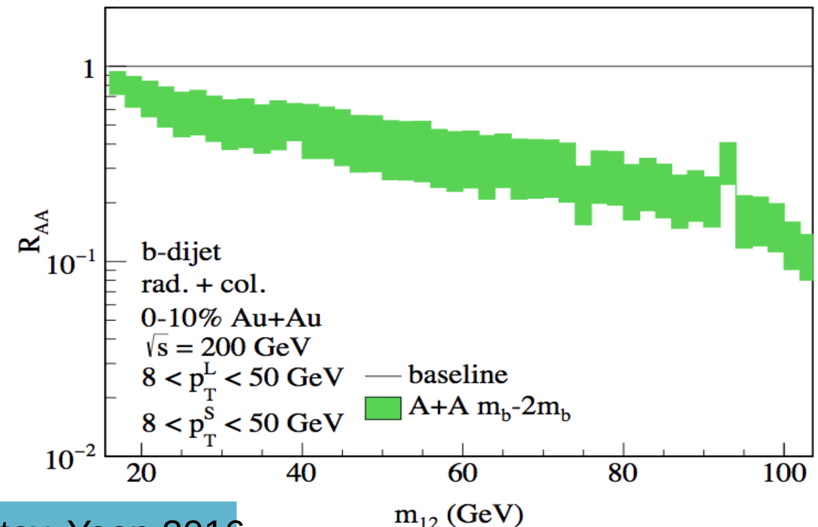
$$\langle z_J\rangle = \left(\int dz_J\, z_J \frac{d\sigma}{dz_J}\right) \Big/ \left(\int dz_J \frac{d\sigma}{dz_J}\right)$$

$$\Delta\langle z_J\rangle = \langle z_J\rangle_{\rm pp} - \langle z_J\rangle_{\rm AA}$$

Dijet mass modification

- When it comes to dijet mass modification the results are very encouraging – RHIC example. Best seen at masses under 100 GeV.
- Also works well at LHC in this mass range and even to a few hundred GeV
- Will be an extremely valuable measurement to make (try it)

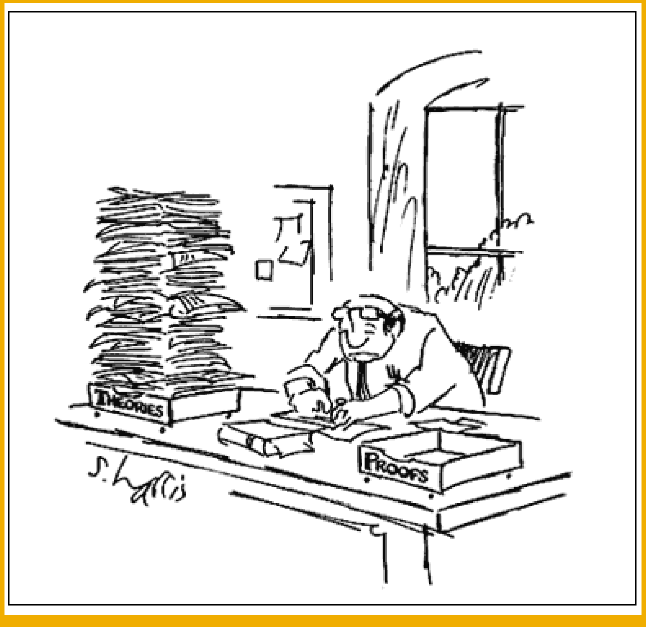




Kang, Reiten, Vitev, Yoon 2016

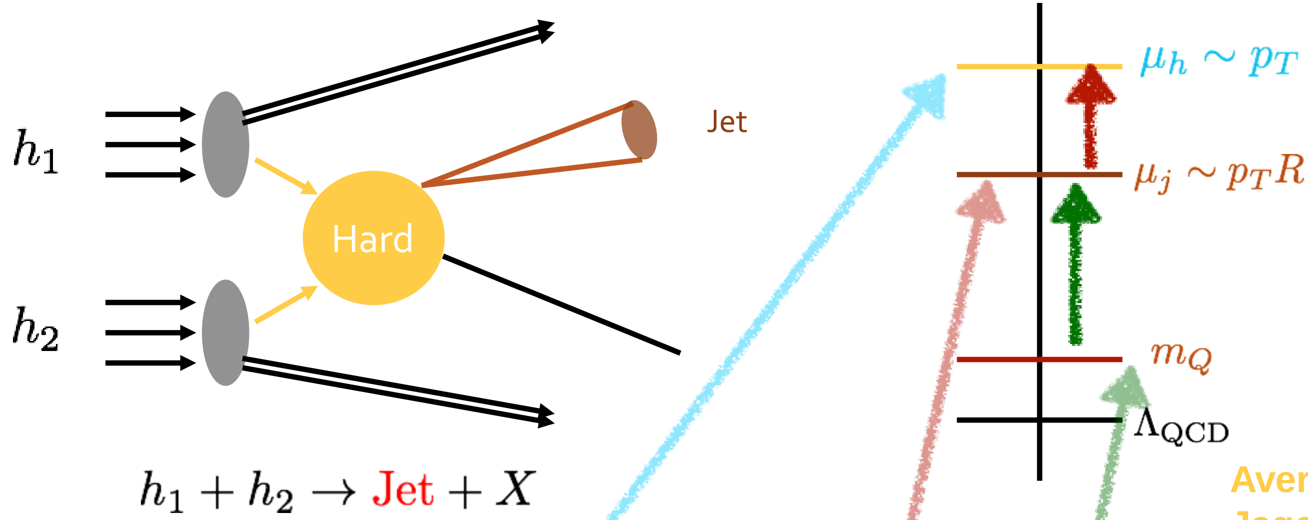
- **Ideal measurement for the sPHENIX collaboration. Suppression of the inclusive dijet mass more than an order of magnitude.**
- **Suppression of b-dijets shows a completely different pattern. We see an enhanced sensitivity to the transport properties of the QGP (here captured by the coupling) and the mass of heay quarks (self-evident from the figures)**

SCET approach to b-jet production



Inclusive jet production

- Jet production is one of the cornerstone processes of QCD. Light jets have been studied for a long time. Recent advances based in SCET



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

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

Semi-inclusive jet function

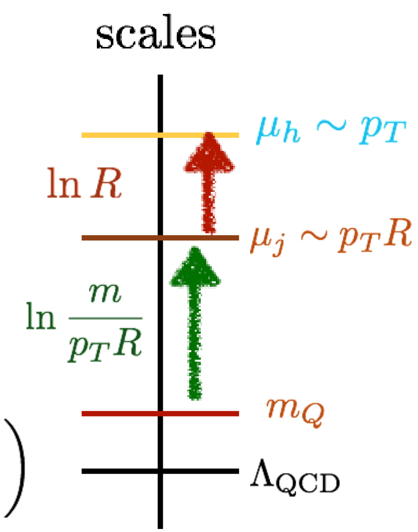
Hard scattering kernel

Aversa et al 1989, Jager et al 2002

light jet: Kang et al 2016, Dai et al 2016
heavy flavor jet: Dai et al 2018

Resummation

- Jet production is one of the cornerstonoe processes of QCD. Light jets have been studied for a long time.
- Recent advances are based in SCET – precision theory for small radius jets and heavy flavor jets



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

Resums ln $\mu/p_T R$

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

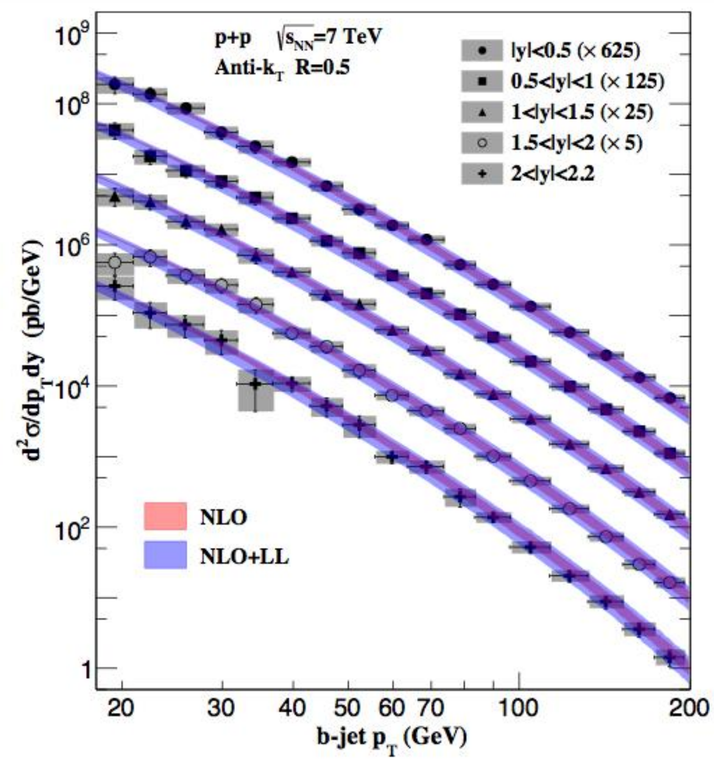
Resums ln $p_T R/m$

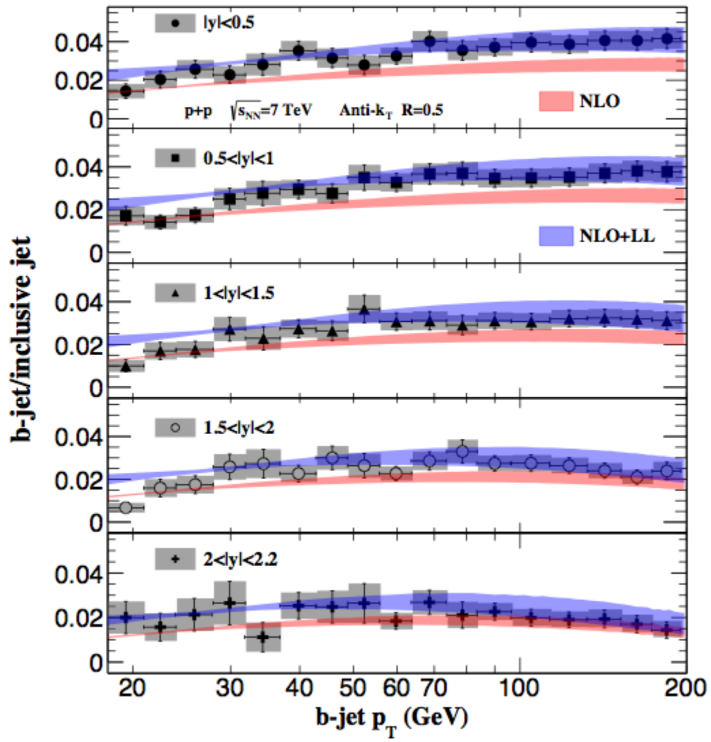
The integrated perturbative kernel at the jet typical scale

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

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

B-jet production in pp collisions





- Data are consistent with the theoretical predictions
- For the ratio b-jets to inclusive jets the difference between NLO+LL and NLO can be traced also to the differences in the inclusive jet cross section

Corrections in A+A collisions

Let us now focus on the jet function and final-state modification in the QGP

$$\frac{d\sigma_{AA\to J+X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^{1}\frac{dx_a}{x_a}f_a(x_a,\mu)\int_{x_b^{\min}}^{1}\frac{dx_b}{x_b}f_b(x_b,\mu)$$

$$\times\int_{z_{\min}}^{1}\frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab\to c}(\hat{s},p_T/z_c,\hat{\eta},\mu)}{dvdz}J_{J/c}(z_c,w_J\tan(R'/2),m_Q,\mu)$$

CNM effects

The short-distance hard part remains the same

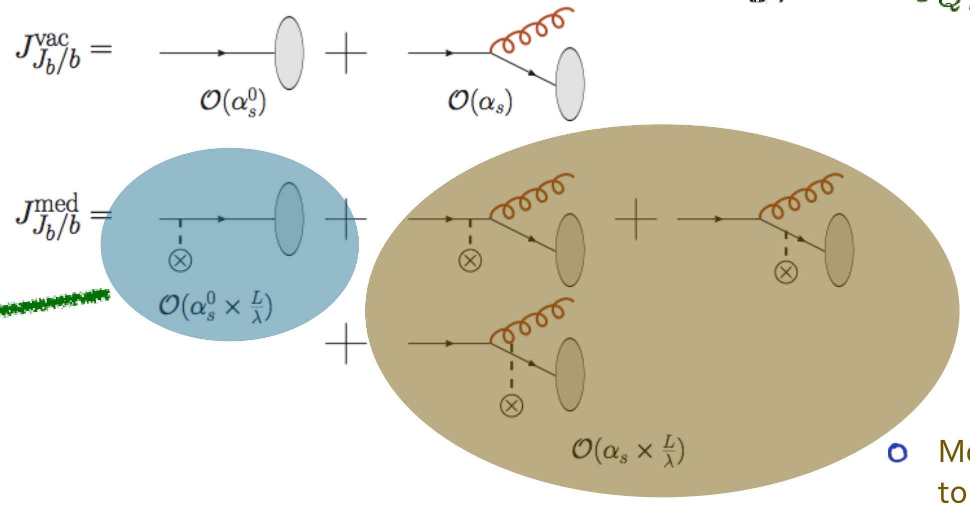
Encodes the effects when the jet evolving in the QCD medium

The jet function receives medium contributions from collisional energy loss and in-medium branching processes

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

Vacuum jet function:

Medium corrections:



- Medium induced corrections to the LO jet function
- Medium induced corrections to the NLO jet function

Corrections in QCD medium

Collisional energy loss evaluated from operator definition. Included in the LO splitting function

Neufeld, Vitev, Xing, 2014

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

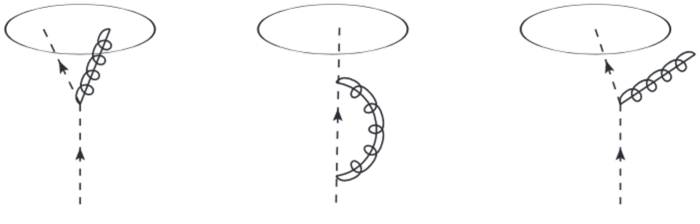
Medium corrections to the NLO jet function are written in terms of integrals over splitting functions. First developed for light jets.

Kang, Ringer, Vitev, 2017

For the heavy quark example

$$Q \to J_Q \qquad B = \delta(1-z)\int_0^1 dx \int_0^{x(1-x)p_T R} dq_\perp P^{\text{med}}_{QQ}(z, m, q_\perp)$$

$$C = -\delta(1-z)\int_0^1 dx \int_0^{\mu} dq_\perp P^{\text{med}}_{QQ}(z, m, q_\perp)$$



After summing over all diagrams

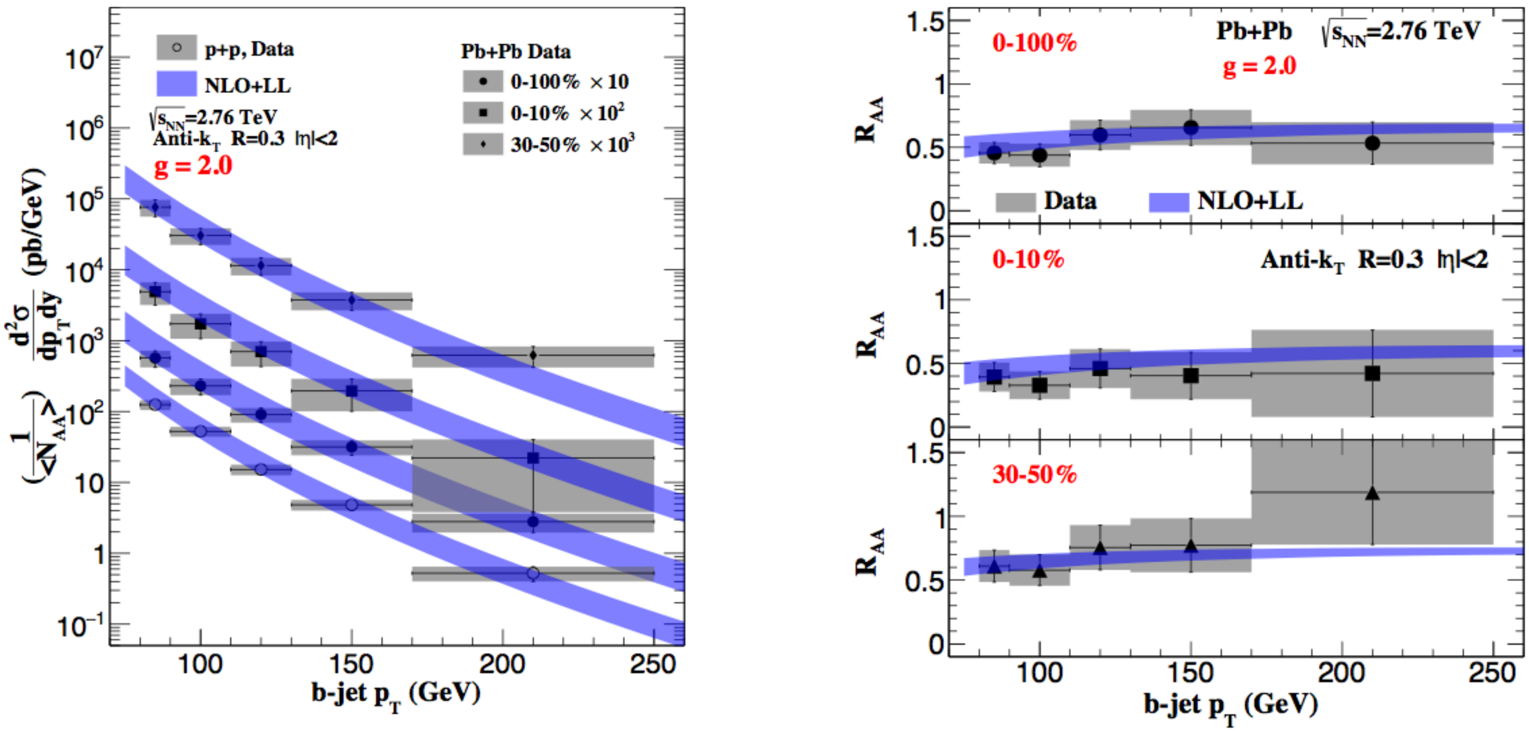
Haitao Li, Vitev, 2018

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

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

Full in-medium splitting functions are now evaluated in the hydro medium

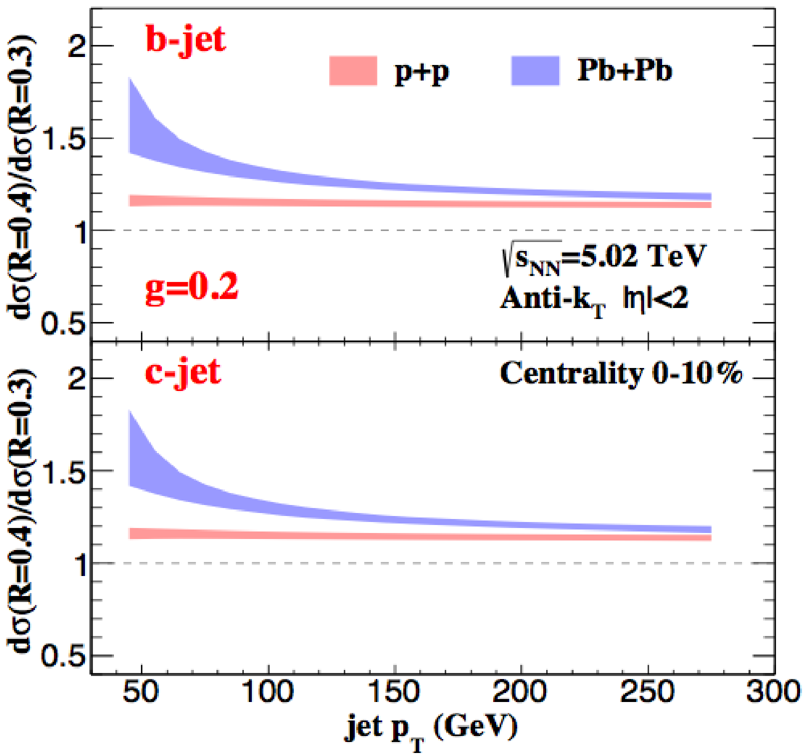
B-jet production in A-A collisions

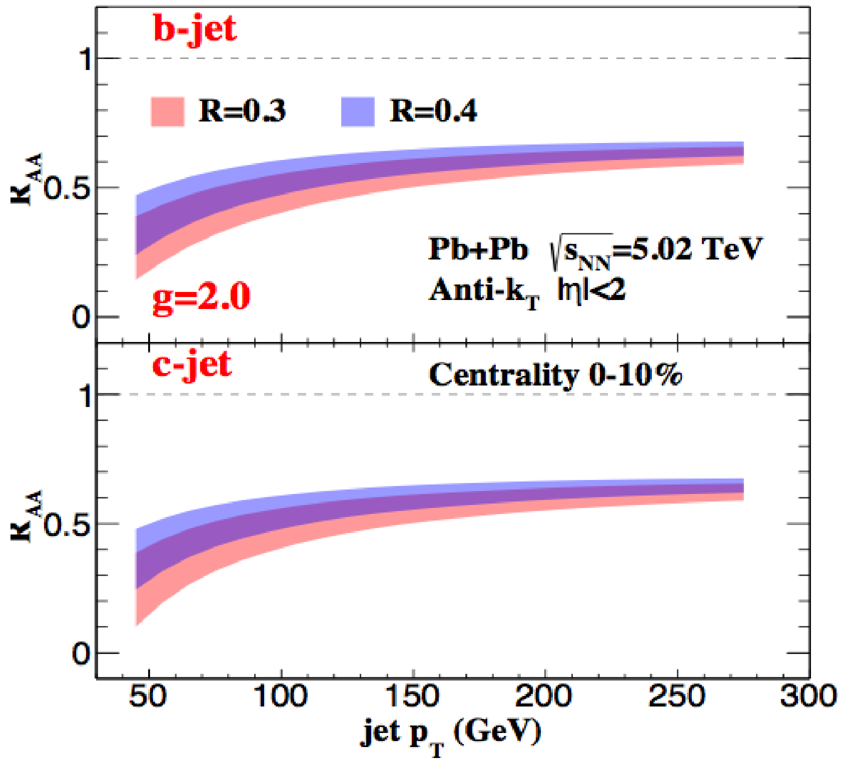


- Slightly less dependence on the centrality when compared to the well-known light jet modification
- Theoretical results agree well with the data for both the inclusive cross sections and the nuclear modification factors

That does not mean there is no room for improvement

B-jet and c-jet production in A-A collisions





Haitao Li, Vitev, 2018

- Not depend on jet p_T in p+p collisions
- Small dependence on jet p_T 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

Future directions

Splitting functions to any order in opacity

- We calculated all full in-medium splitting functions to any order in opacity
- Used lightcone wavefunction approach applicable to light and heavy partons, captures the universal features of all splittings

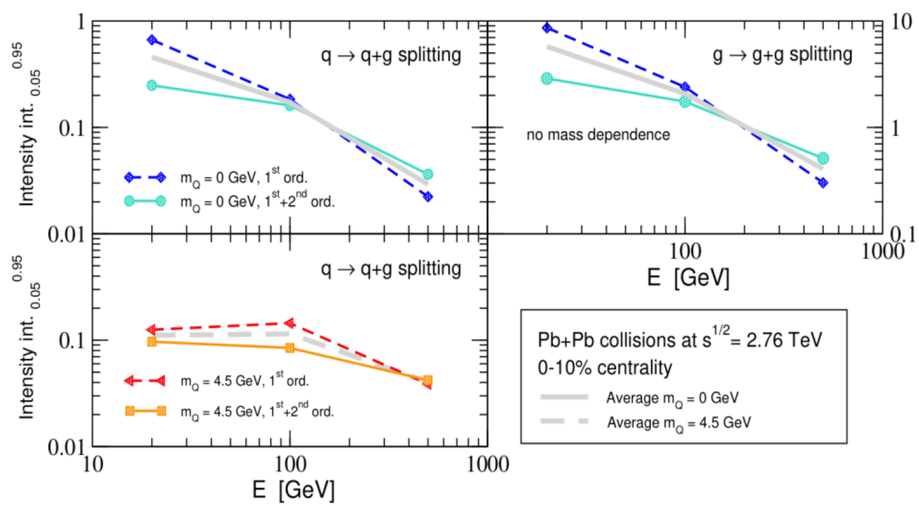
M. Sievert et al . (2019)

In the vacuum (all needed information is in the table below)

$$\langle \psi(x,\underline{\kappa})\,\psi^*(x,\underline{\kappa}')\rangle = \frac{8\pi\alpha_s\, f(x)}{[\kappa_T^2+\nu^2 m^2]\,[\kappa_T'^2+\nu^2 m^2]}\left[g(x)\,(\underline{\kappa}\cdot\underline{\kappa}')+\nu^4 m^2\right]$$

$$\Delta E^-(x,\underline{\kappa}) = -\frac{\kappa_T^2+\nu^2 m^2}{2x(1-x)p^+},$$

- Splitting kernels are solutions to iterative matrix equations
- The remarkable part is also the ability to actually evaluate the analytic results in a hydrodynamic medium. They are prepared for phenomenology



In the medium

$$\mathcal{I}_{x_{\min}}^{x_{\max}} = \int_{x_{\min}}^{x_{\max}} dx \int d^2k\; x\frac{dN}{d^2k\,dx}$$

Conclusions and outlook

- There is growing interest in b-jets but theoretical studies are limited
- It is important to find observables with enhanced sensitivity to the medium properties. Dijet mass is one such very promising observable
- Ideal way to probe the mass dependence. Preferred mass range under 100 – 200 GeV. Ideal at SPHENIX energies. Can also be studied at the LHC before sPHENIX

- Performed the first calculation of inclusive b-jets in A+A collisions using SCET and $SCET_G$ – using semi-inclusive jet functions. Allows to perform higher orders calculation and resummation
- Incorporated full in-medium splitting functions (radiative processes) and included collisional energy dissipation as well
- R_{AA} has somewhat smaller centrality dependence and R dependence for heavy flavor jets. Somewhat limited by the fixed order calculation for lower p_T

- Further investigate heavy flavor-tagged jet substructure observables
- Implement higher orders-in-opacity corrections in the medium