

Ivan Vitev

Aspects of heavy flavor jet physics in heavy ion collisions

*13th International Workshop on High p_T Physics in the RHIC/LHC Era
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Outline of the talk



- Motivation
- Light and heavy dijets and dijet mass modification
- Inclusive heavy flavor jet production from SCET_G
- Future directions
- Conclusions

Thanks to the organizers for the invitation

This talk is based on

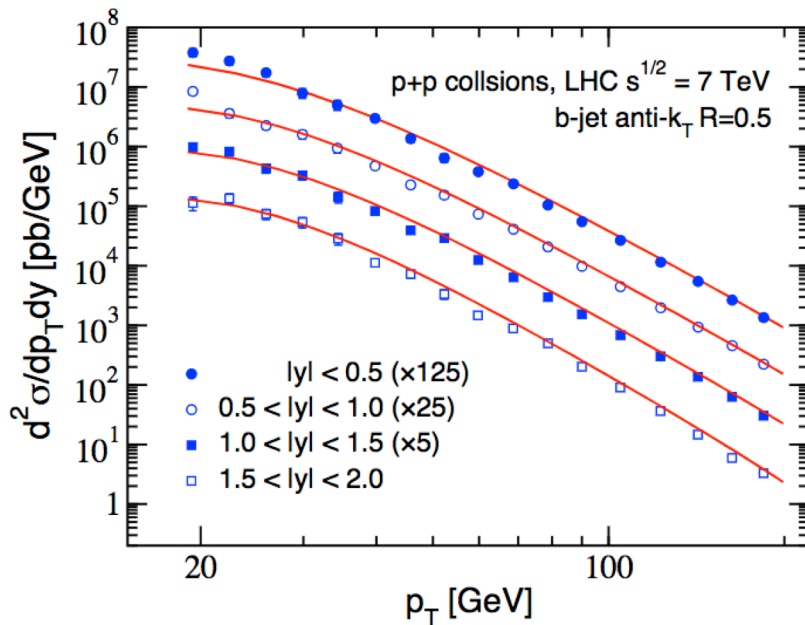
Light and heavy flavor dijet production and dijet mass modification in heavy ion collisions, Zhong-Bo Kang, Jared Reiten, Ivan Vitev, Boram Yoon, arXiv:1810.10007

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



Heavy flavor jet

- 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

- A b-jet is a jet containing one or more b-hadrons, not necessary to be initiated by a heavy quark

- 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-jets HI studies in the literature

Inclusive b-jet

Huang, Kang, Vitev 2013

Senzel, Uphoff, Xu, Greiner, 2016

energy loss approach

modifying the vacuum shower (AMPS)

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

Kang, Reiten, Vitev, Yoon, 2018

transverse momentum balance and angular distribution

dijet invariant mass for light and heavy flavors

B-jet substructure

Haitao Li, Vitev, 2018

Haitao Li, Vitev, 2018

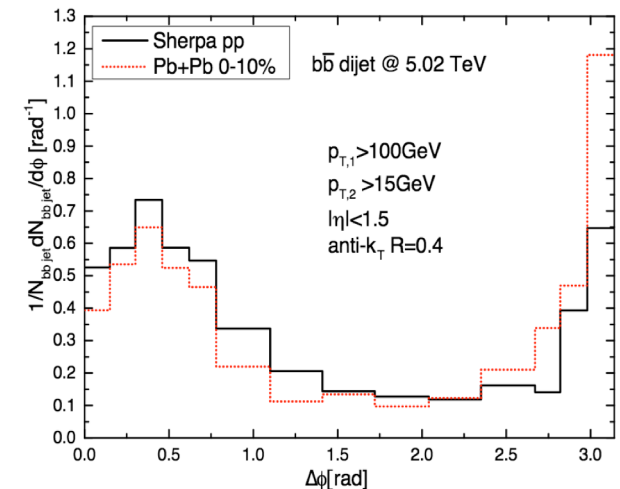
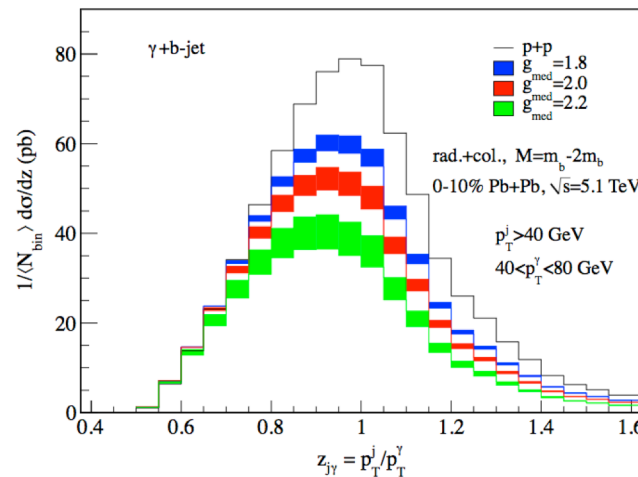
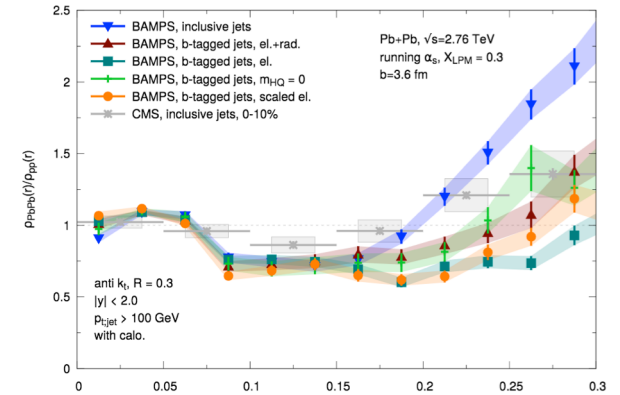
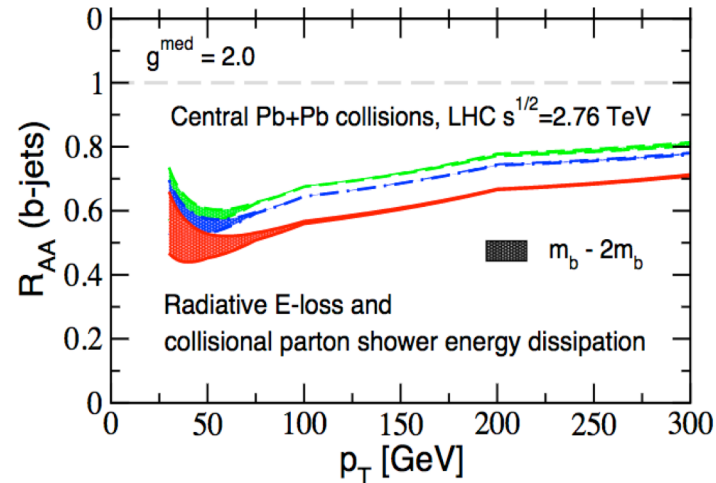
soft-drop groomed momentum sharing distribution

the inclusive b-jet production

SCETG

Examples of b-jet observables

- Many observables have reduced sensitivity to the QGP properties, especially dijet based. They subtract rather than add the quenching effects, affected by fluctuations
- Go beyond the energy loss model for b-jets and c-jets. Incorporate the advances in QCD and SCET – fixed order and resummed calculations



$$\frac{1}{\langle N_{bin} \rangle} \frac{d^2 \sigma_{AA}^{b-jet}(R)}{dy dp_T} = \sum_{(s)} \int_0^1 d\epsilon \frac{P_{(s)}(\epsilon)}{(1 - [1 - f(R, \omega^{coll})]_{(s)}) \epsilon} \frac{d^2 \sigma_{(s)}^{CNM, LO+PS} (|J(\epsilon)|_{(s)} p_T)}{dy dp_T}$$

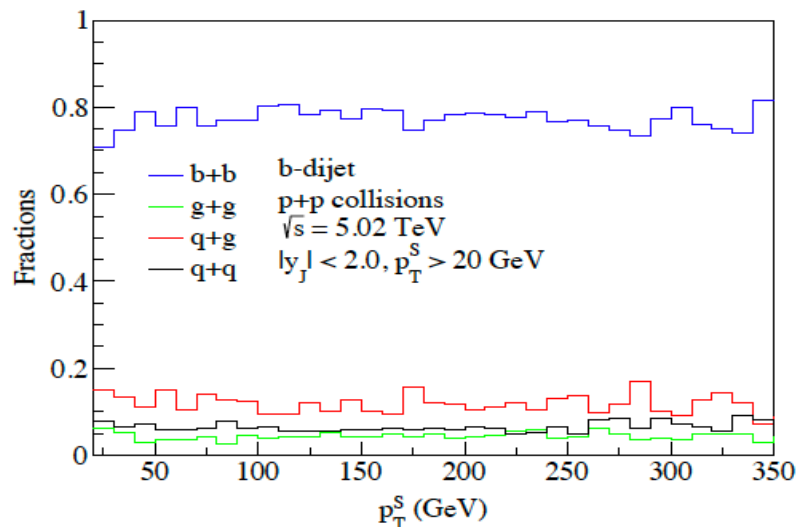
Invariant mass modification for light and heavy dijets



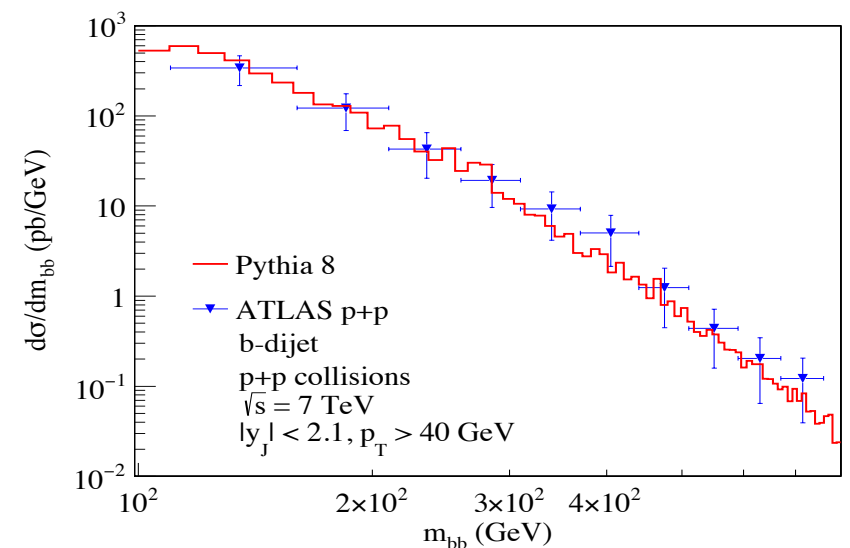
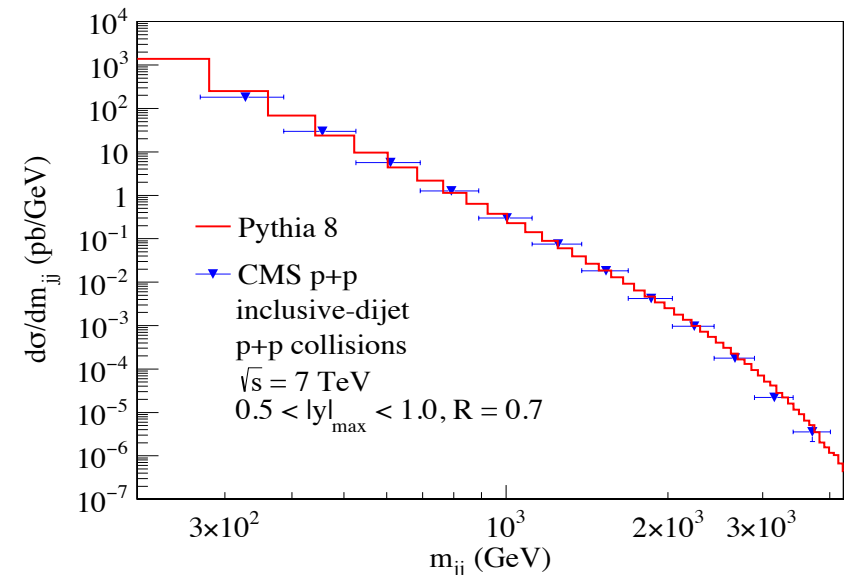
PYTHA baseline

Kang, Reiten, Vitev, Yoon 2018

- Appears to do a reasonable job in describing light dijet production. There are some differences in describing the dijet 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

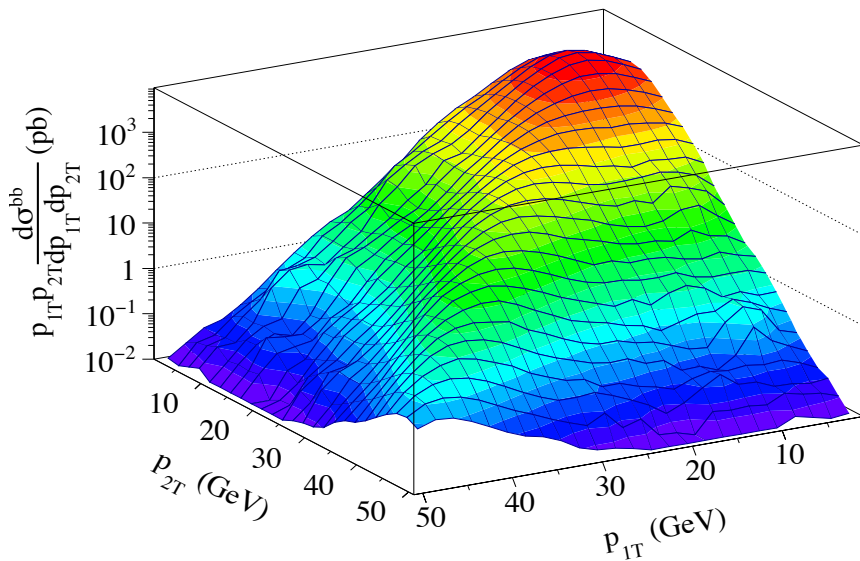
- Approximating the dijet cross section with individual jet pT, rapidity, mass and angular distributions (which we simulate from PYHIA)
- We have checked that any difference are < 10%, also cancel in R_{AA} ratios

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

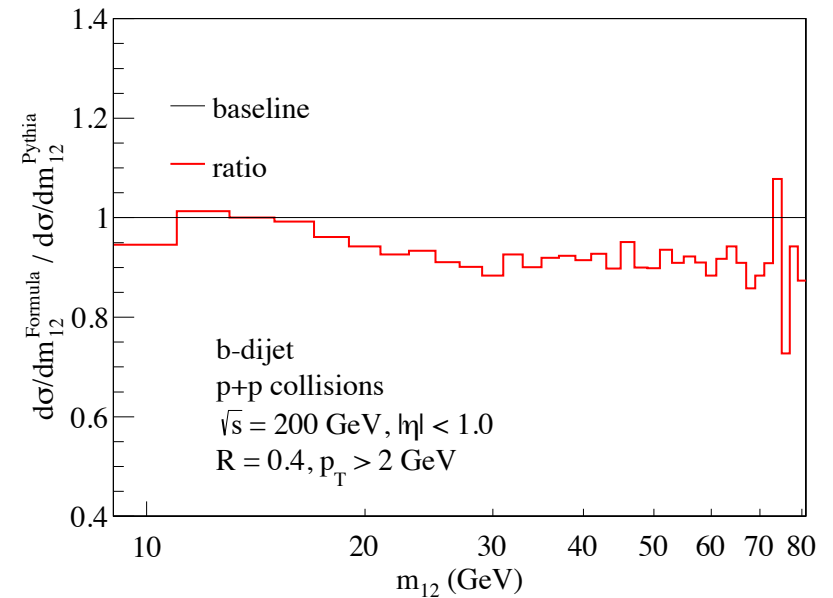
2-D nuclear modification factor needed

inclusive jet mass remains the same

angular information remains the same



2D distributions for inclusive dijets and Di-bjets

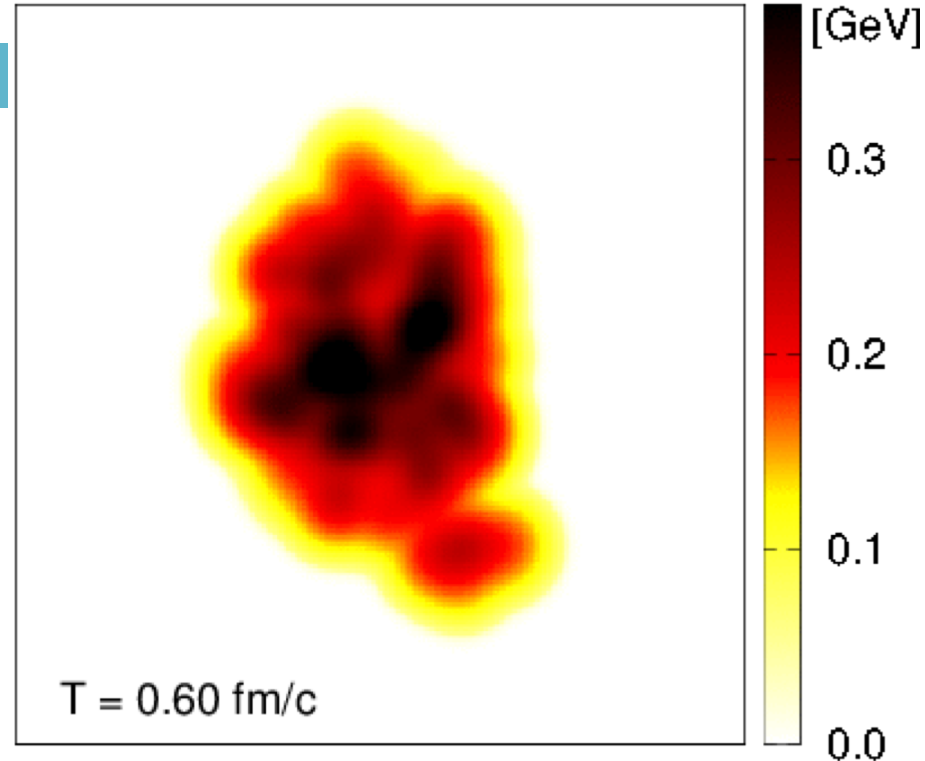


Differences very small

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

$$\begin{aligned} \left(\frac{dN^{\text{med}}}{dx d^2\mathbf{k}_\perp} \right)_{Q \rightarrow Qg} &= \frac{\alpha_s}{2\pi^2} C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2q_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\text{med}}}{d^2q_\perp} \left\{ \left(\frac{1+(1-x)^2}{x} \right) \left[\frac{B_\perp}{B_\perp^2 + \nu^2} \right. \right. \\ &\times \left(\frac{B_\perp}{B_\perp^2 + \nu^2} - \frac{C_\perp}{C_\perp^2 + \nu^2} \right) (1 - \cos[(\Omega_1 - \Omega_2)\Delta z]) + \frac{C_\perp}{C_\perp^2 + \nu^2} \cdot \left(2 \frac{C_\perp}{C_\perp^2 + \nu^2} - \frac{A_\perp}{A_\perp^2 + \nu^2} \right. \\ &- \left. \left. \frac{B_\perp}{B_\perp^2 + \nu^2} \right) (1 - \cos[(\Omega_1 - \Omega_3)\Delta z]) + \frac{B_\perp}{B_\perp^2 + \nu^2} \cdot \frac{C_\perp}{C_\perp^2 + \nu^2} (1 - \cos[(\Omega_2 - \Omega_3)\Delta z]) \right. \\ &+ \frac{A_\perp}{A_\perp^2 + \nu^2} \cdot \left(\frac{D_\perp}{D_\perp^2 + \nu^2} - \frac{A_\perp}{A_\perp^2 + \nu^2} \right) (1 - \cos[\Omega_4\Delta z]) - \frac{A_\perp}{A_\perp^2 + \nu^2} \cdot \frac{D_\perp}{D_\perp^2 + \nu^2} (1 - \cos[\Omega_5\Delta z]) \\ &+ \left. \left. \frac{1}{N_c^2} \frac{B_\perp}{B_\perp^2 + \nu^2} \cdot \left(\frac{A_\perp}{A_\perp^2 + \nu^2} - \frac{B_\perp}{B_\perp^2 + \nu^2} \right) (1 - \cos[(\Omega_1 - \Omega_2)\Delta z]) \right] \right. \\ &+ \left. x^3 m^2 \left[\frac{1}{B_\perp^2 + \nu^2} \cdot \left(\frac{1}{B_\perp^2 + \nu^2} - \frac{1}{C_\perp^2 + \nu^2} \right) (1 - \cos[(\Omega_1 - \Omega_2)\Delta z]) + \dots \right] \right\} \end{aligned}$$



- Quenched dijet cross sections

$$\begin{aligned} \frac{d\sigma^{AA}(|\mathbf{b}_\perp|)}{dp_{1T} dp_{2T}} &= \int d^2\mathbf{s}_\perp T_A \left(\mathbf{s}_\perp - \frac{\mathbf{b}_\perp}{2} \right) T_A \left(\mathbf{s}_\perp + \frac{\mathbf{b}_\perp}{2} \right) \\ &\times \sum_{q,g} \int_0^1 d\epsilon \frac{P_{q,g}^1(\epsilon; \mathbf{s}_\perp, |\mathbf{b}_\perp|)}{1 - f_{q,g}^1 \text{loss}(R; \mathbf{s}_\perp, |\mathbf{b}_\perp|) \epsilon} \int_0^1 d\epsilon' \frac{P_{q,g}^2(\epsilon'; \mathbf{s}_\perp, |\mathbf{b}_\perp|)}{1 - f_{q,g}^2 \text{loss}(R; \mathbf{s}_\perp, |\mathbf{b}_\perp|) \epsilon'} \\ &\times \frac{d\sigma_{q,g}^{NN}(p_{1T}/[1 - f_{q,g}^1 \text{loss}(R; \mathbf{s}_\perp, |\mathbf{b}_\perp|) \epsilon], p_{2T}/[1 - f_{q,g}^2 \text{loss}(R; \mathbf{s}_\perp, |\mathbf{b}_\perp|) \epsilon'])}{dp_{1T} dp_{2T}} \end{aligned}$$

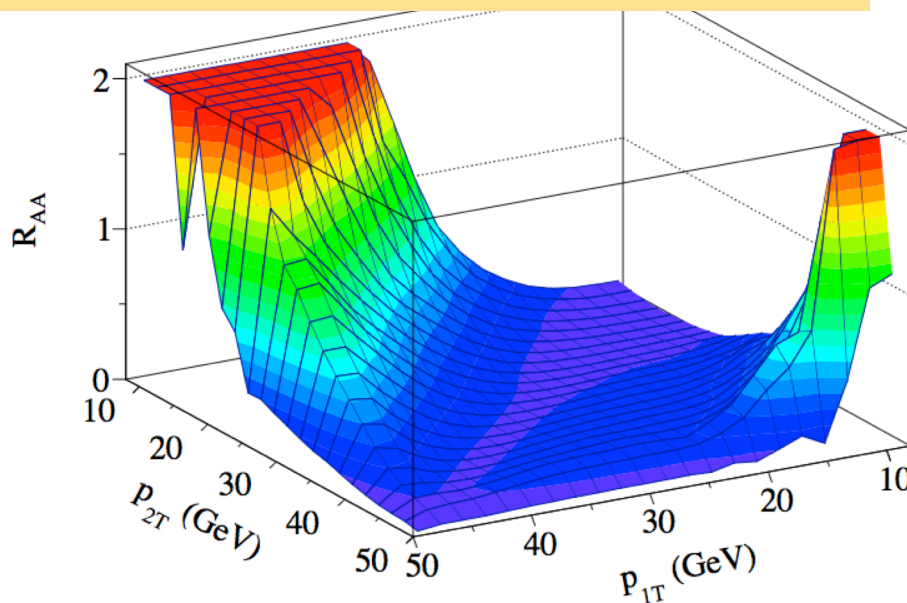
[C. Shen et al, 2014](#)

Results for the dijet suppression

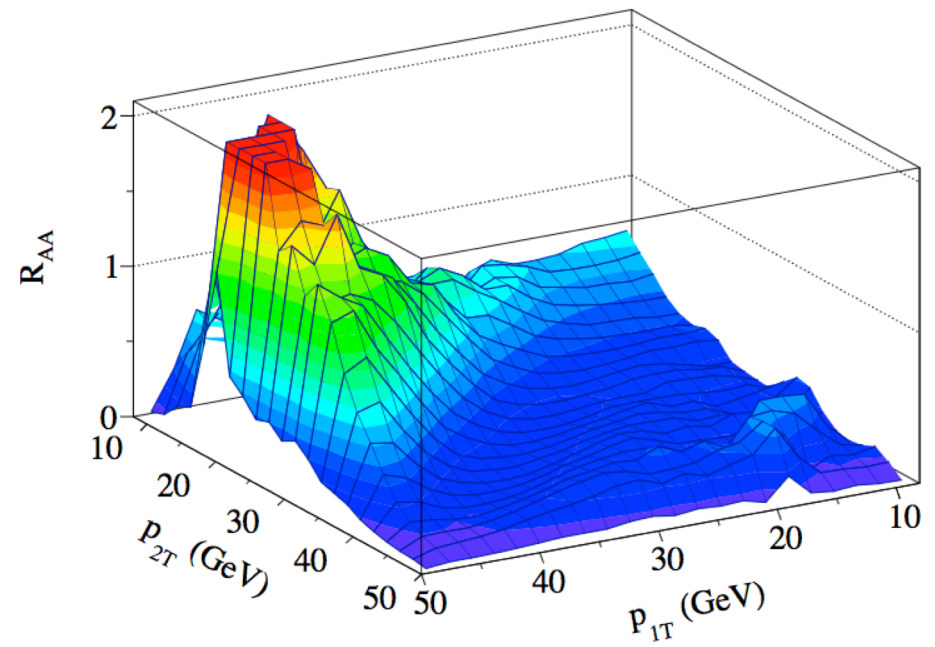
- All the information in this calculation is contained in the full 2D di-jet suppression pattern
- Examples here given for RHIC energies

Double differential dijet suppression pattern

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



inclusive dijet



b dijet

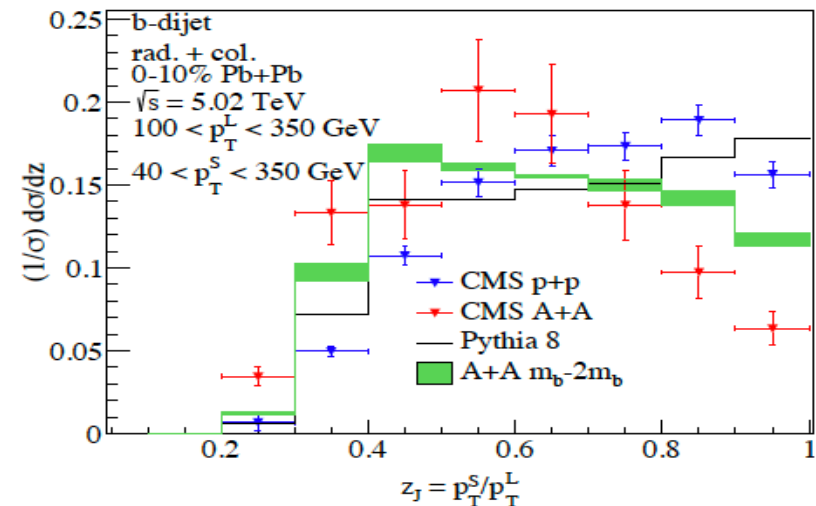
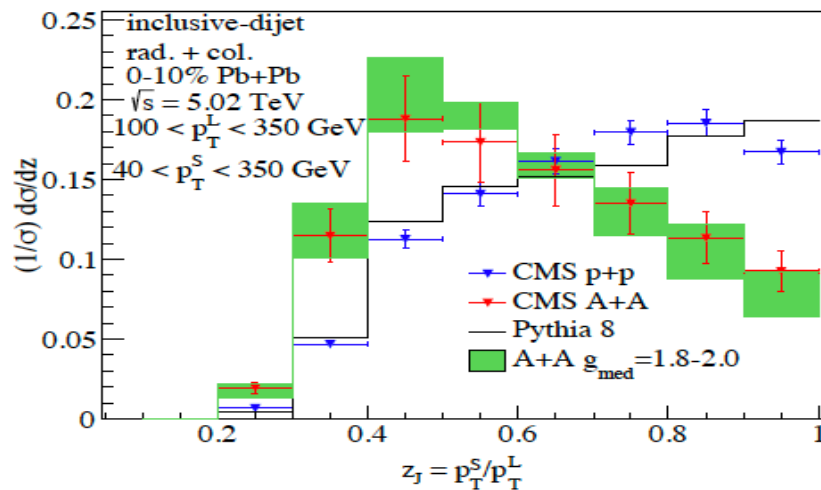
- The suppression is largest along the main diagonal; can get enhancement in asymmetric phase space. Arises from flavor bias (mostly) and geometric bias

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

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

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



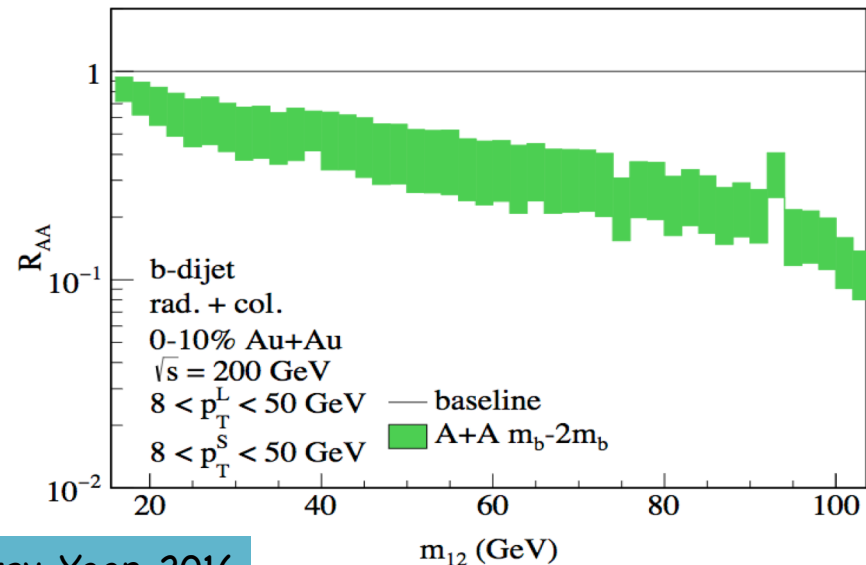
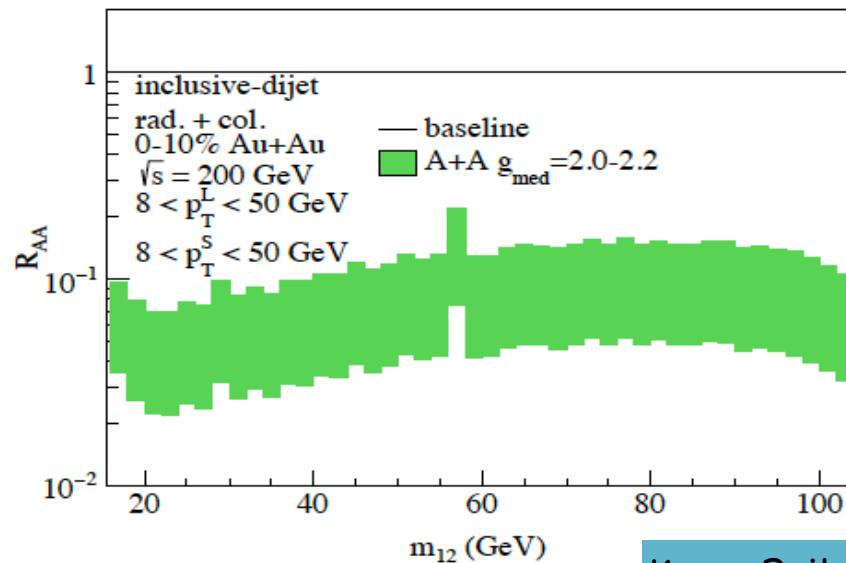
PYTHIA does not do a great job on the b-dijet baseline. In such cases the physics is captured by the mean imbalance shift. It is subtle – of order 10%

$$\langle z_J \rangle = \left(\int dz_J z_J \frac{d\sigma}{dz_J} \right) / \left(\int dz_J \frac{d\sigma}{dz_J} \right) \quad \Delta \langle z_J \rangle = \langle z_J \rangle_{pp} - \langle z_J \rangle_{AA}$$

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
	inclusive	0.669 ± 0.002	0.617 ± 0.027	0.052 ± 0.024
LHC theory	b-tagged	0.685	0.626 ± 0.013	0.059 ± 0.013
	inclusive	0.701	0.605 ± 0.022	0.096 ± 0.022
sPHENIX theory	b-tagged	0.730	0.665 ± 0.012	0.065 ± 0.012
	inclusive	0.743	0.643 ± 0.005	0.100 ± 0.005

Dijet mass modification

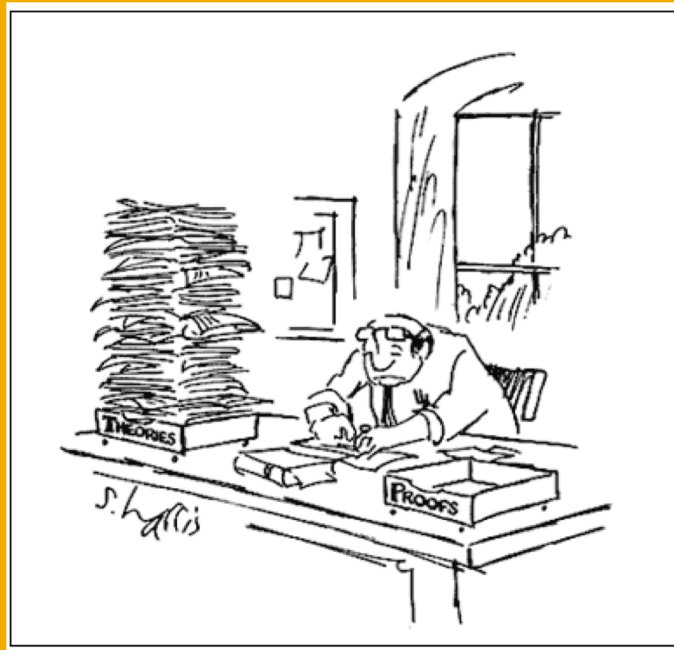
- When it comes to dijet mass modification the results are very encouraging – RHIC example. Best seen at masses under 100 GeV.
- Also works well at LHC in this mass range and even to a few hundred GeV
- Will be an extremely valuable measurement to make (try it)



Kang, Reiten, Vitev, Yoon 2016

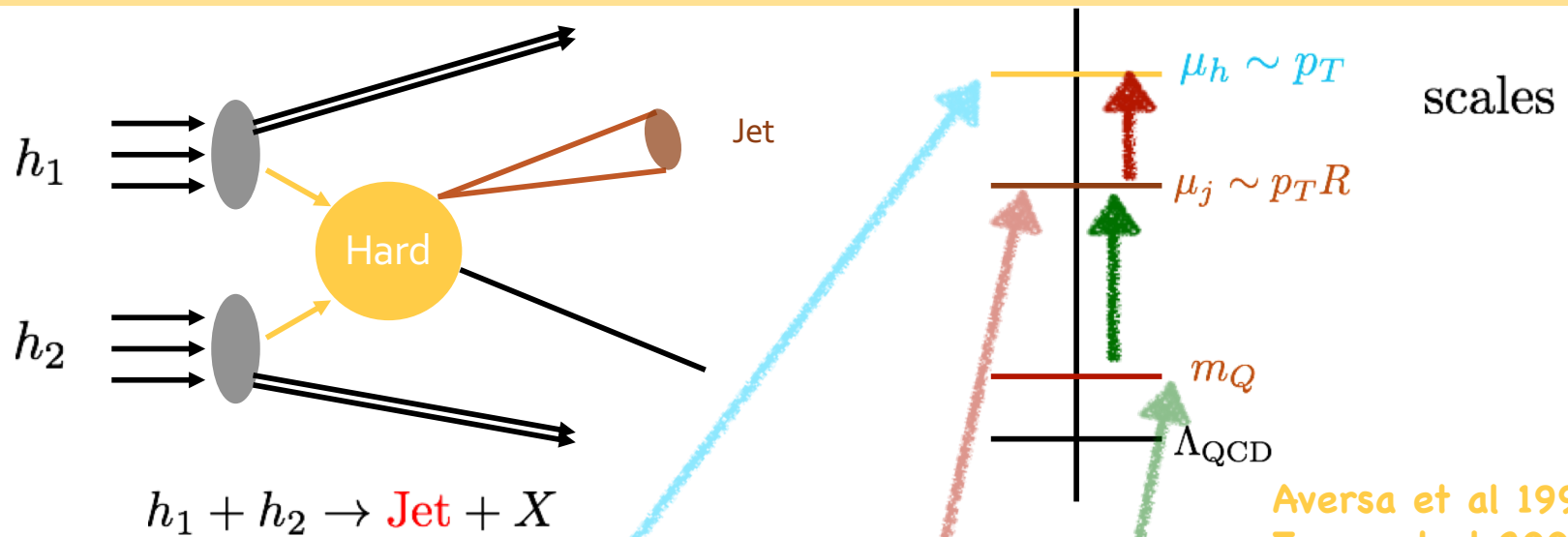
- Ideal measurement for the sPHENIX collaboration. Suppression of the inclusive dijet mass more than an order of magnitude.
- Suppression of b-dijets shows a completely different pattern. We see an enhanced sensitivity to the transport properties of the QGP (here captured by the coupling) and the mass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



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

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

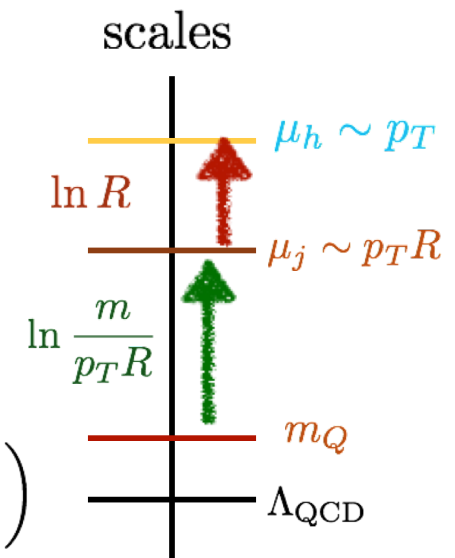
Aversa et al 1990
Jager et al 2004
Mukherjee et al 2012
Kaufmann et al 2016
...

Resummation

- Jet production is one of the cornerstones 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 $\ln \mu/p_T R$

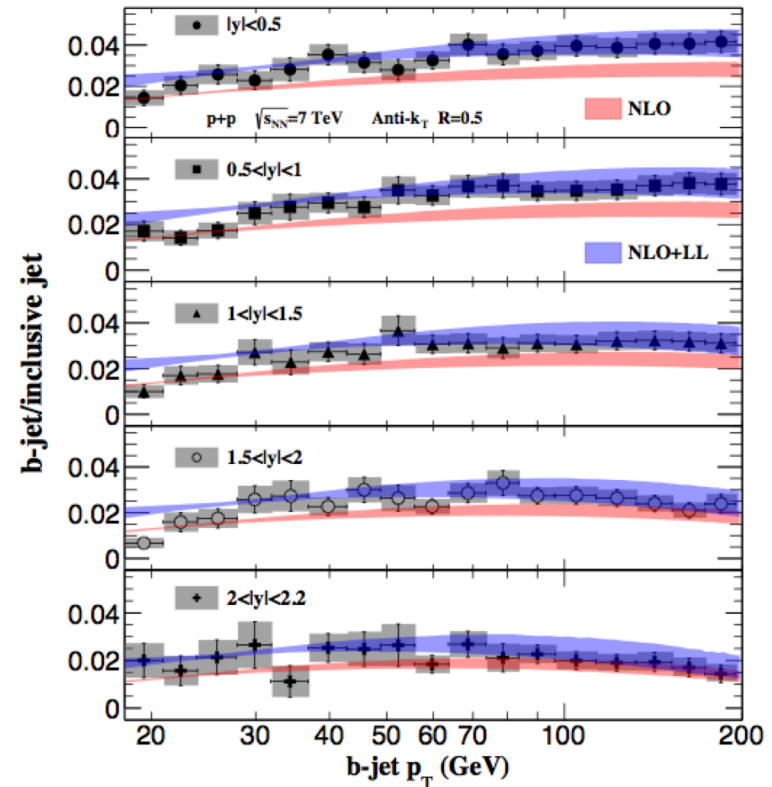
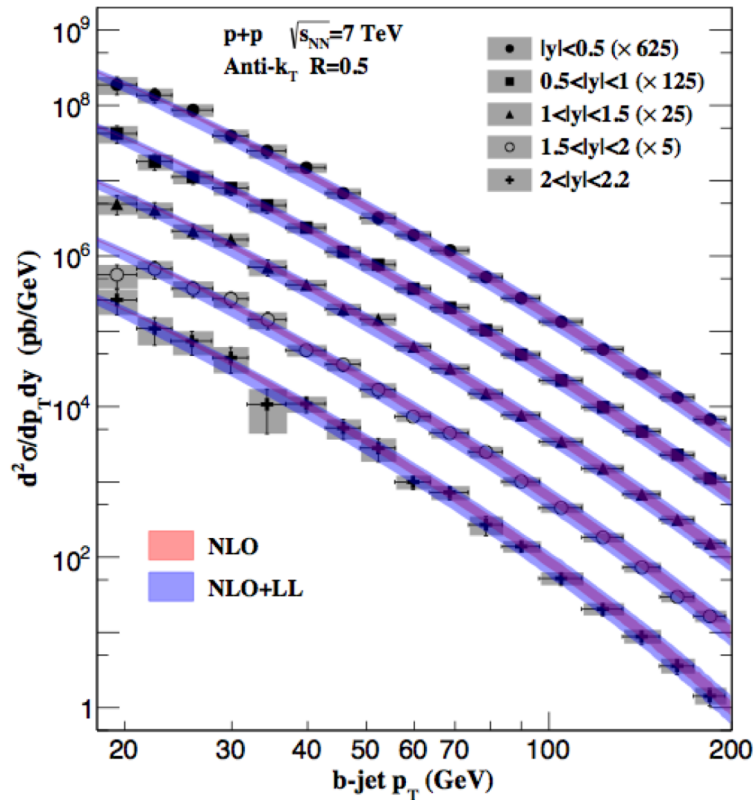
$$\mathcal{M}_{g \rightarrow Q \bar{Q}}^{\text{in-jet}}(p_T R, m) = 2 \sum_{l=g, Q} \bar{K}_{l/g}(p_T R, m, \mu_F) \bar{D}_{Q/l}(m, \mu_F)$$

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

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 p+A collisions

Assume the factorization works in heavy ion collisions, with calculable process-dependent corrections

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



Can be modified for nuclear collisions

The short-distance hard part remains the same



Not changed



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

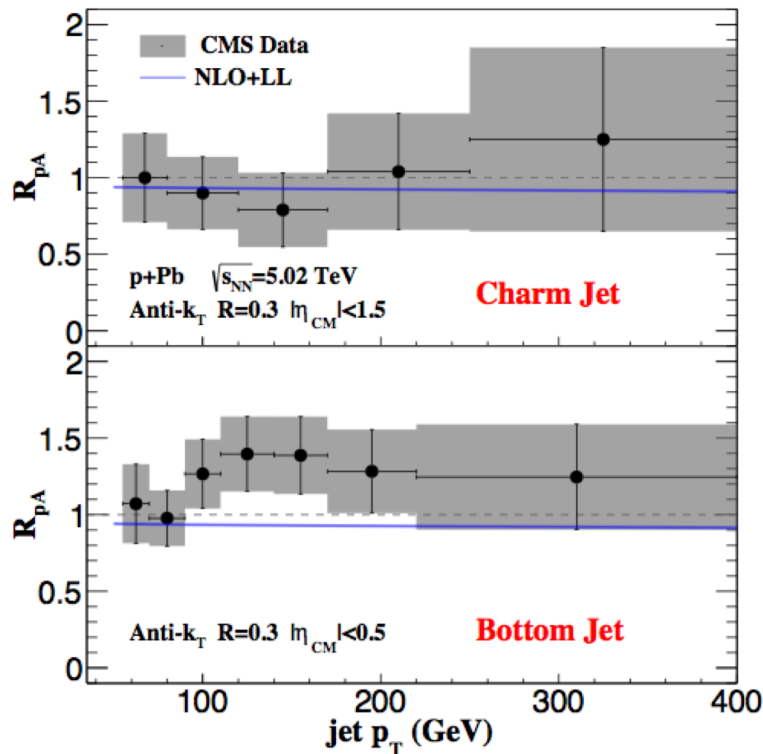
The point of view we take is that beyond isospin effects, nuclear matter effects are dynamically generated. Consider Bertsch - Gunion like CNM energy loss. At these jet p_T s Cronin effects and power corrections are not relevant

$$f_{q/A}(x, \mu) \rightarrow f_{q/A} \left(\frac{x}{1 - \epsilon_q}, \mu \right)$$

$$f_{g/A}(x, \mu) \rightarrow f_{g/A} \left(\frac{x}{1 - \epsilon_g}, \mu \right)$$

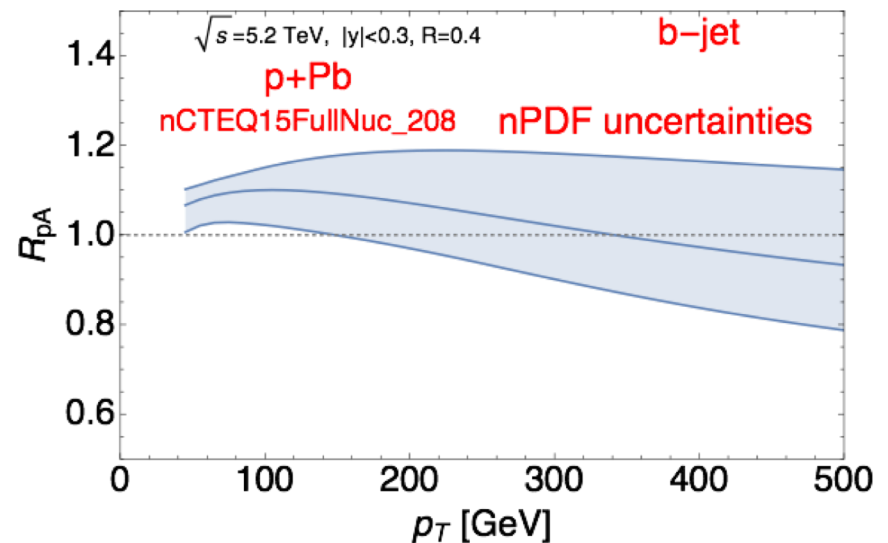
p+A collisions can be used to study the nuclear modifications at the initial state of the collisions, which is essential for the interpretation of the A+A results

R_{AA} in p-A collisions



Measurements:

- Large uncertainty
- Not enough to fully constrain the cold nuclear matter effects



Theory:

- 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

Naively speaking:

$$\text{Pb} + \text{Pb} : \underbrace{(1 \pm \epsilon)}_{\text{Pb}} \underbrace{(1 \pm \epsilon)}_{\text{Pb}}$$

Corrections in A+A collisions

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

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

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

The short-distance hard part remains the same

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

$$J_{J_Q/i}^{\text{med}} = J_{J_Q/i}^{\text{med},(0)} + J_{J_Q/i}^{\text{med},(1)}$$

Vacuum jet function:

$$J_{b/b}^{\text{vac}} = \text{[Diagram 1]} + \text{[Diagram 2]}$$

$\mathcal{O}(\alpha_s^0)$ $\mathcal{O}(\alpha_s)$

Medium corrections:

$$J_{b/b}^{\text{med}} = \text{[Diagram 3]} + \text{[Diagram 4]} + \text{[Diagram 5]}$$

$\mathcal{O}(\alpha_s^0 \times \frac{L}{\lambda})$ $\mathcal{O}(\alpha_s \times \frac{L}{\lambda})$

- 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

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

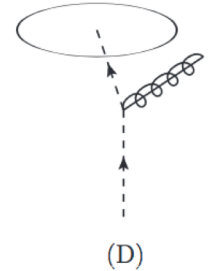
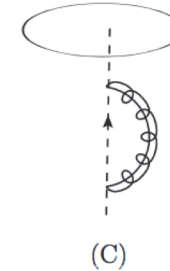
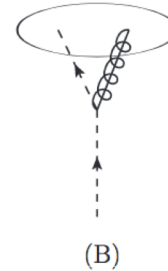
Medium corrections to the NLO jet function are written in terms of integrals over splitting functions. First developed for light jets.

Kang, Ringer, Vitev, 2017

For the heavy quark example

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

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



After summing over all diagrams

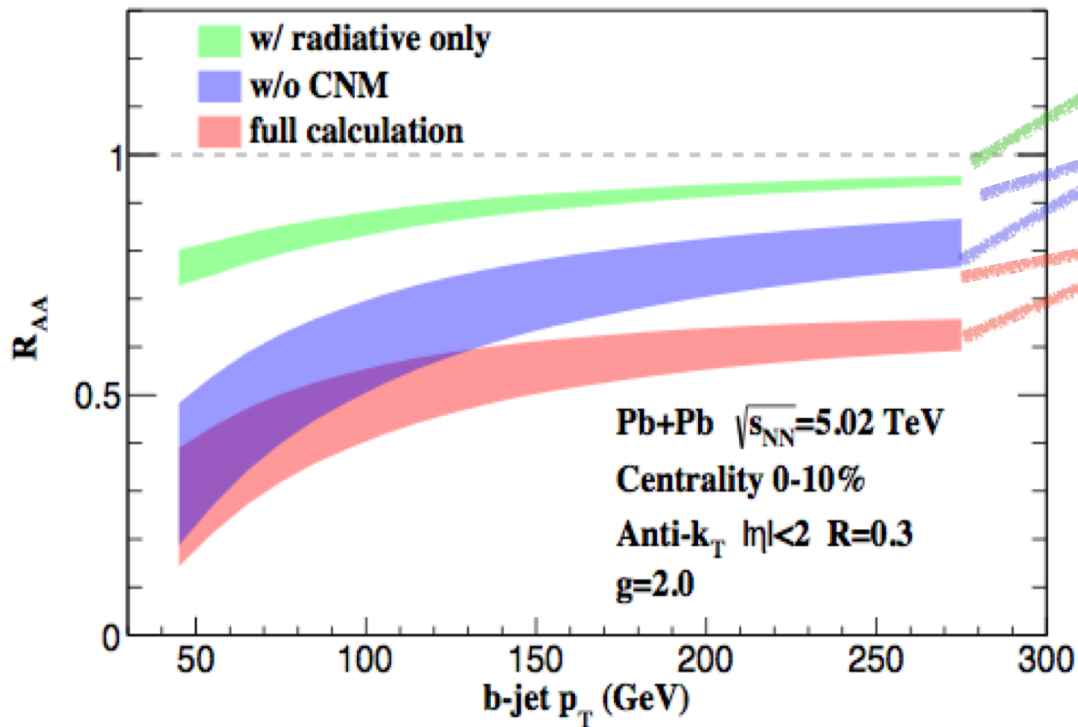
$$J_{J_Q/Q}^{\text{med},(1)}(z, p_T R, m, \mu) = \left[\int_{z(1-z)p_T R}^\mu dq_\perp P_{QQ}^{\text{med}}(z, m, q_\perp) \right]_+$$

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

Haitao Li, Vitev, 2018

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

R_{AA} in A+A collisions



Haitao Li, Vitev, 2018

In medium parton showers only

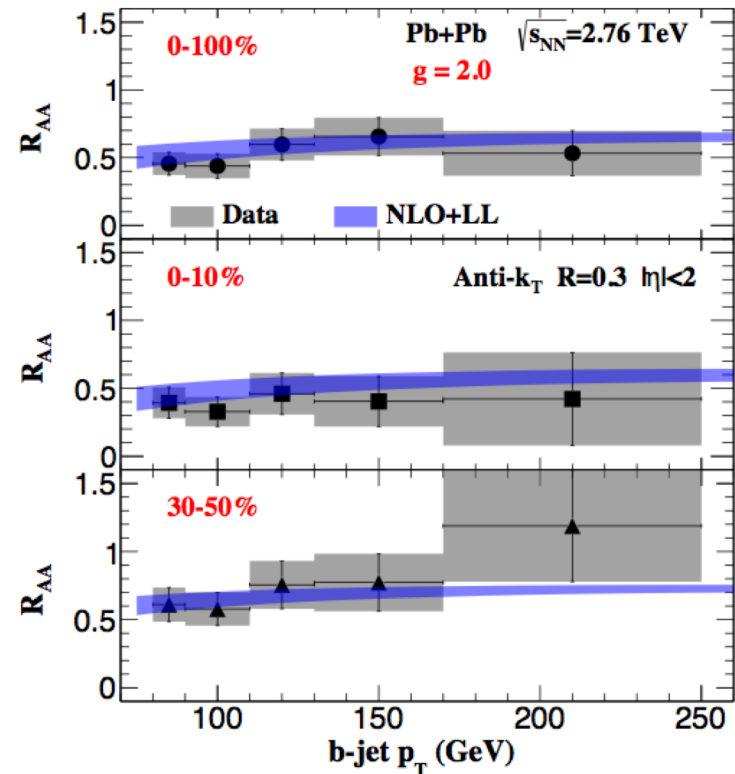
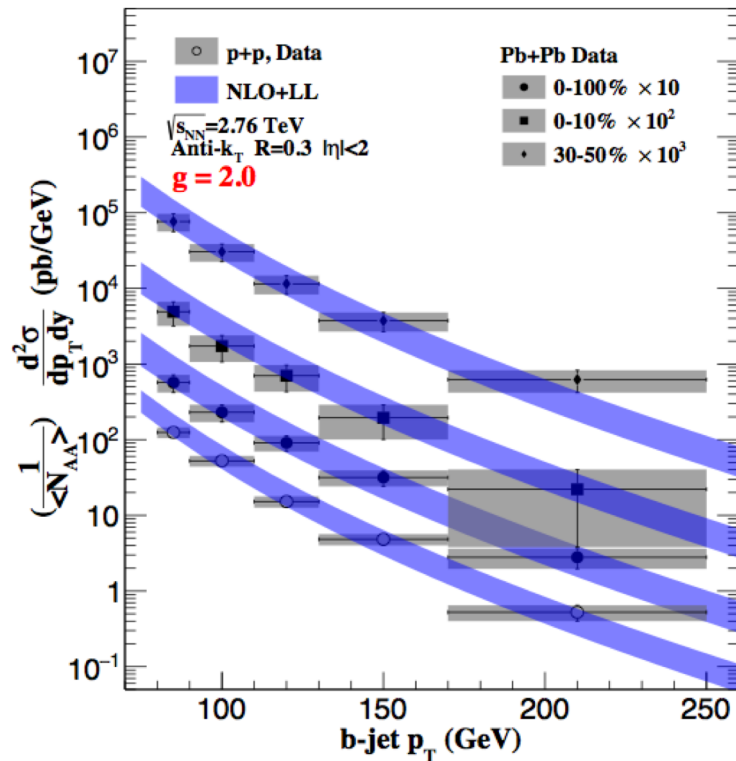
the difference is collisional energy loss

the difference is CNM effects

- Compared to light jet the radiative corrections are 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

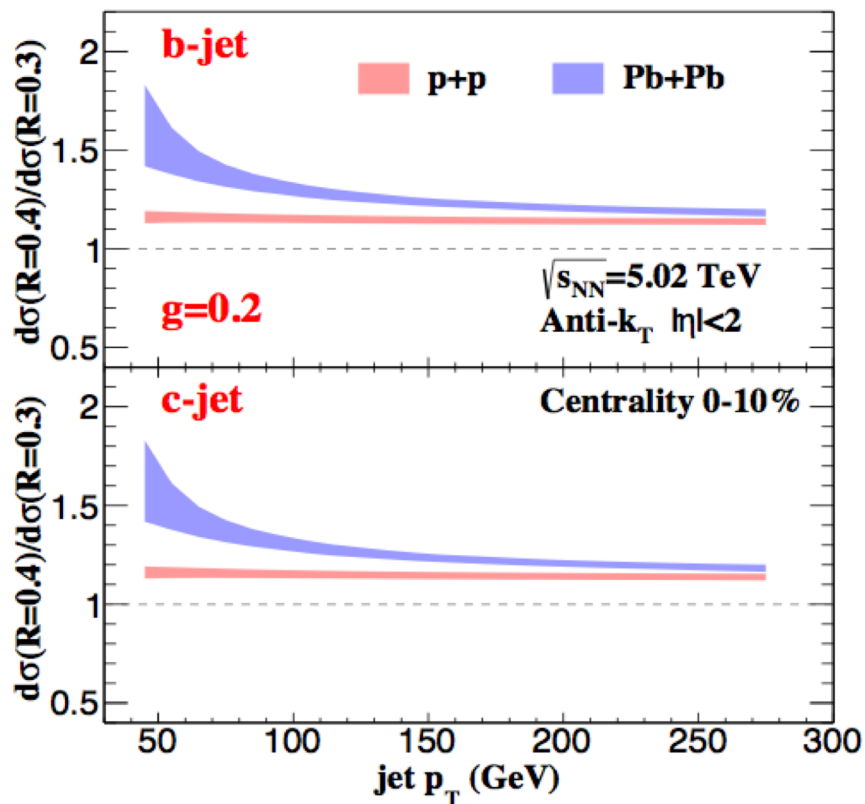
B-jet production in A-A collisions



- 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

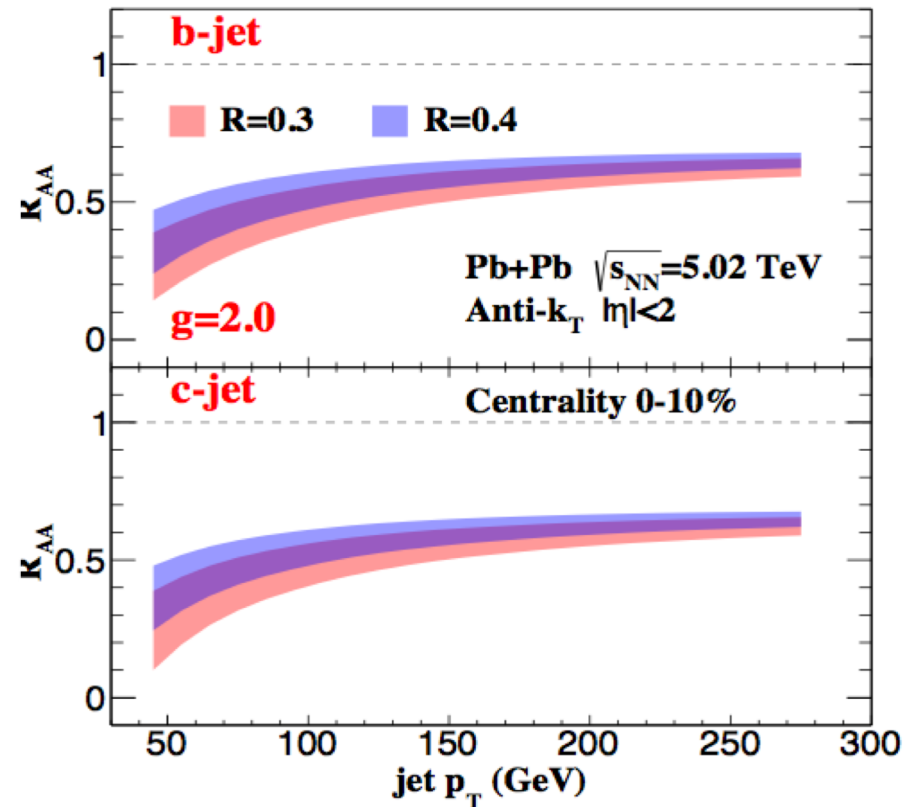
That does not mean there is no room for improvement

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

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

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

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

M. Sievert, Vitev (2018)

- Splitting kernels are solutions to iterative matrix equations

Mathematica, port to code

1st order ~ 1 page

2nd order ~ 10 pages

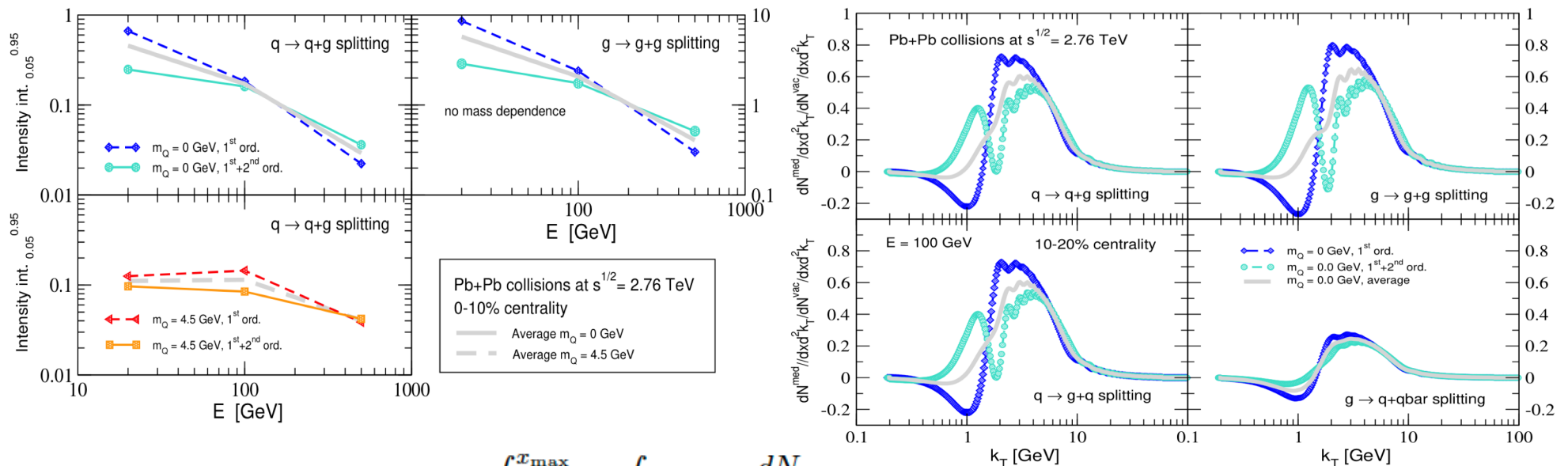
$$\begin{bmatrix} f_{F/F}^{(N)}(\underline{k}, \underline{k}', \underline{p}; x^+, y^+) \\ f_{I/F}^{(N)}(\underline{k}', \underline{p}; x^+, y^+) \\ f_{F/I}^{(N)}(\underline{k}, \underline{p}; x^+, y^+) \\ f_{I/I}^{(N)}(\underline{p}; x^+, y^+) \end{bmatrix} = \int_{x_0^+}^{\min[x^+, y^+, R^+]} \frac{dz^+}{\lambda^+} \int \frac{d^2q}{\sigma_{el}} \frac{d\sigma_{el}}{d^2q} \begin{bmatrix} \mathcal{K}_1 & \mathcal{K}_2 & \mathcal{K}_3 & \mathcal{K}_4 \\ 0 & \mathcal{K}_5 & 0 & \mathcal{K}_6 \\ 0 & 0 & \mathcal{K}_7 & \mathcal{K}_8 \\ 0 & 0 & 0 & \mathcal{K}_9 \end{bmatrix} \begin{bmatrix} f_{F/F}^{(N-1)}(\underline{k}, \underline{k}', \underline{p}; x^+, y^+) \\ f_{I/F}^{(N-1)}(\underline{k}', \underline{p}; x^+, y^+) \\ f_{F/I}^{(N-1)}(\underline{k}, \underline{p}; x^+, y^+) \\ f_{I/I}^{(N-1)}(\underline{p}; x^+, y^+) \end{bmatrix}$$

	d_1	d_2	d_3	d_4	d_5	d_6	v_1	v_3	v_5	v_7	λ_R^+	C_0	ν	$f(x)$	$g(x)$
$q \rightarrow qg$	1	1	$\frac{N_c}{C_F}$	$\frac{-1}{2N_c C_F}$	$\frac{N_c}{2C_F}$	$\frac{-N_c}{2C_F}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{-N_c}{2C_F}$	$\frac{N_c}{2C_F}$	λ_q^+	C_F	x	$1-x$	$1 + (1-x)^2$
$q \rightarrow gq$	1	1	$\frac{N_c}{C_F}$	$\frac{-1}{2N_c C_F}$	$\frac{N_c}{2C_F}$	$\frac{-N_c}{2C_F}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{-N_c}{2C_F}$	$\frac{N_c}{2C_F}$	λ_q^+	C_F	$1-x$	x	$1 + x^2$
$g \rightarrow q\bar{q}$	1	$\frac{C_F}{N_c}$	$\frac{C_F}{N_c}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2N_c^2}$	$-\frac{1}{2}$	$-\frac{C_F}{2N_c}$	$\frac{-C_F}{2N_c}$	$\frac{-1}{2N_c^2}$	λ_G^+	$\frac{1}{2}$	1	$x(1-x)$	$x^2 + (1-x)^2$
$g \rightarrow gg$	1	1	1	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	λ_G^+	N_c	0	$1 + x^4 + (1-x)^4$	1

M. Sievert et al. (2019)

Splitting functions to any order in opacity

- The remarkable part is also the ability to actually evaluate the analytic results in a hydrodynamic medium. They are prepared for phenomenology
- What we find is that 2nd order in opacity can change the p_T dependence – make it flatter. Flatter R_{AA}
- More significant changes at the differential splitting probabilities, and angular distributions. Oscillating series (experience) – upper and lower bounds and average for phenomenology



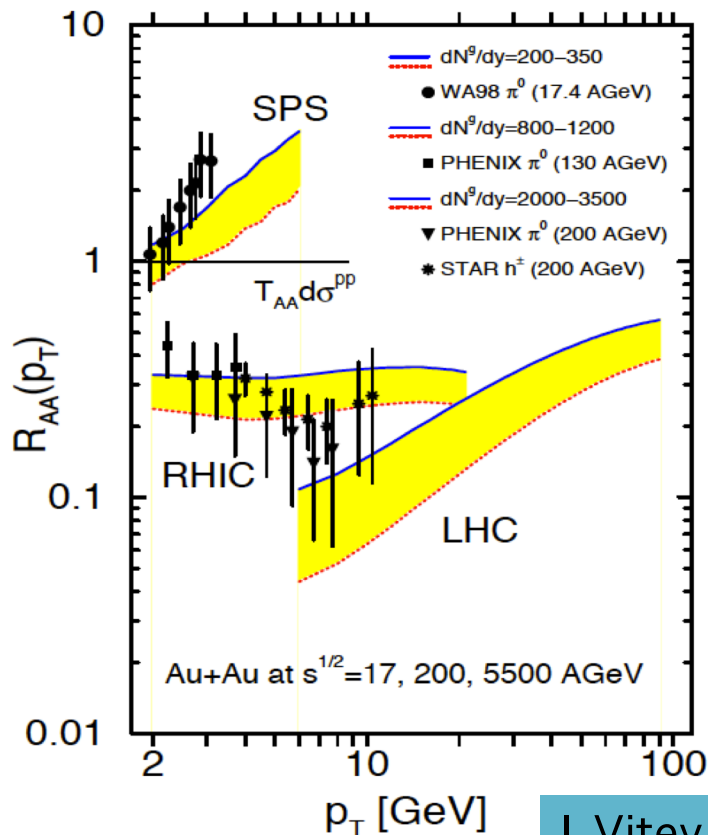
In the medium
$$\mathcal{I}_{x_{\min}}^{x_{\max}} = \int_{x_{\min}}^{x_{\max}} dx \int d^2k x \frac{dN}{d^2k dx}$$

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 took first steps toward incorporating collisional energy dissipation
- 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
- Further study the kinematic domain where mass effects on the heavy flavor jet production and propagation in medium are important

Traditional E-loss approach – successful but incomplete

- There is abundance of heavy ion data on inclusive and tagged jet cross sections, open heavy flavor, quarkonia, asymmetries, jet substructure, fragmentation functions, jet shapes even even groomed soft dropped subjet distributions they all show strong modification in A+A relative to p+p.



I. Vitev et al. (2002)

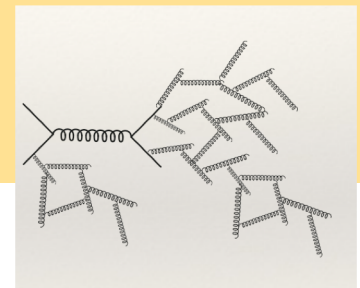
Nuclear modification ratio

$$R_{AA}(I_{AA} \dots) = \frac{\text{Yield}_{AA} / \langle N_{\text{binary}} \rangle_{AA}}{\text{Yield}_{pp}} = \frac{1}{\langle N_{\text{binary}} \rangle_{\text{AuAu}}} \frac{d\sigma_{\text{AuAu}} / dp_T dy}{d\sigma_{pp} / dp_T dy}$$

N_{binary} – the # of elementary p+p like collisions

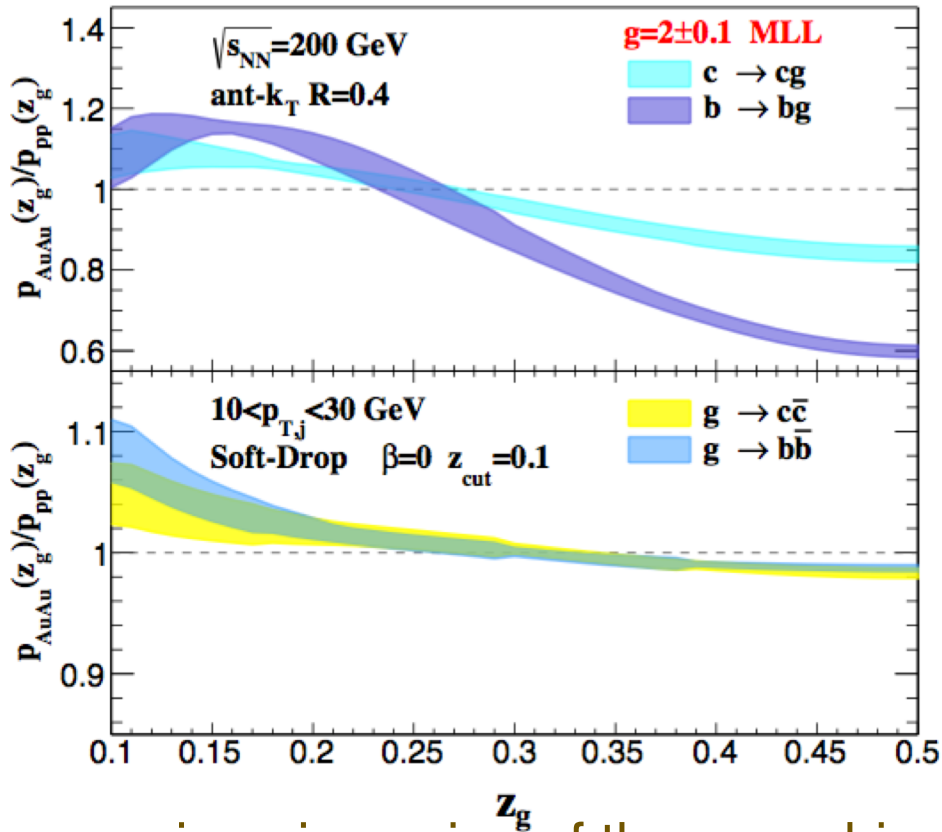
- Traditional non-Abelian energy loss has been refined. Difficult to make connection to the standard LO, NLO, ...; LL, NLL ... pQCD approach (higher orders and resummation)

- Bring some of the logs, legs and loops technology to HI

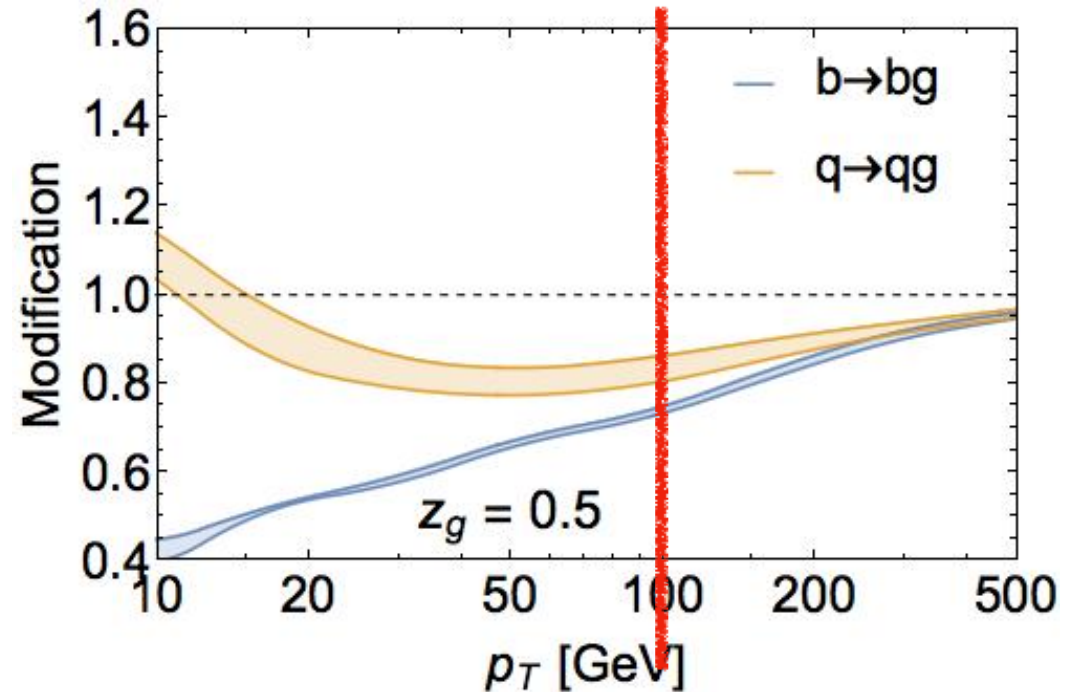


Substructure

HTL, Vitev, 2018



We can see the mass effects even for the b-jet with $p_T \sim 50 \text{ GeV}$ and a bit beyond.

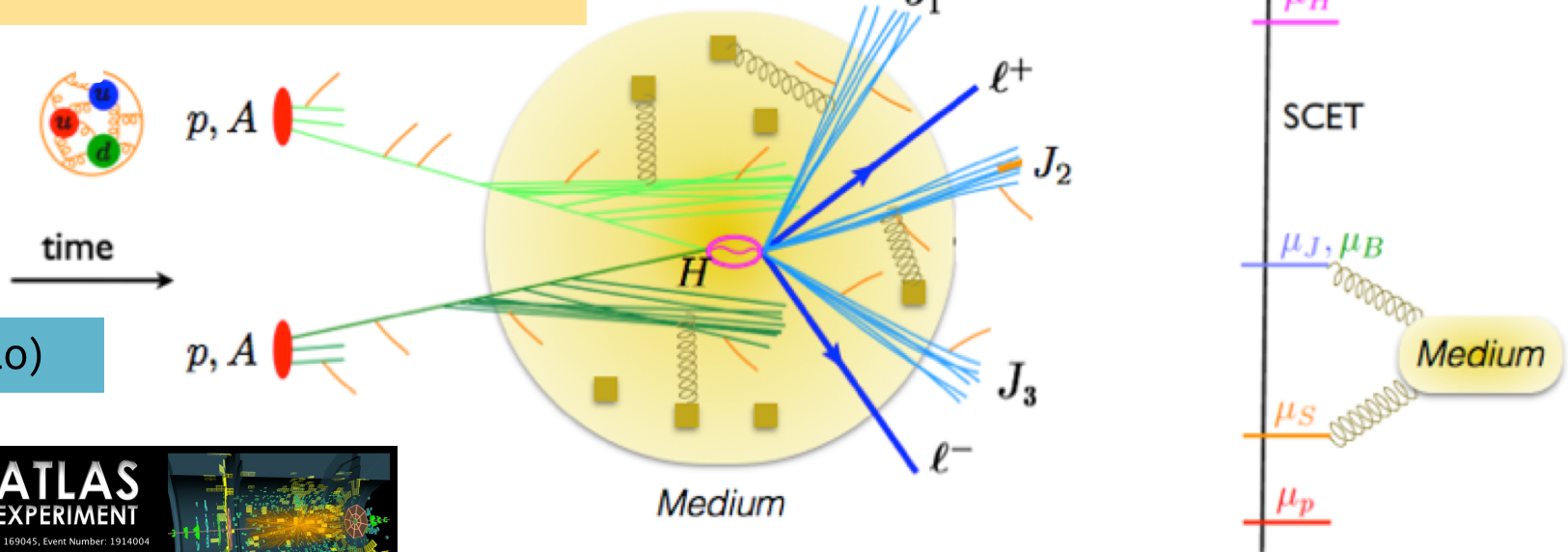


- a unique inversion of the mass hierarchy of jet quenching effects,
- be used to constrain the still not well understood dead cone effect in the QGP
- It is measurable at RHIC and LHC

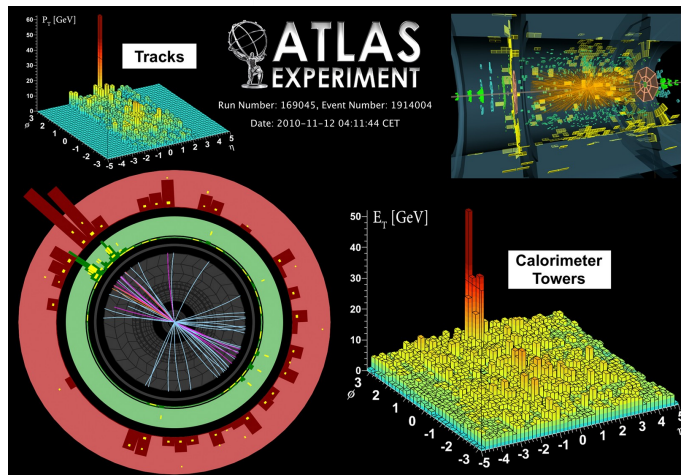
The HIC picture for hard probes

- QCD in the medium remains a multi-scale problem

Ovanesyan et al. (2011)



Aad et al. (2010)



- Factorization, with modified J (jet), B (beam), S (soft) functions

$$\sigma = \text{Tr}(HS) \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^N J_j + \text{power corrections}$$

Heavy quarks in the vacuum and the medium

SCET_{M,G} – for massive quarks with Glauber gluon interactions

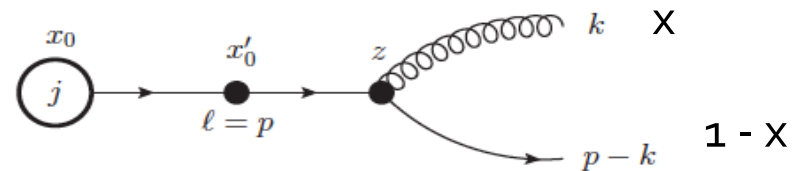
$$\mathcal{L}_{\text{QCD}} = \bar{\psi}(i\not{D} - m)\psi \quad iD^\mu = \partial^\mu + gA^\mu \quad A^\mu = A_c^\mu + A_s^\mu + A_G^\mu \quad \text{A. Leibovich et al. (2003)}$$

Feynman rules depend on the scaling of m . The key choice is $m/p^+ \sim \lambda$

With the field scaling in the covariant gauge for the Glauber field there is no room for interplay with mass in the LO Lagrangian

Result: SCET_{M,G} = SCET_M × SCET_G

- You see the dead cone effects
- You also see that it depends on the process – it not simply $x^2 m^2$ everywhere:
 $x^2 m^2, (1-x)^2 m^2, m^2$



$$\left(\frac{dN}{dx d^2 k_\perp} \right)_{g \rightarrow Q\bar{Q}} = T_R \frac{\alpha_s}{2\pi^2} \frac{1}{k_\perp^2 + m^2} \left[x^2 + (1-x)^2 + \frac{2x(1-x)m^2}{k_\perp^2 + m^2} \right]$$

$$\left(\frac{dN}{dx d^2 k_\perp} \right)_{Q \rightarrow Qg} = C_F \frac{\alpha_s}{\pi^2} \frac{1}{k_\perp^2 + x^2 m^2} \left[\frac{1-x+x^2/2}{x} - \frac{x(1-x)m^2}{k_\perp^2 + x^2 m^2} \right]$$

G. Altarelli et al. (1977)

F. Ringer et al. (2016)