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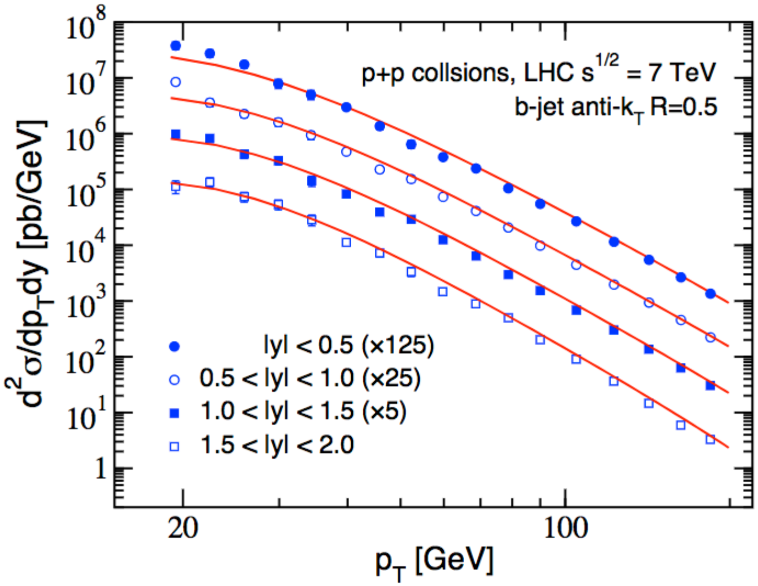
# Ideas for future HF measurements at the LHC

- ArXiv: 1801.00008
- ArXiv: 1810.10007
- ArXiv: 1811.07905

Snowmass 2021, ***EF 07 meeting***
***November 2, 2020***

# Motivation

**Jet production**




**Heavy flavor jet**

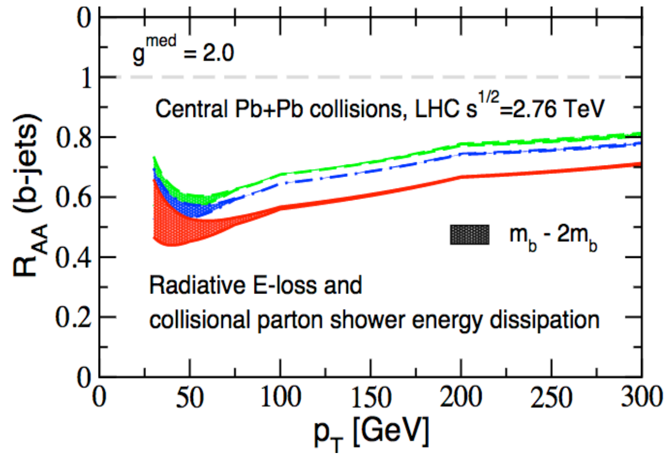
- Is characterized by large cross sections and has been measured with unprecedented precision in comparison to other high energy processes
- Can reveal the fundamental thermodynamic and transport properties of the QGP in A+A collisions

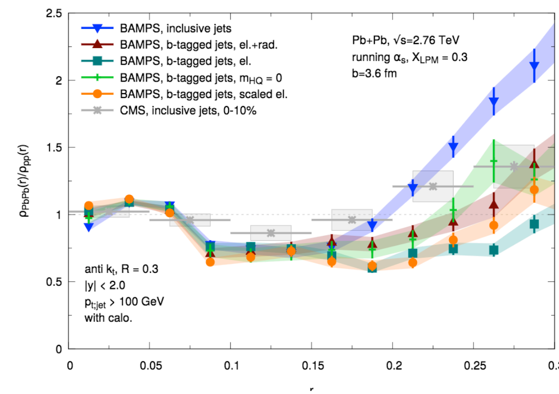
- A b-jet is a jet containing one or more b-hadrons, not necessary to be initiated by a heavy quark
- Experiences the full evolution of the hot and dense medium
- Seems to lose less energy; used to study the energy loss mechanisms in QCD medium

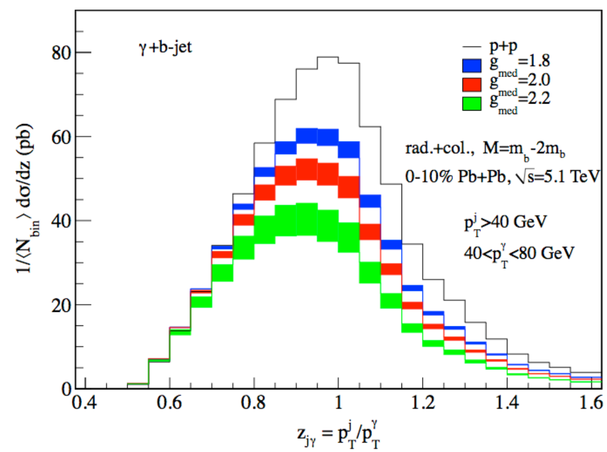
# Examples of b-jet observables

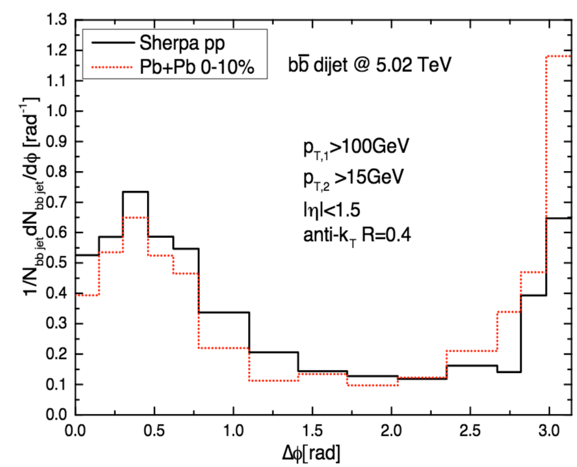
- Many observables have reduced sensitivity to the QGP properties, especially dijet based. They subtract rather than add the quenching effects, affected by fluctuations

- Go beyond the energy loss model for b-jets and c-jets. Incorporate the advances in QCD and SCET – fixed order and resumed calculations



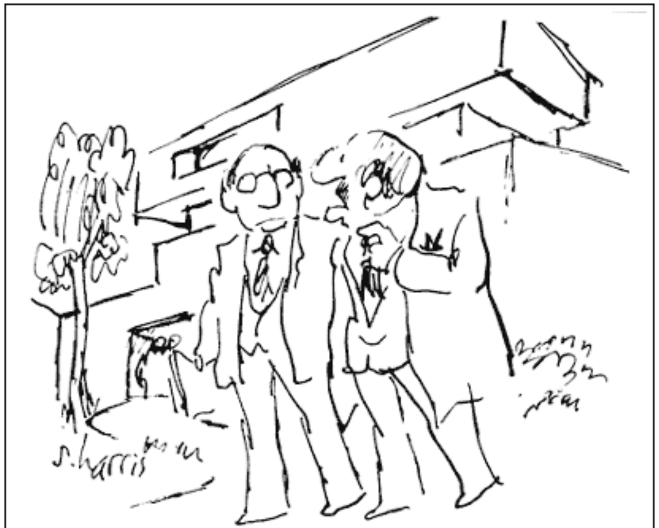




$$\frac{1}{\langle N_{\rm bin}\rangle}\frac{d^2\sigma_{AA}^{\rm b-jet}(R)}{dydp_T} = \sum_{(s)}\int_0^1 d\epsilon \frac{P_{(s)}(\epsilon)}{(1-[1-f(R,\omega^{\rm coll})_{(s)}]\epsilon)} \frac{d^2\sigma_{(s)}^{\rm CNM,LO+PS}\left(|J(\epsilon)|_{(s)}p_T\right)}{dydp_T}$$

# Invariant mass modification for light and heavy dijets

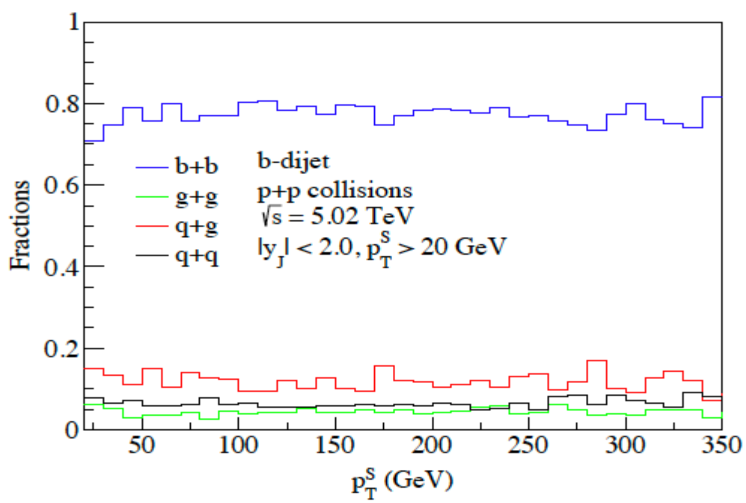



"I'm firmly convinced that behind every great man is a great computer."

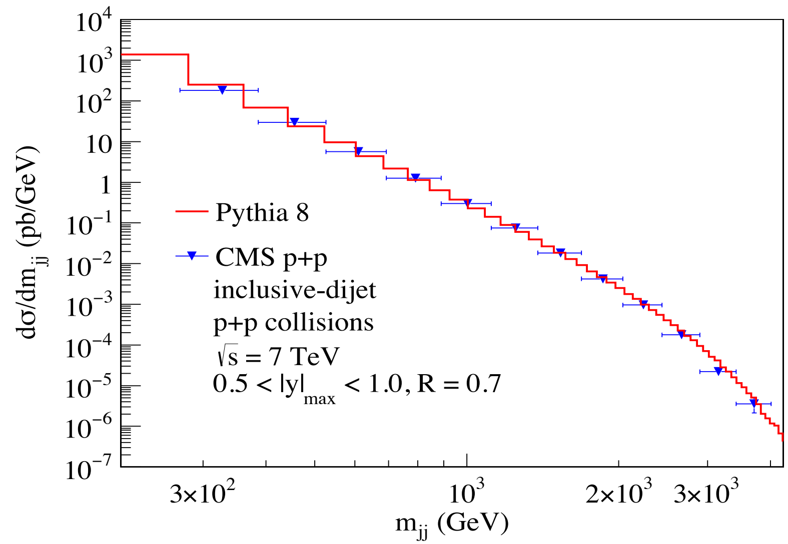
# PYTHA baseline

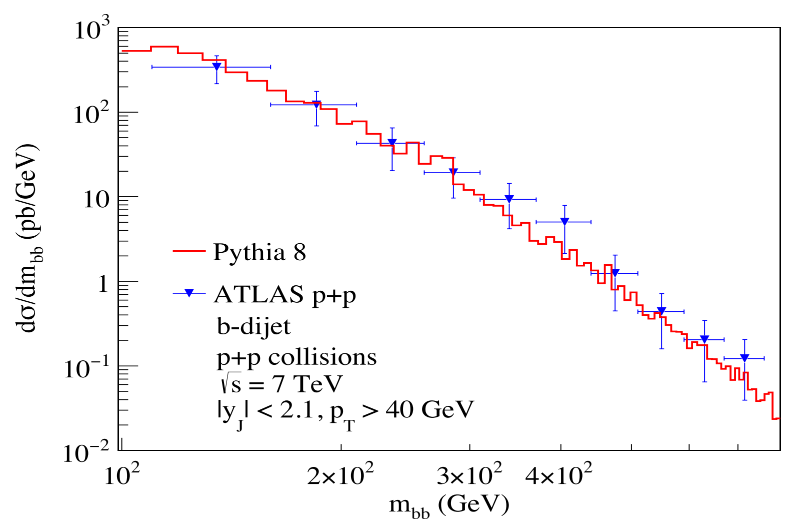
Kang, Reiten, Vitev, Yoon 2018

- 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

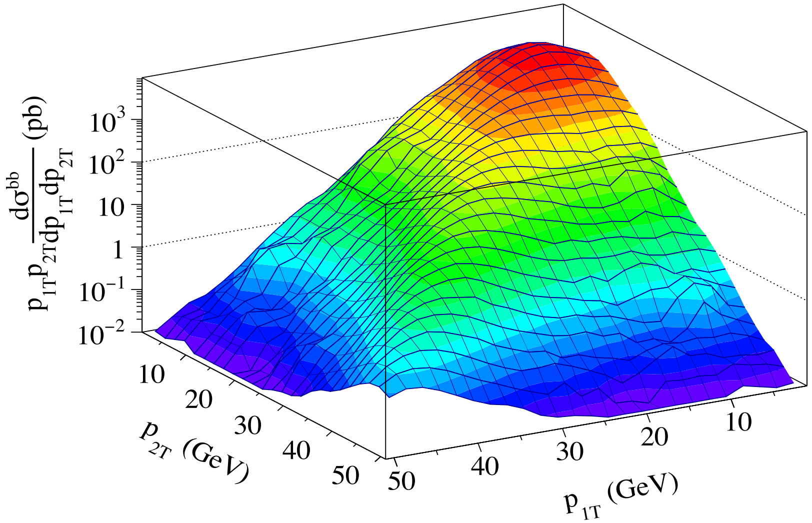
- Approximating the dijet cross section with individual jet pT, rapidity, mass and angular distributions (which we simulate from PYHIA )
- We have checked that aby difference are < 10%, also cancel in $R_{AA}$ ratios

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

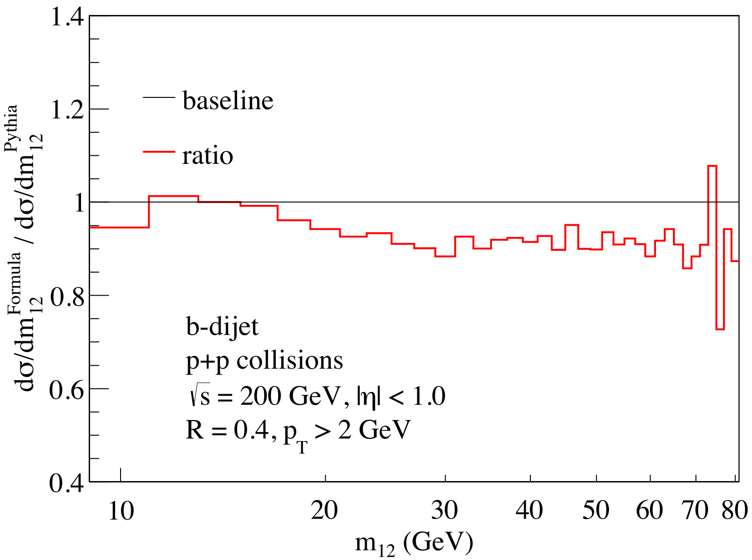
2-D nuclear modification factor needed

inclusive jet mass remains the same

angular information remains the same




2D distributions for inclusive dijets and Di-bjets

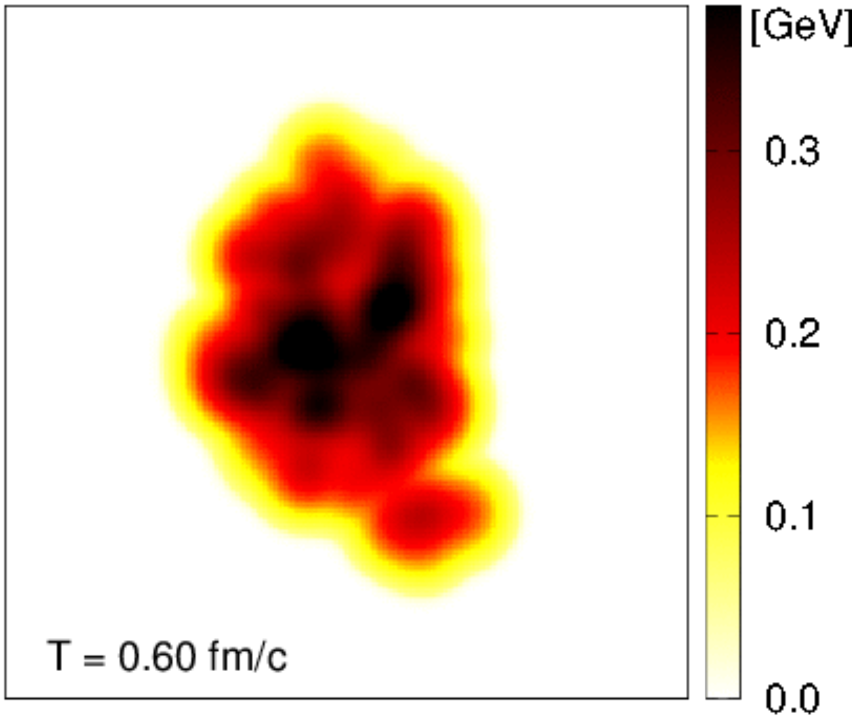



Differences very small

# 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

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




- Quenched dijet cross sections

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

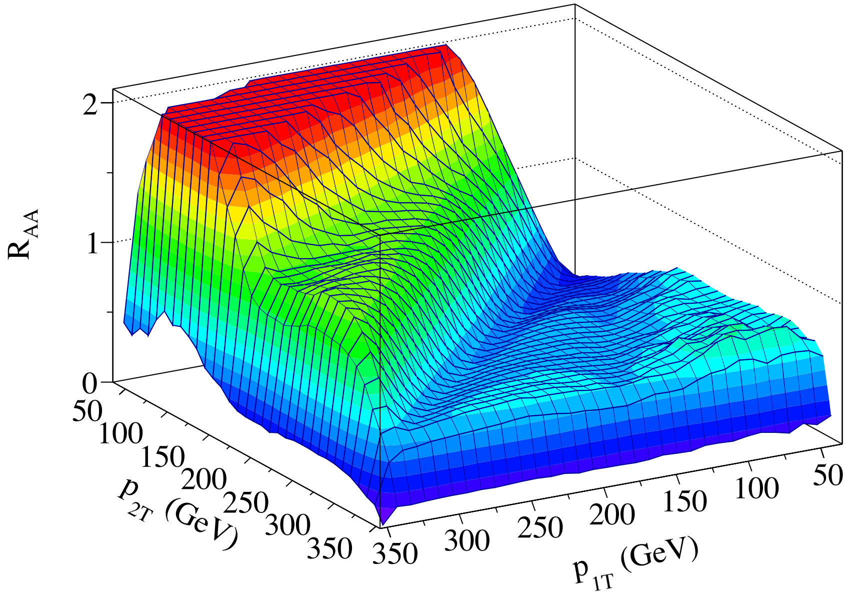
C. Shen et al, 2014

# Results for the dijet suppression

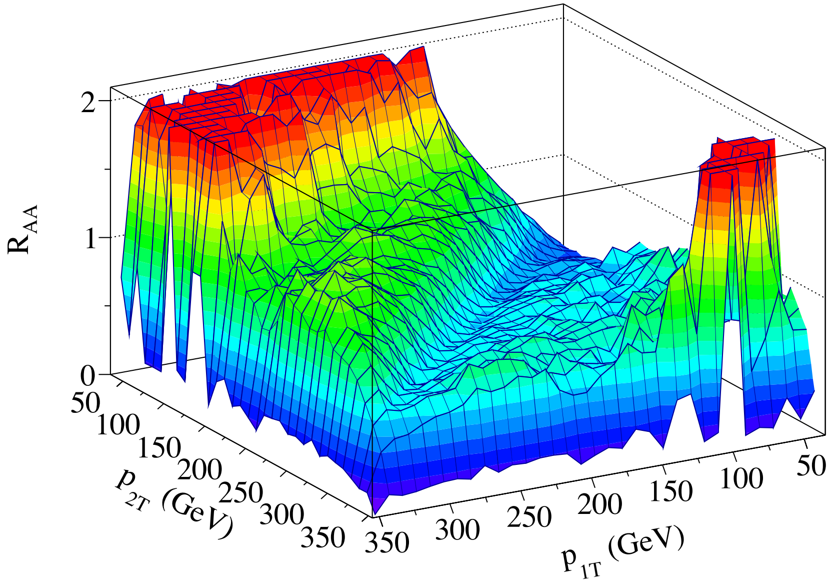
- All the information in this calculation is contained in the full 2D di-jet suppression pattern
- Examples here given for RHIC energies

**Double differential dijet suppression pattern**

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




**inclusive dijet**




**b dijet**

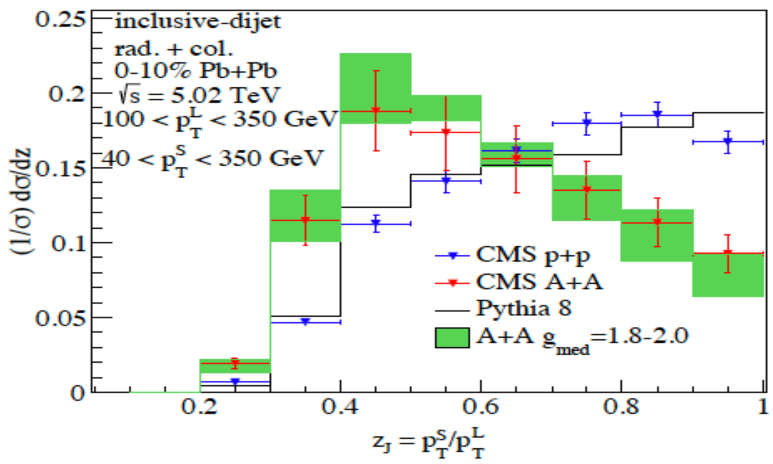
- The suppression is largest along the main diagonal; can get enhancement in asymmetric phase space . Arises form flavor bias (mostly) and geometric bias

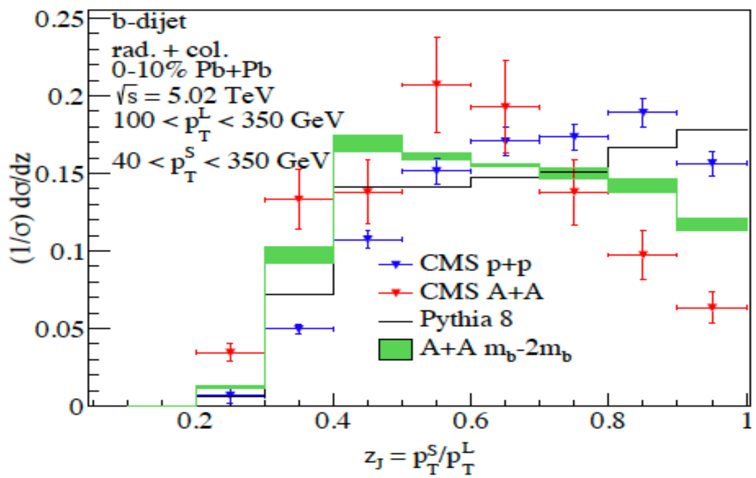
# Inclusive dijet and b-dijet momentum imbalance

- 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

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

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



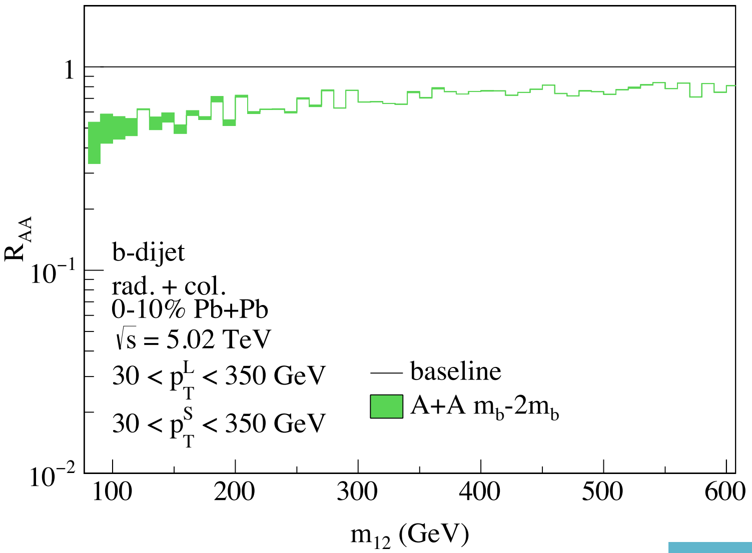

**PYTHIA does not do a great job on the b-dijet baseline. In such cases the physics is captured by the mean imbalance shift. It is subtle – of order 10%**

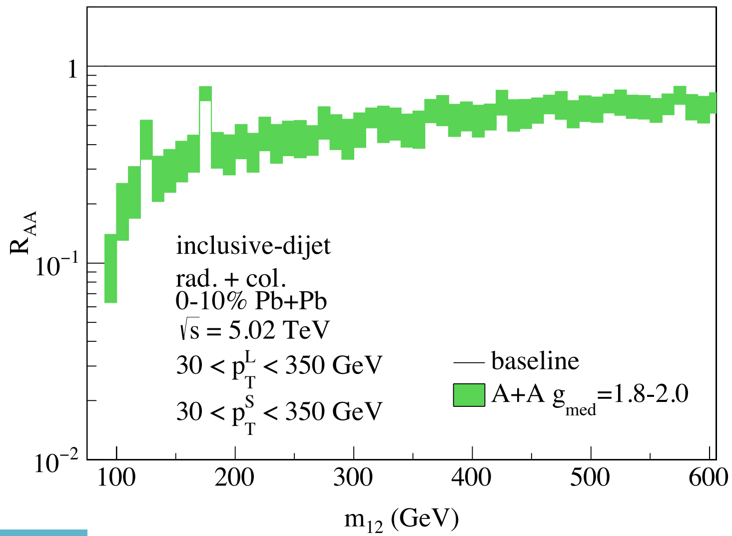
| Kinematics | dijet flavor | $\langle z_J\rangle_{pp}$ | $\langle z_J\rangle_{AA}$ | $\Delta\langle z_J\rangle$ |
|---|---|---|---|---|
| CMS [25] | b-tagged | $0.661 \pm 0.003$ | $0.601 \pm 0.023$ | $0.060 \pm 0.025$ |
| Experiment | inclusive | $0.669 \pm 0.002$ | $0.617 \pm 0.027$ | $0.052 \pm 0.024$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

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

# 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)

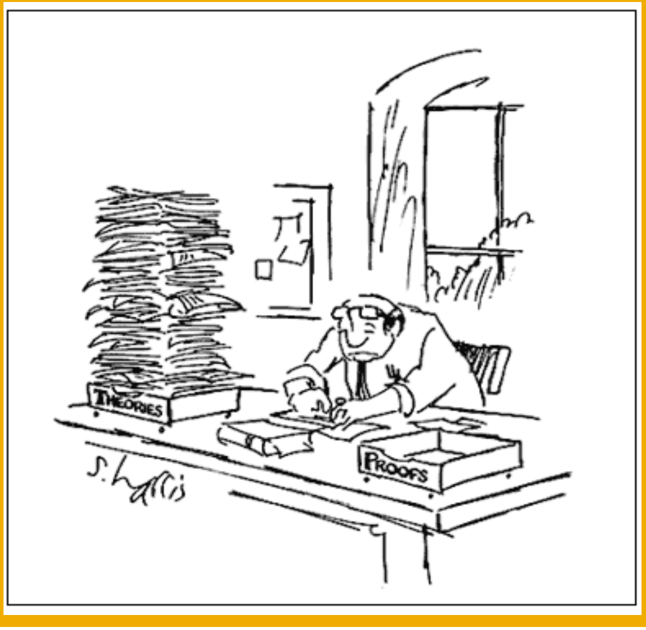



Kang, Reiten, Vitev, Yoon 2018

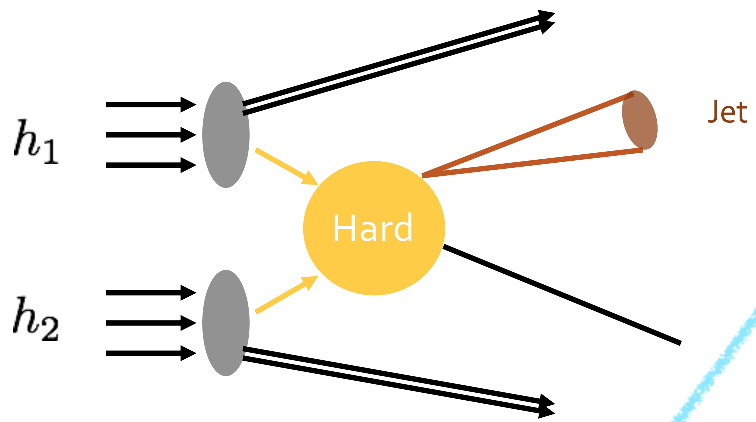
- **Suppression of b-dijets shows a completely different pattern. We see an enhanced sensitivity to the transport properties of the QGP (here captured by the coupling) and the mass of heay quarks (self-evident from the figures)**
- **Ideal measurement for the sPHENIX collaboration. Suppression of the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

# SCET approach to b-jet production

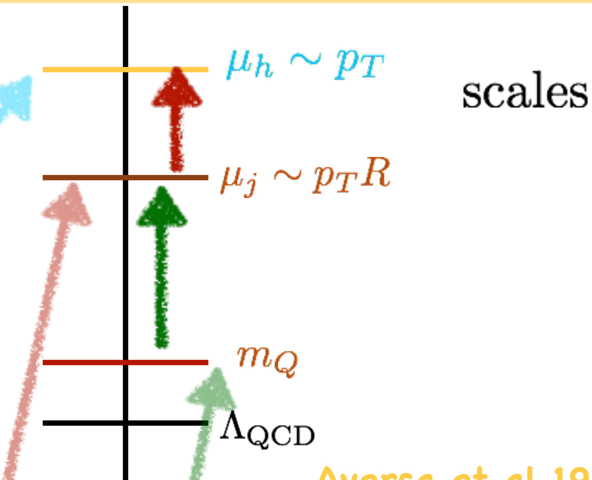


# Inclusive jet production

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




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




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

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

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

Semi-inclusive jet function

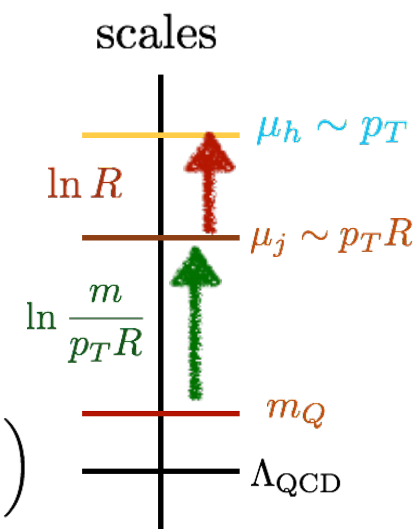
Hard scattering kernel

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 $\mu/p_T R$

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

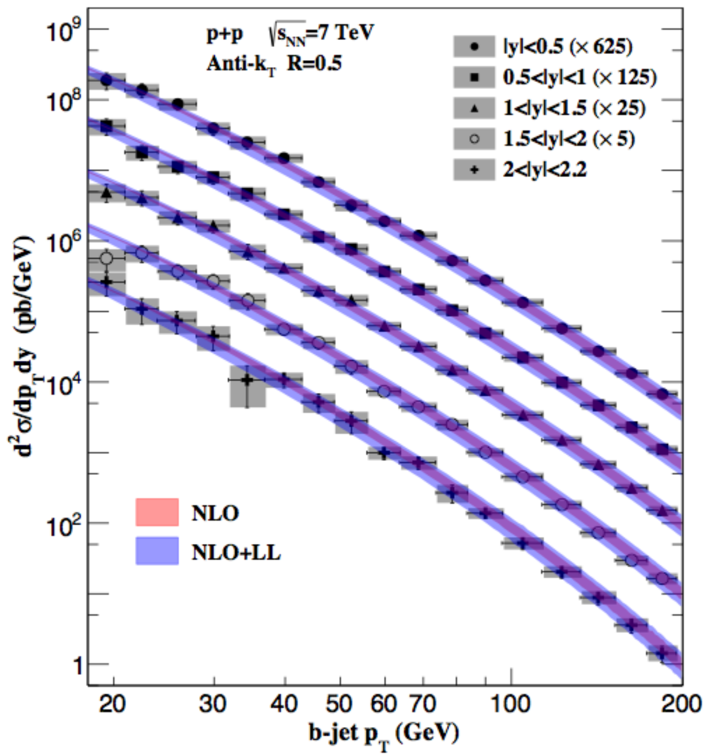
Resums ln $p_T R/m$

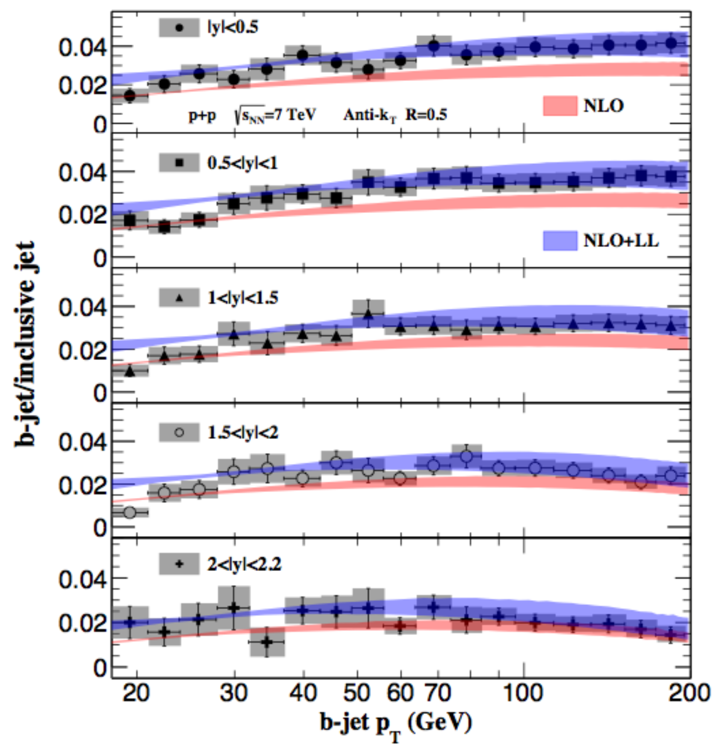
The integrated perturbative kernel at the jet typical scale

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 p+A collisions

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

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

Can be modified for nuclear collisions

The short-distance hard part remains the same

Not changed

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

**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**

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

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

# Corrections in A+A collisions

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

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

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

CNM effects

The short-distance hard part remains the same

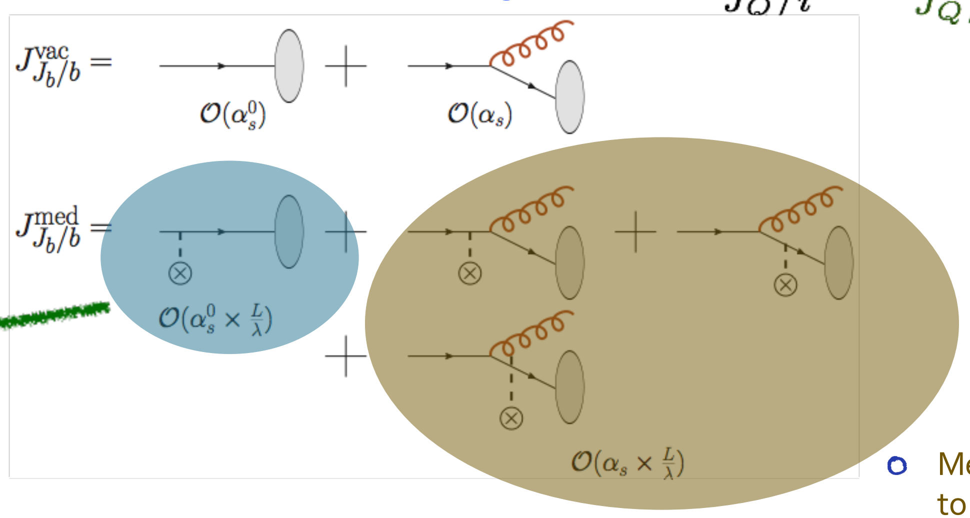
Encodes the effects when the jet evolving in the QCD medium

**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

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

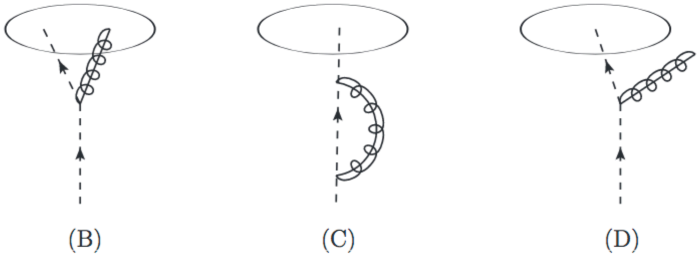
Medium corrections to the NLO jet function are written in terms of integrals over splitting functions. First developed for light jets.

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**

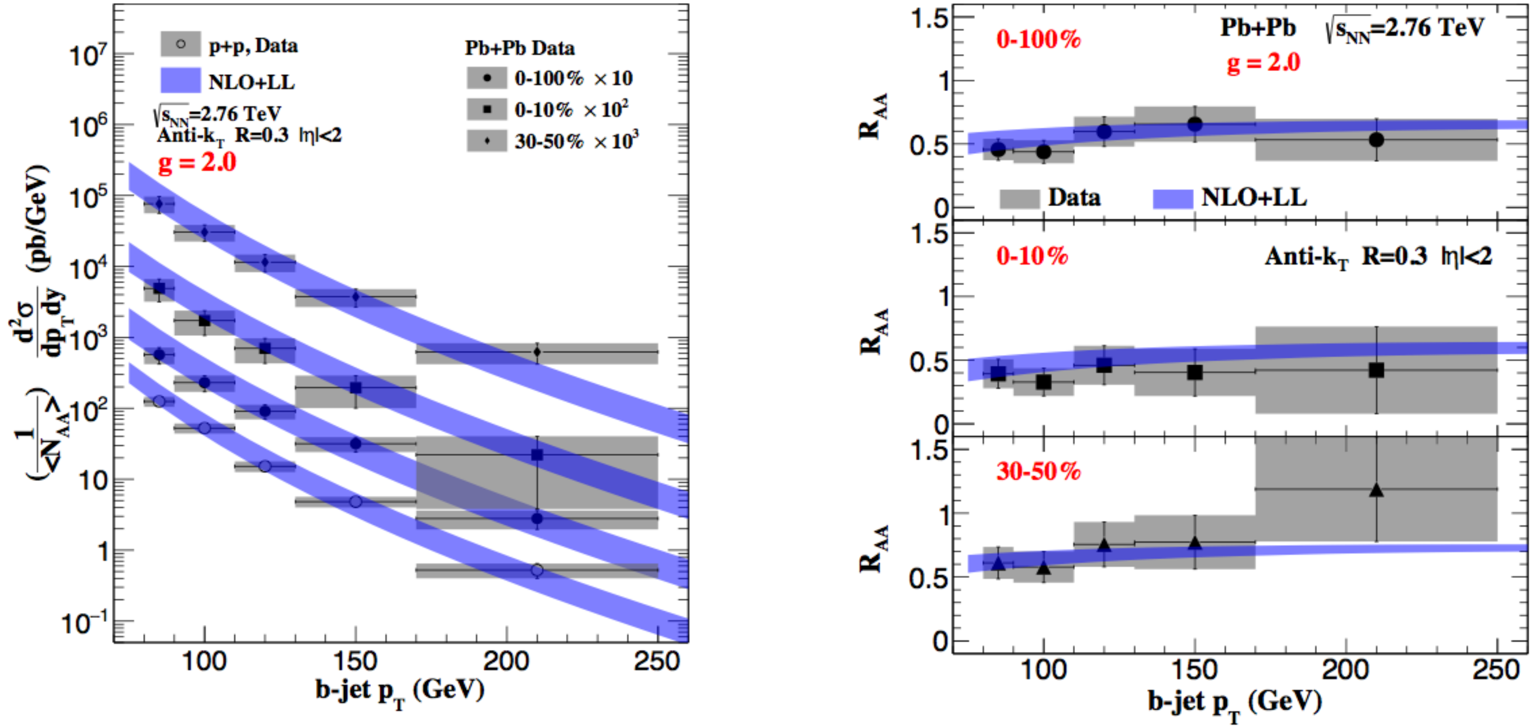
Haitao Li, Vitev, 2018

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

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

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

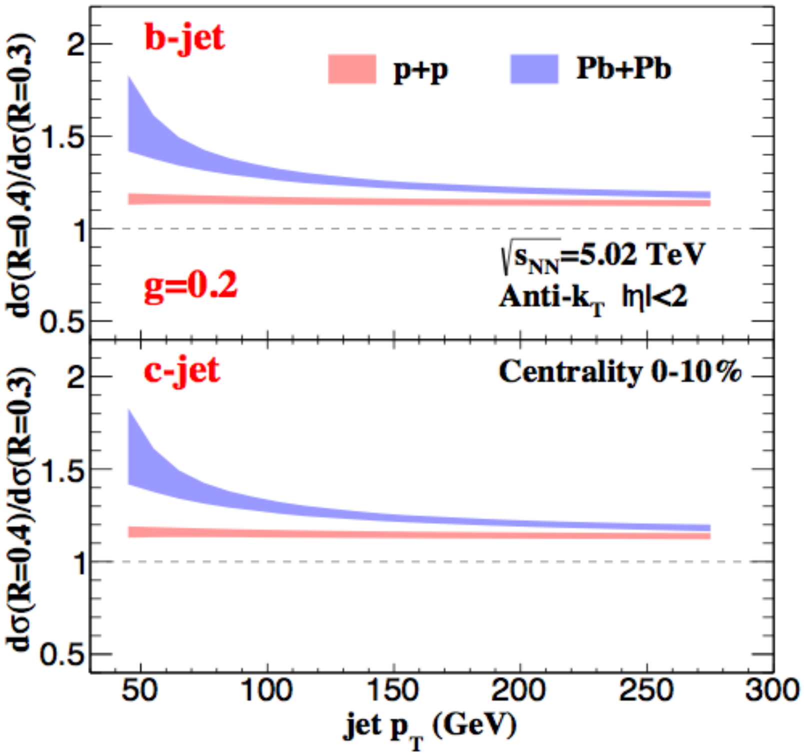
# B-jet production in A-A collisions

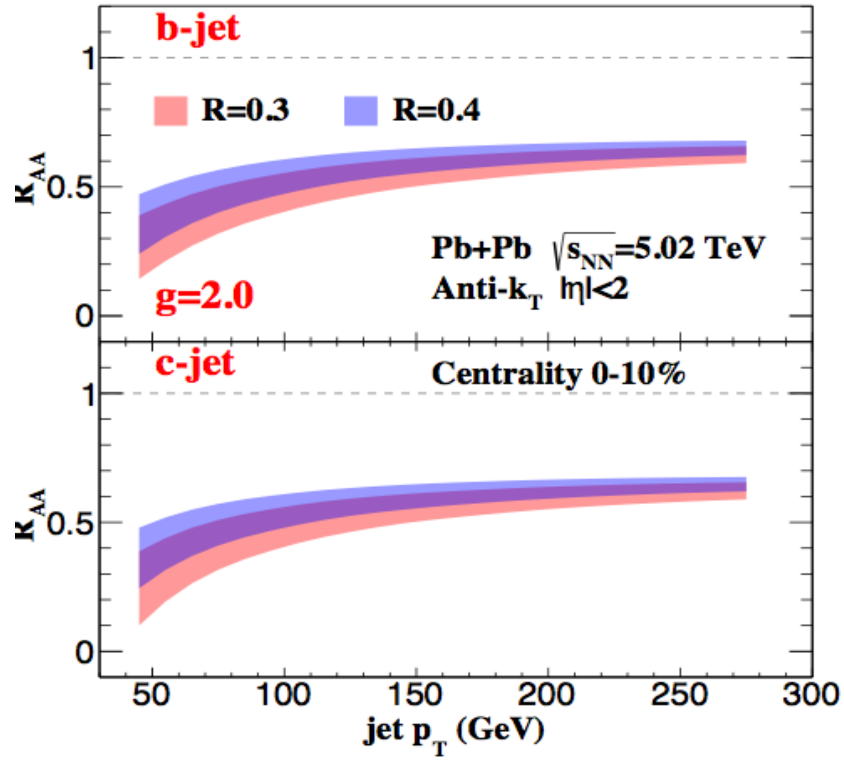



- Slightly less dependence on the centrality when compared to the well-known light jet modification
- Theoretical results agree well with the data for both the inclusive cross sections and the nuclear modification factors

**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

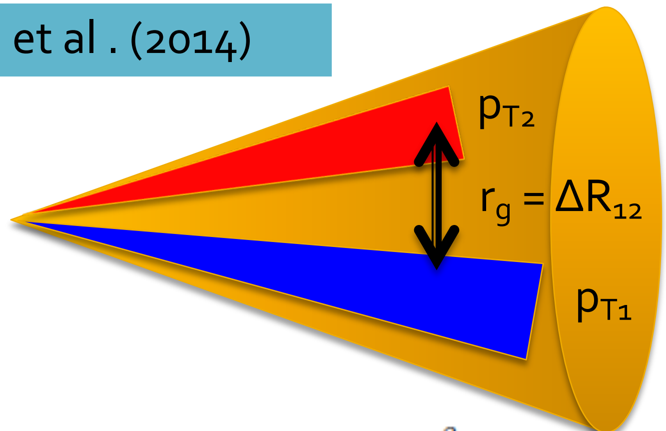
- The smaller radius jet tends to dissipate more energy in the medium
- No significant difference between the c-jet and b-jet due to the high transverse momentum

# Heavy flavor jet substructure

# Groomed soft dropped distributions in $SCET_G$

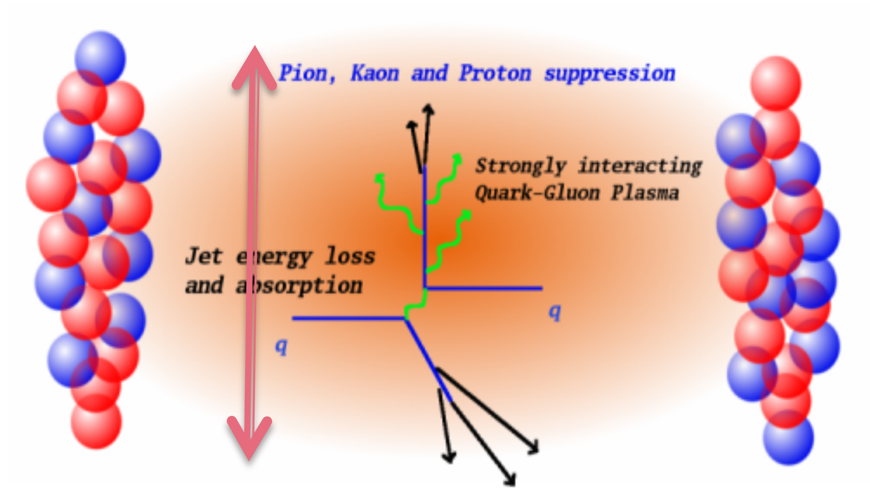
- Groomed jet distribution using "soft drop"

A. Larkoski et al . (2014)




$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\rm cut} \left( \frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

The great utility of these new distributions: probe the early time dynamics / splitting




QGP size ~ 10fm

$$\tau_{\rm br}[{\rm fm}] = \frac{0.197\ {\rm GeV\ fm}}{z_g(1 - z_g)\,\omega[{\rm GeV}]\,\tan^2(r_g/2)}$$

Typical situation: E=200 GeV, $r_g$ = 0.1

Branching time < 2 fm for $z_g$ studied

Y. T. Chien et al . (2016)

# Improvements beyond the fixed order

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

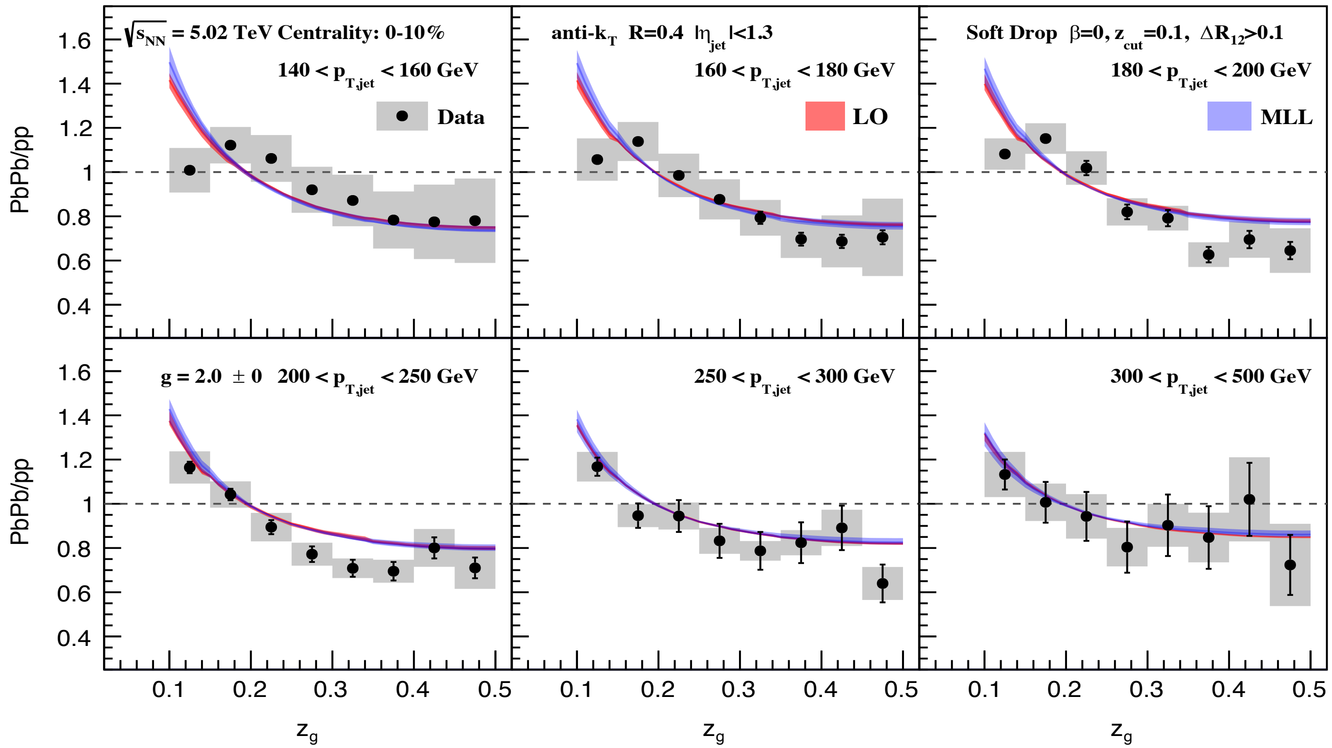
$$p(\theta_g, z_g)\Big|_j = \frac{\frac{dN_j^{\mathrm{vac,MLL}}}{dz_g d\theta_g}}{\int_0^1 d\theta \int_{z_{\mathrm{cut}}}^{1/2} dz \frac{dN_j^{\mathrm{vac,MLL}}}{dz d\theta}}$$

H. Li et al . (2017)

Joint probability distribution

Treat more generally the divergence at small theta

There is always a $z_g$ cut

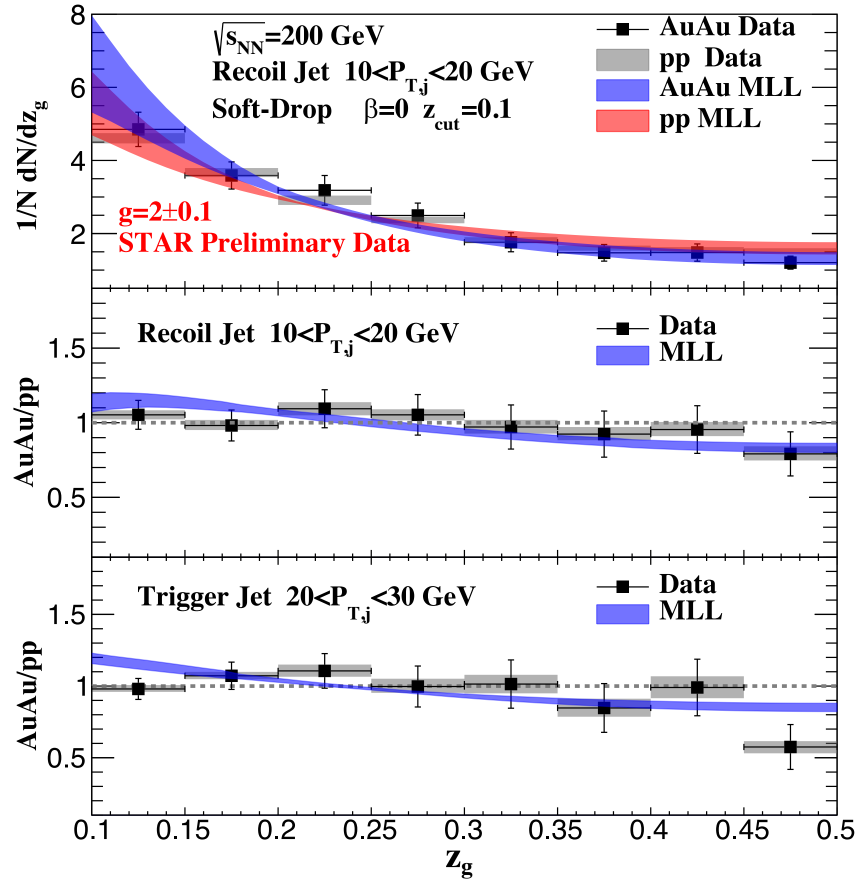


# Different center-of-mas energies

Results by STAR did appear somewhat surprising. Naively consistent with lack of modification (but also consistent with small modification)

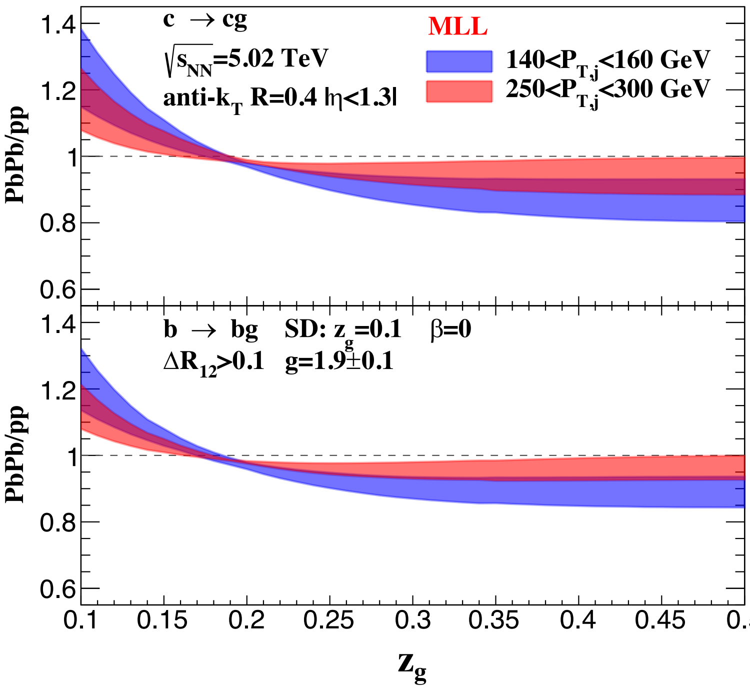
Did take into account different CM energy, geometric bias, centrality 0-20%

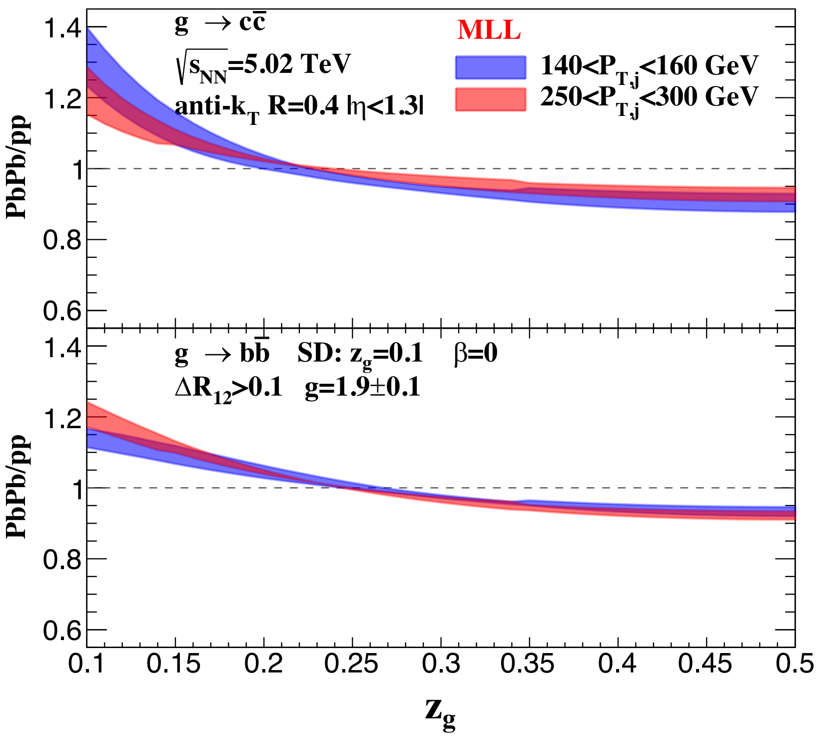
Find small modification but it is consistent with the data




H. Li et al . (2017)

# Heavy flavor splitting functions – single and double tagged



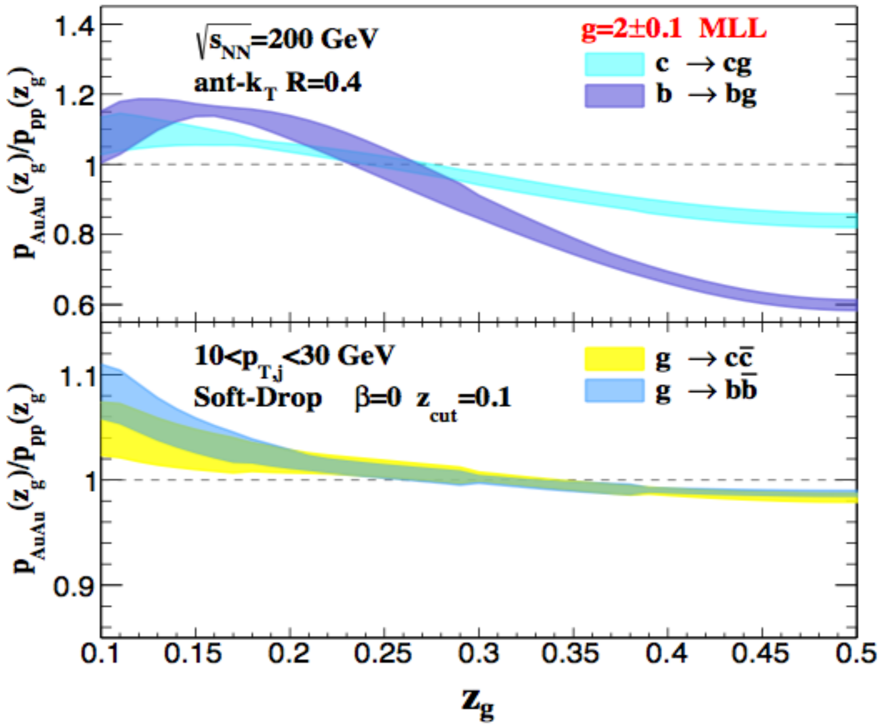




Shows slightly smaller modfication

And even smaller here

H. Li et al . (2016)

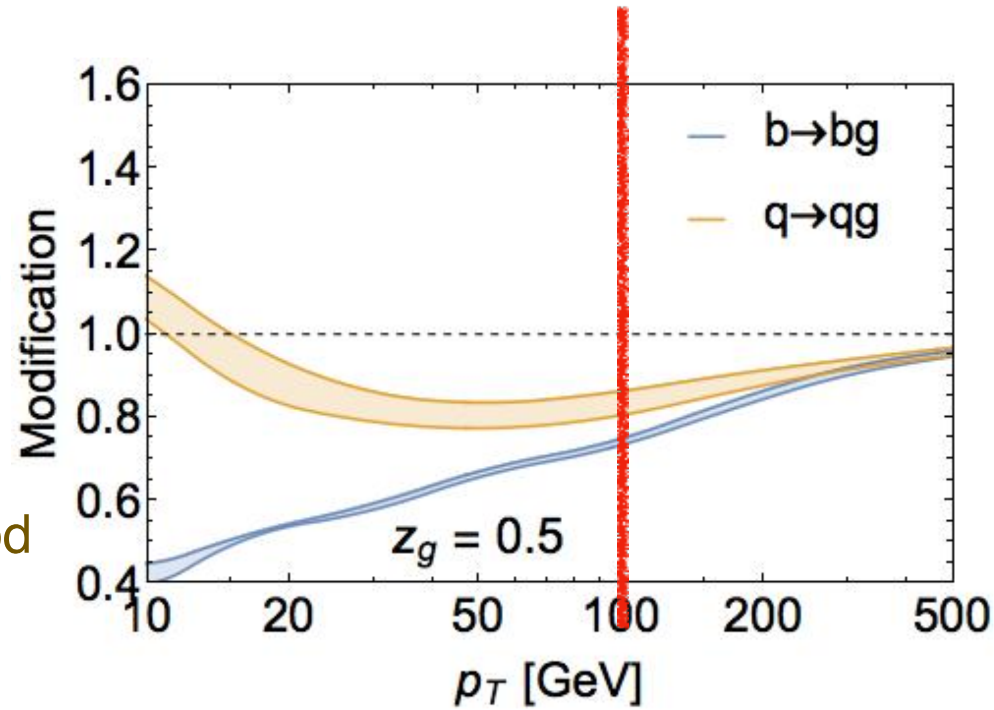
# Substructure




We can see the mass effects
even for the b-jet with $p_T$~50 GeV and a bit beyond.

$$\frac{p_{med}^{Q\to Qg}(z_g)}{p_{pp}^{Q\to Qg}(z_g)} \sim \frac{1}{z_g^2}, \quad \frac{p_{med}^{j\to i\bar{i}}(z_g)}{p_{pp}^{j\to i\bar{i}}(z_g)} \sim \frac{1}{z_g}, \quad \frac{p_{med}^{g\to Q\bar{Q}}(z_g)}{p_{pp}^{g\to Q\bar{Q}}(z_g)} \sim \text{const.}$$

**Regime** $k_T^2 < M_Q^2$




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

# Conclusions and outlook

- There is growing interest in heavy flavor jets in A A (also pp, pA) 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.

- 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
- $R_{AA}$ has somewhat smaller centrality dependence and R dependence for heavy flavor jets. Somewhat limited by the fixed order calculation for lower $p_T$
- Experimentally measure to higher and lower pT. Measure for different radii

- Further investigate heavy flavor-tagged jet substructure observables, Example is splitting functions. At relatively low transverse momenta – the effect of mass on in-medium showers
- Concentrate on kinematic domain where mass effects on the heavy flavor jet production and propagation in medium are important

# 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 (BAMPS)

## B-jet + photon (b hadron) production

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

Based on Monte Carlo Event Generators

## 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

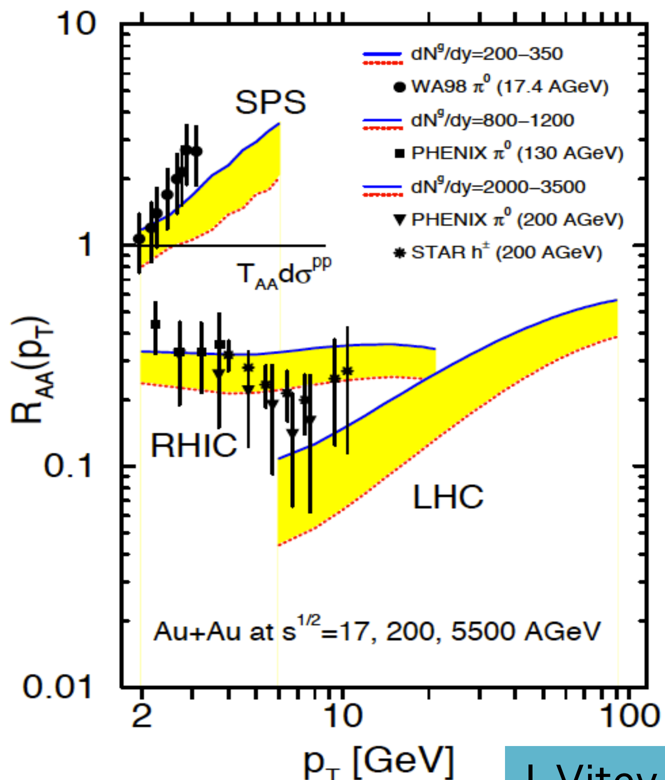
Haitao Li, Vitev, 2018 — soft-drop groomed momentum sharing distribution

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

$SCET_G$

# 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.



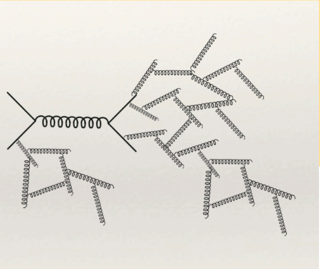

I. Vitev et al. (2002)

## Nuclear modification ratio

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

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

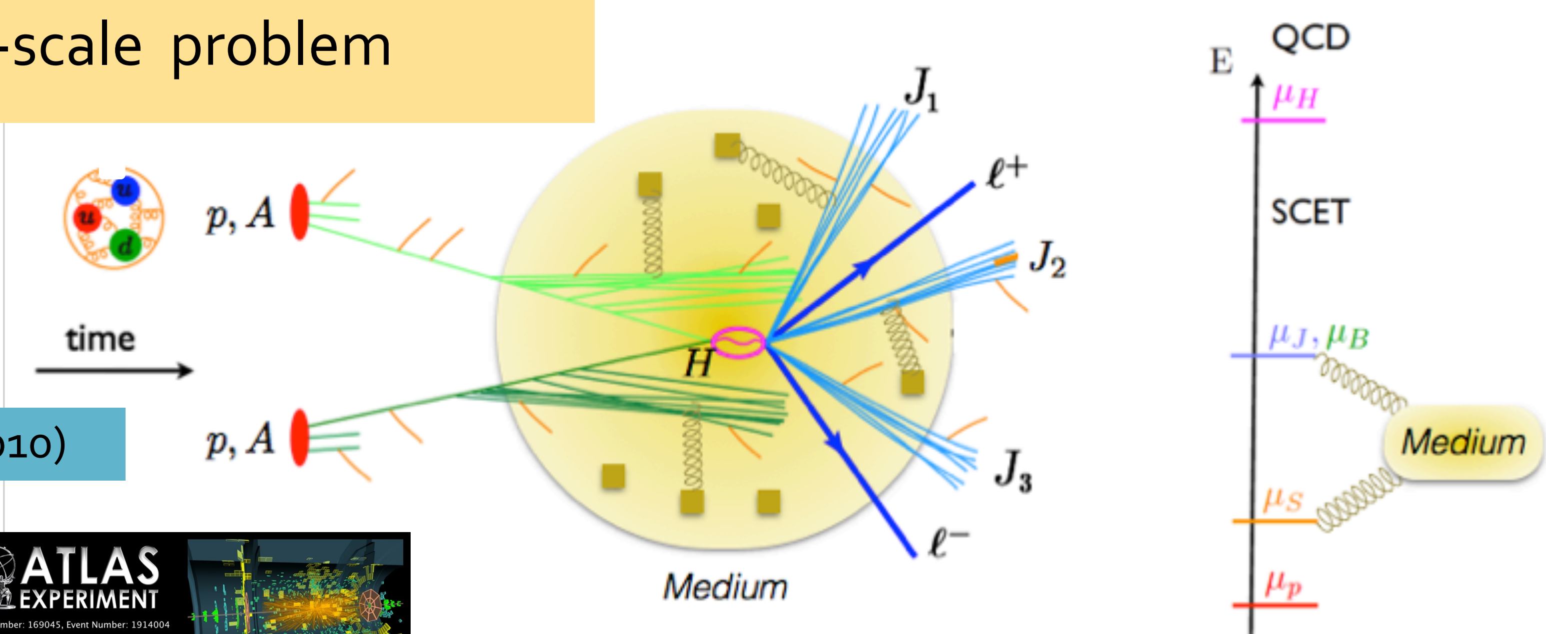
- Traditional non-Abelian energy loss has been refined. Difficult to make connection to the standard LO, NLO, …; LL, NLL … pQCD approach (higher orders and resummation)
- Bring some of the logs, legs and loops technology to HI



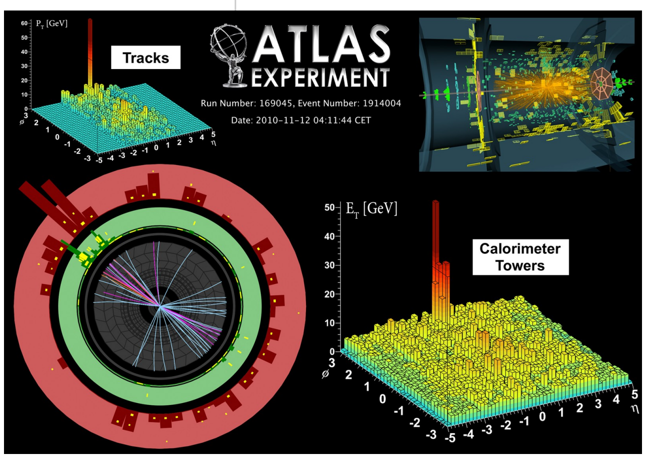
# The HIC picture for hard probes

- 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

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

# Heavy quarks in the vacuum and the medium

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

$$\mathcal{L}_{\rm QCD} = \bar{\psi}(i\not{D} - m)\psi \qquad iD^\mu = \partial^\mu + gA^\mu \qquad A^\mu = A_c^\mu + A_s^\mu + A_G^\mu$$

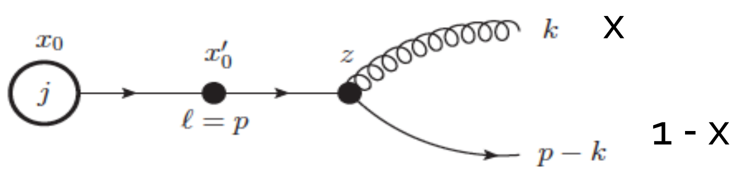
A. Leibovich et al. (2003)

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: $SCET_{M,G} = SCET_M \times SCET_G$**

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




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

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

G. Altarelli et al. (1977)

F. Ringer et al . (2016)