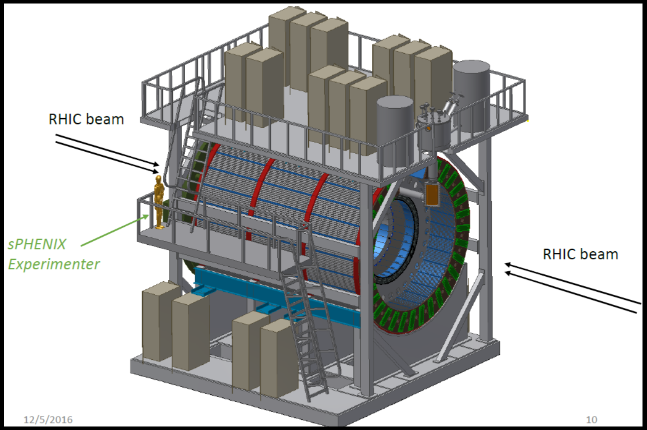
Light and heavy flavor probes of dense QCD matter at sPHENIX



Ivan Vitev

RBRC Workshop "Predictions for sPHENIX"
BNL, Upton, NY, July 20-22, 2022

Los Alamos NATIONAL LABORATORY EST. 1943

In place of introduction

One crisp New York morning in 1999 I walked to the Apple Tree Supermarket …

the village VOICE

THE WORLD ENDS HERE

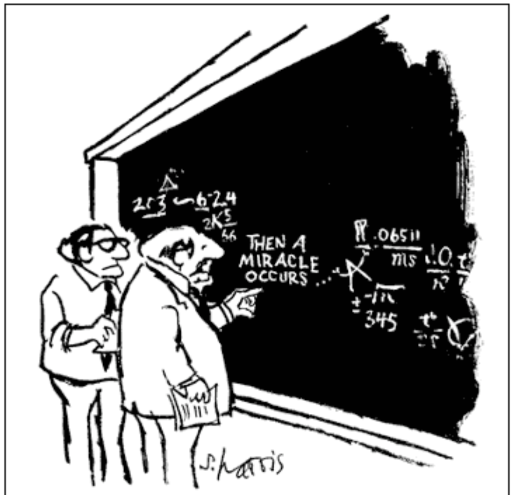
The world did not end in 2000 when RHIC started (around 1995 strangelets were all the rage)

However,

- The heavy ion program (at high energies) in the US is coming to an close
- It is important to maximize the scientific output of RHIC before the EIC phase transition
- sPHENIX and STAR will not exist in isolation, connection to LHC, transition to EIC

- QGP formation in small and large systems / hadron production
- Light flavor jets and jet correlations - photon tagged jets
- Heavy flavor jets, di jets, and jet substructure
- Conclusions

I. Hadron production and Large/Small systems



"I think you should be more explicit here in step two."

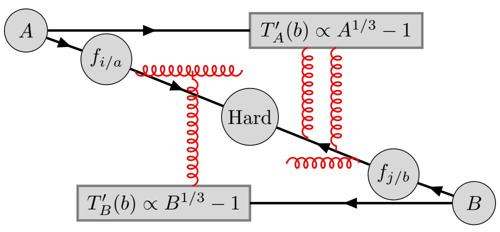
Production of light and heavy hadrons

QCD factorization approach is well established. Still large uncertainties remain related to non-perturbative physics / hadronization (fragmentation functions). This is especially true for heavy flavor

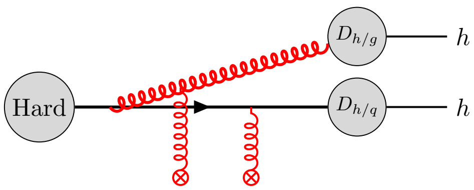
$$\frac{d\sigma^{H_1 H_2 \to hX}}{dp_T d\eta} = \frac{2p_T}{S} \sum_{abc} f_a^{H_1} \otimes f_b^{H_2} \otimes d\hat{\sigma}_{ab}^{c} \otimes D_c^h$$

Specific applications include LO, NLO, + resummation and parton showers. Also PYTHIA baseline (LO+PS)

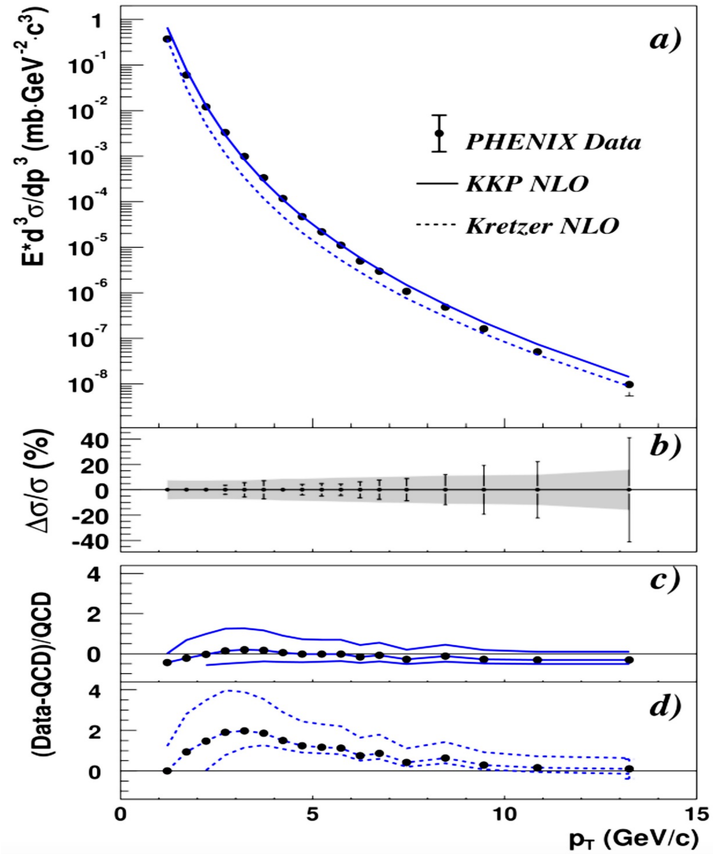
In the presence of nuclear matter – initial-state (CNM) and final-state (QGP effects)



Initial-state (IS)



Final-state (FS)



A. Adare et al. (2003)

Calculate those effects dynamically (vs parameterize them from data)

Cold nuclear matter effects

Process dependent corrections to QCD factorization

W. Kei et al. (2022)

Calculated corrections appear as kinematic modifications

$$\frac{d\sigma_k}{d\mathbf{q}^2 dy} = \frac{4}{s}\sum_{ij}\int d\eta_{\text{c.m.}} \int d^2\mathbf{k}_i f_{i/A}(x_i+\Delta x_i, \mathbf{k}_i; \mu_F)\int d^2\mathbf{k}_j f_{j/B}(x_j+\Delta x_j, \mathbf{k}_j; \mu_F) \times \frac{d\sigma_{ij\to k}}{d\cos\theta_{\text{c.m.}}}(x_i x_j s, \cos\theta_{\text{c.m.}}; \mu_R).$$

$$y = \frac{1}{2}\ln\frac{x_i}{x_j} + \eta_{\text{c.m.}}$$

$$\left[\mathbf{q}_T - \frac{\mathbf{k}_i+\mathbf{k}_j}{2}\right]^2 = \frac{x_i x_j s \sin^2\theta_{\text{c.m.}}}{4}.$$

- **Cronin effect (and of course isospin)** — M. Gyulassy et al. (2002)

$$g(\mathbf{k}) = \exp(-\mathbf{k}_T^2/\langle\mathbf{k}_T^2\rangle_{pp})/\pi\langle\mathbf{k}_T^2\rangle_{pp},$$

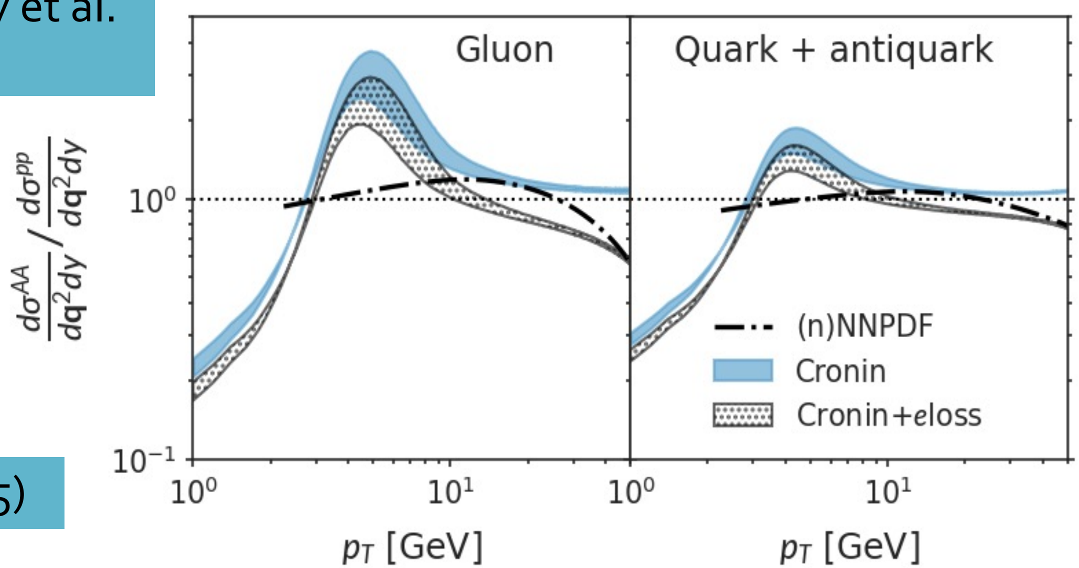
$$\langle k_T^2\rangle_{pA} \approx \langle k_T^2\rangle_{pp} + L_A\frac{\mu^2}{\lambda}\ln(1+c\,p_T^2/\mu^2)$$

- **CNM energy loss** — I.V. (2007)

$$\Delta x/x = \epsilon_{\text{fl}}\int_{m_N/p^+}^{1} dx \int_{x m_N \le |\mathbf{k}| \le x p^+} d^2\mathbf{k}\, x\frac{dN_{\text{IS}}}{dx d^2\mathbf{k}}.$$

- **Coherent power corrections** — J. Qiu et al. (2005)

$$\Delta x_i/x_i \sim \mu^2 A^{1/3}/(-u) \qquad \Delta x_j/x_j \sim \mu^2 B^{1/3}/(-t)$$



Parton level results at RHIC compared to nPDF parameterization

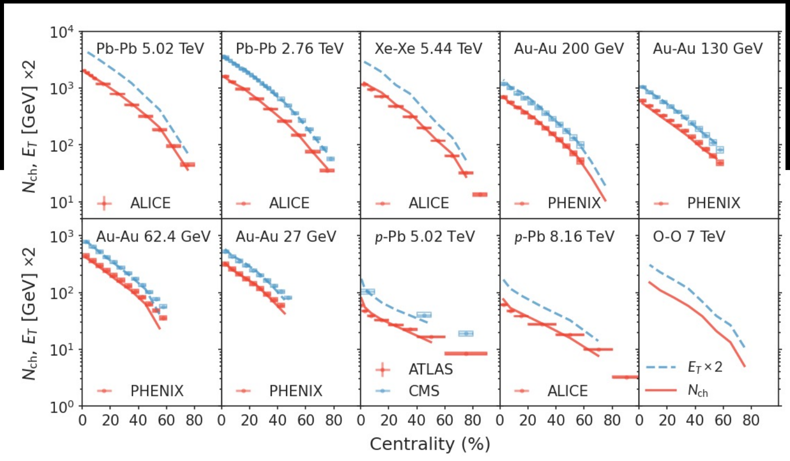
QGP effects

Final-state collisional and radiative processes

- **Collisional energy loss**

$$\frac{dE_{\rm el}}{d\Delta z} = \frac{C_F}{4}\left(1+\frac{N_f}{6}\right)\alpha_s(ET)g_s^2T^2\ln\left(\frac{ET}{m_D^2}\right)\left(\frac{1}{v}-\frac{1-v^2}{2v^2}\ln\frac{1+v}{1-v}\right)$$

- **In-medium splitting functions / radiative energy loss**



Hydro medium and TRENTO initial conditions

J. Bernhard (2018)

M. Sievert et al. (2019)

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

$$\omega_1=\frac{\mathbf{B}^2}{x(1-x)p^+},\quad \omega_2=\frac{\mathbf{C}^2}{x(1-x)p^+},$$
$$\omega_3=\frac{\mathbf{C}^2-\mathbf{B}^2}{x(1-x)p^+},\quad \omega_4=\frac{\mathbf{A}^2}{x(1-x)p^+},\quad \omega_5=\frac{\mathbf{A}^2-\mathbf{D}^2}{x(1-x)p^+}.$$

$$\frac{dN_{qq}^{\rm med}}{dxd\mathbf{k}^2} \equiv P_{qq}(x,\mathbf{k}^2)\int_0^\infty d\Delta z\int d^2\mathbf{q}\frac{dR_g(\Delta z)}{d^2\mathbf{q}}$$
$$\left\{\left[\frac{\mathbf{B}}{\mathbf{B}^2}\cdot\left(\frac{\mathbf{B}}{\mathbf{B}^2}-\frac{\mathbf{C}}{\mathbf{C}^2}\right)+\frac{1}{N_c^2}\frac{\mathbf{B}}{\mathbf{B}^2}\cdot\left(\frac{\mathbf{A}}{\mathbf{A}^2}-\frac{\mathbf{B}}{\mathbf{B}^2}\right)\right][1-\cos(\omega_1\Delta z)]\right.$$
$$+\frac{\mathbf{C}}{\mathbf{C}^2}\cdot\left(2\frac{\mathbf{C}}{\mathbf{C}^2}-\frac{\mathbf{A}}{\mathbf{A}^2}-\frac{\mathbf{B}}{\mathbf{B}^2}\right)[1-\cos(\omega_2\Delta z)]+\frac{\mathbf{B}}{\mathbf{B}^2}\cdot\frac{\mathbf{C}}{\mathbf{C}^2}[1-\cos(\omega_3\Delta z)]$$
$$\left.-\frac{\mathbf{A}}{\mathbf{A}^2}\cdot\left(\frac{\mathbf{A}}{\mathbf{A}^2}-\frac{\mathbf{D}}{\mathbf{D}^2}\right)[1-\cos(\omega_4\Delta z)]-\frac{\mathbf{A}}{\mathbf{A}^2}\cdot\frac{\mathbf{D}}{\mathbf{D}^2}[1-\cos(\omega_5\Delta z)]\right\},$$

Also evaluated branching for heavy flavor and the energy loss limit

System size dependence (expanding QGP)

$$\frac{\Delta E_{\rm el}}{E}\propto\int_{\tau_0}^{\tau_0+L}\mu^2 d\Delta z\propto L^{1/3}\qquad \frac{\Delta E_{\rm rad}}{E}\propto\int_{\tau_0}^{\tau_0+L}\frac{\mu^2}{\lambda_g}\Delta z d\Delta z\propto L$$

Much weaker path length dependence of collisional vs radiative E-loss. Implies increased importance in small systems

Light and heavy flavor fragmentation and evolution

Light – DSS, heavy - Lund-Bowers

$$D(z) = z^{-1-bM_\perp^2}(1-z)^a e^{-\frac{bM_\perp^2}{z}}$$

M. Bowers (1981)

$$\frac{\partial D^0_{h/i}(z,Q^2)}{\partial \ln Q^2} = \sum_j \int_z^1 \frac{dx}{x}\left[P'_{ji}(x\to 1-x,Q^2) + d_{ji}(Q^2)\delta(1-x)\right] D_{h/j}\left(\frac{z}{x},Q^2\right)$$

In-medium evolution

$$d_{qq}(Q^2) = \frac{\alpha_s(Q^2)}{2\pi} C_F \frac{3}{2},$$

$$d_{HH}(Q^2,r) = \frac{\alpha_s(Q^2)}{2\pi} C_F c_{HH}(r),$$

$$d_{gg}(Q^2,r) = \frac{\alpha_s(Q^2)}{2\pi}\left[\frac{11}{6}N_c - N_f T_F \frac{2}{3} + \sum_{H=c,b} T_F c_{gH}(r)\right]$$

Heavy flavor specific $r = M/Q$

$$c_{gH}(r) = F\left(\frac{1+\sqrt{1-4r^2}}{2}\right) - F\left(\frac{1-\sqrt{1-4r^2}}{2}\right) - 2r^2\sqrt{1-4r^2},$$

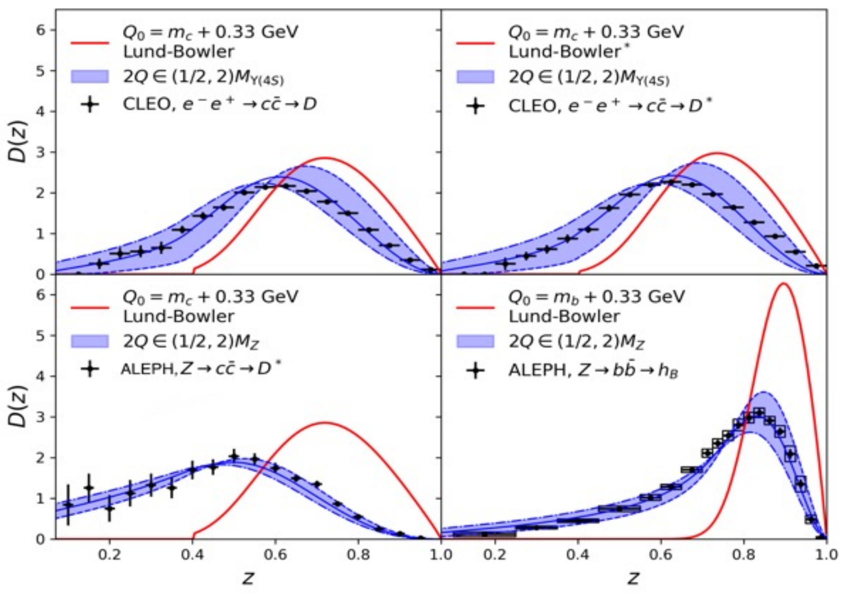
$$F(x) = -x^4 + \frac{4}{3}x^3 - x^2,$$

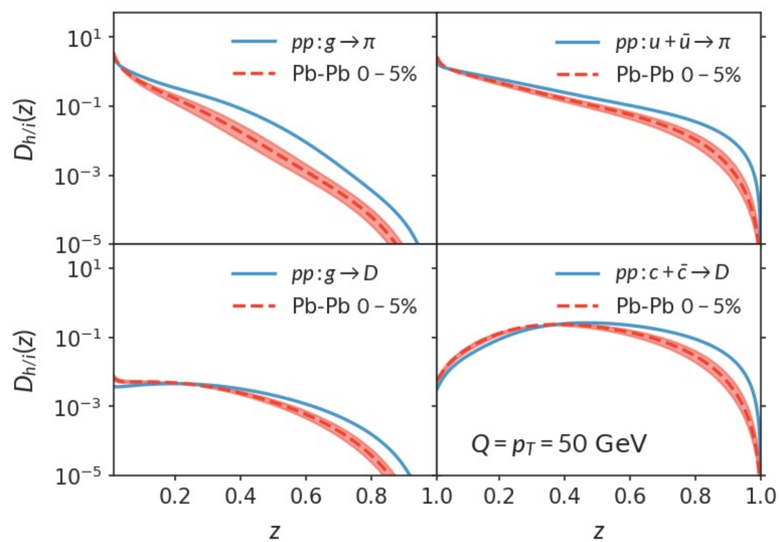
$$c_{HH}(r) = \frac{1}{1+r^2} + \frac{2r^2+1}{2(1+r^2)^2} + \frac{2r^2}{1+r^2} - 2\ln\frac{1}{1+r^2}.$$

Additional medium-induced scaling violations

$$P'_{ji} \to P'_{ji} + \mathbf{k}^2 \frac{dN^{\text{med}\,\prime}_{ji}}{\ldots} \quad \text{with } x \to 1-x,$$

$$d_{ji}(Q^2) \to d_{ji}(Q^2) + d^{\text{med}}_{ji}(Q^2)$$





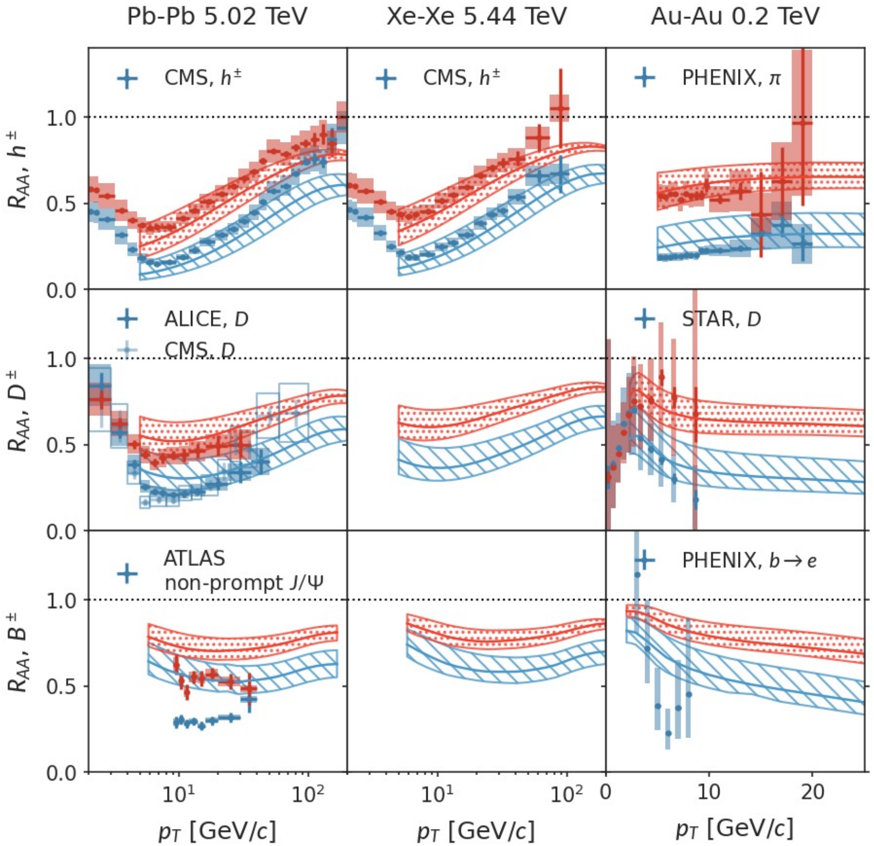
Phenomenological results

Large systems

Radiative processes dominate

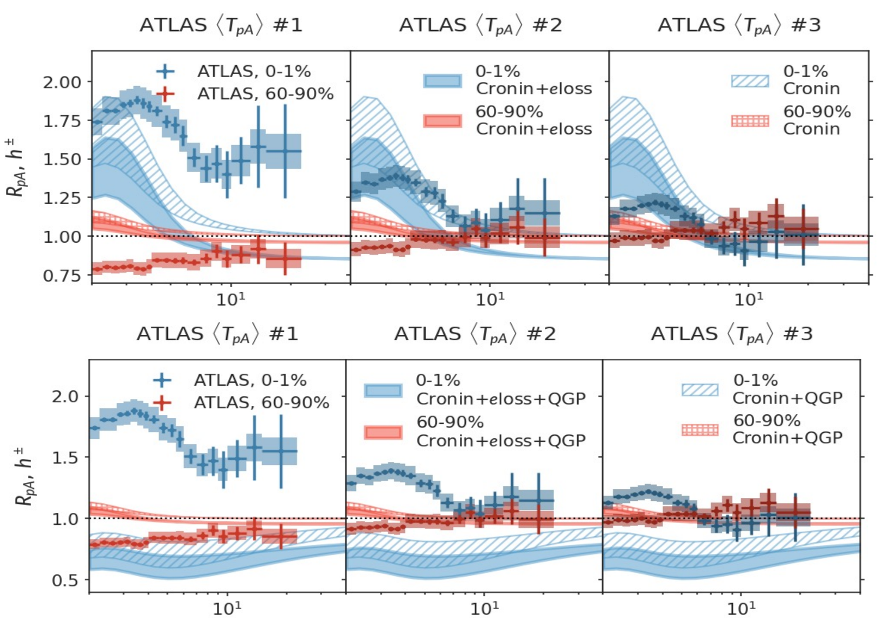
Theoretical results agree with existing light hadron and D meson measurements at RHIC and LHC. True for both central and peripheral collisions

There is tension with the B meson production (or non-prompt J/psi). May be dissociation?



W. Ke et al. (2022)

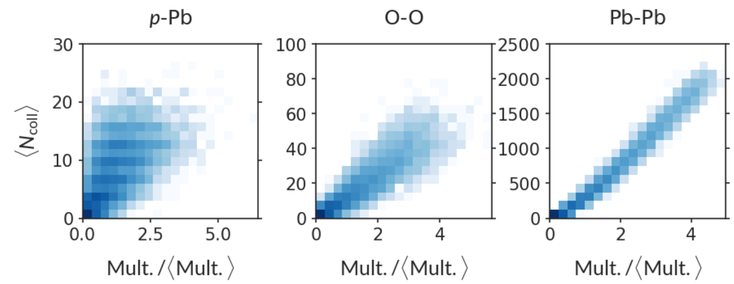
Small systems



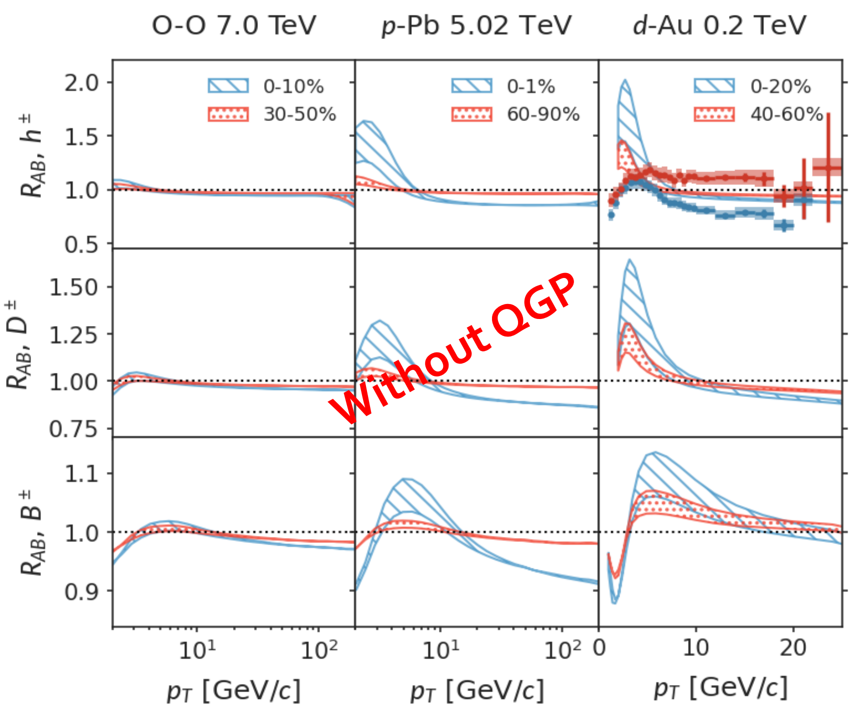
Centrality determination in p/d+A challenging.
No room for quenching effects in p+Pb

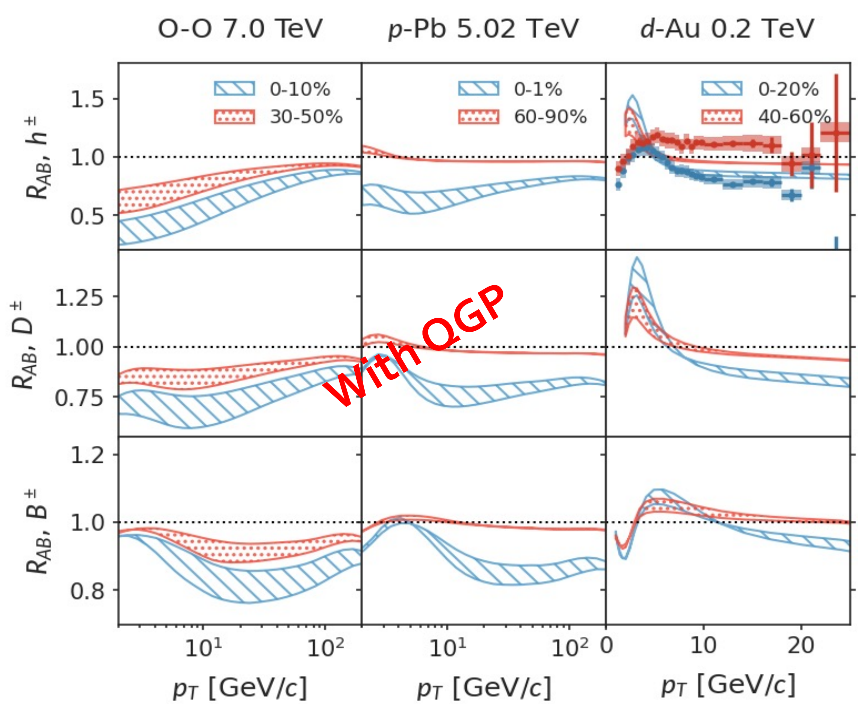
QGP in small systems?

Correlation between multiplicity and number of collisions can be vastly improved in collisions of small nuclei (such as O+O). If there is even a small chance, it should be considered at RHIC.

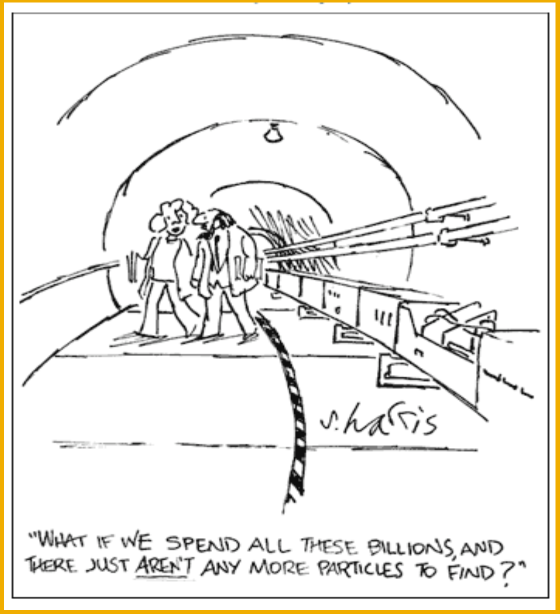


From jet quenching perspective whether QGP is produced or not can be easily distinguished in small systems (assuming good determination of centrality)



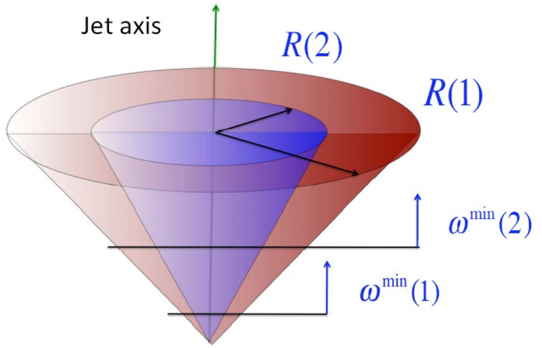


II. Inclusive jet production, correlations and substructure



Jets – the next step in understanding the QCD with nuclei

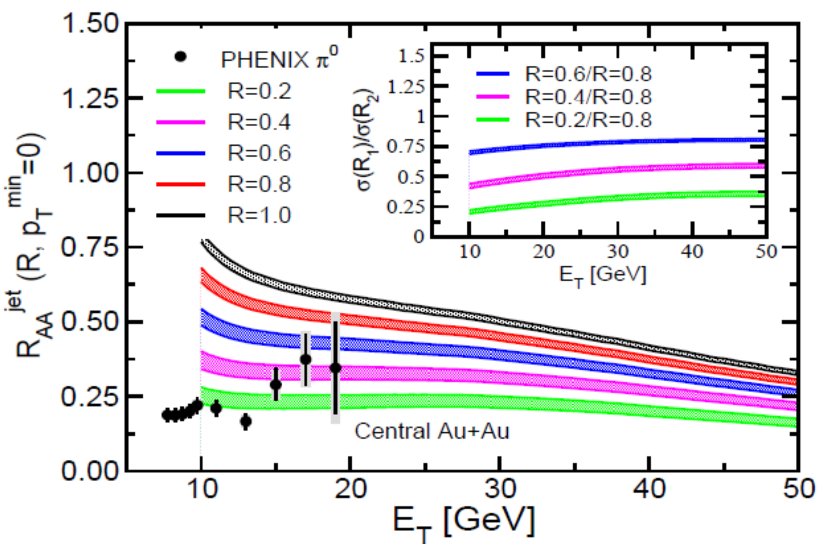
- One can leverage the differences between the vacuum parton showers and the medium-induced showers to predict jets to experimental signatures of parton interaction in matter



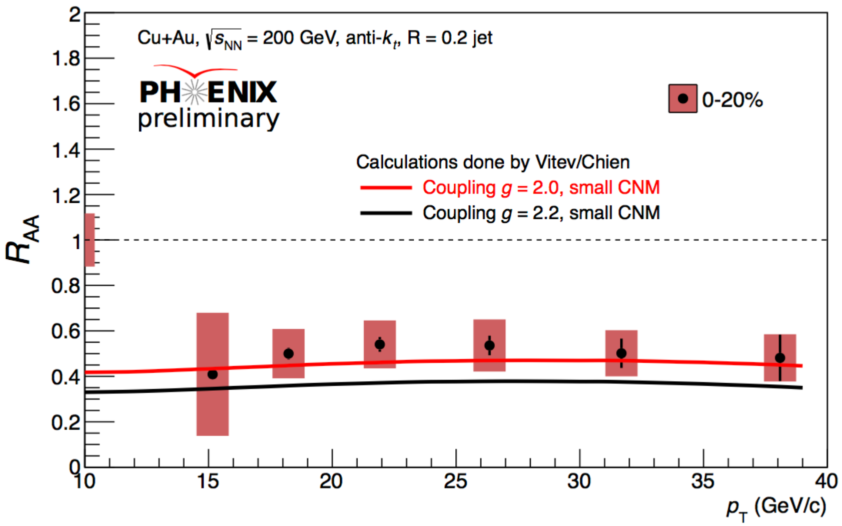
$$|J_i(\epsilon_i)| = 1/\left(1 - [1 - f(R_i, p_{T\,i}^{\min})_{q,g}]\epsilon_i\right)$$

$$\frac{\sigma^{AA}(R,\omega^{\min})}{d^2E_T dy} = \int_{\epsilon=0}^{1} d\epsilon \sum_{q,g} P_{q,g}(\epsilon) \frac{1}{(1-(1-f_{q,g})\cdot\epsilon)^2} \frac{\sigma_{q,g}^{NN}(R,\omega^{\min})}{d^2E'_T dy}$$

Y. Chien et al. (2015)



I. V. et al. (2009)



Rather flat inclusive jet suppression and distinct radius dependence

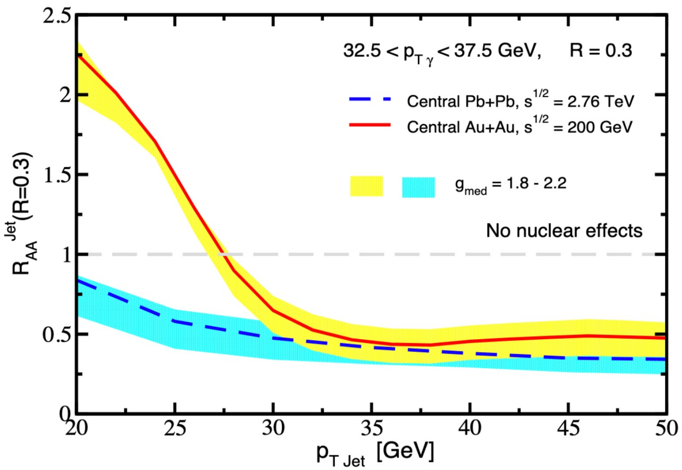
Jet radius dependence of observables and gamma tagging

Predicted in 2009, there are still no conclusive measurements for inclusive jets at RHIC. This brings us to photon-tagged jets

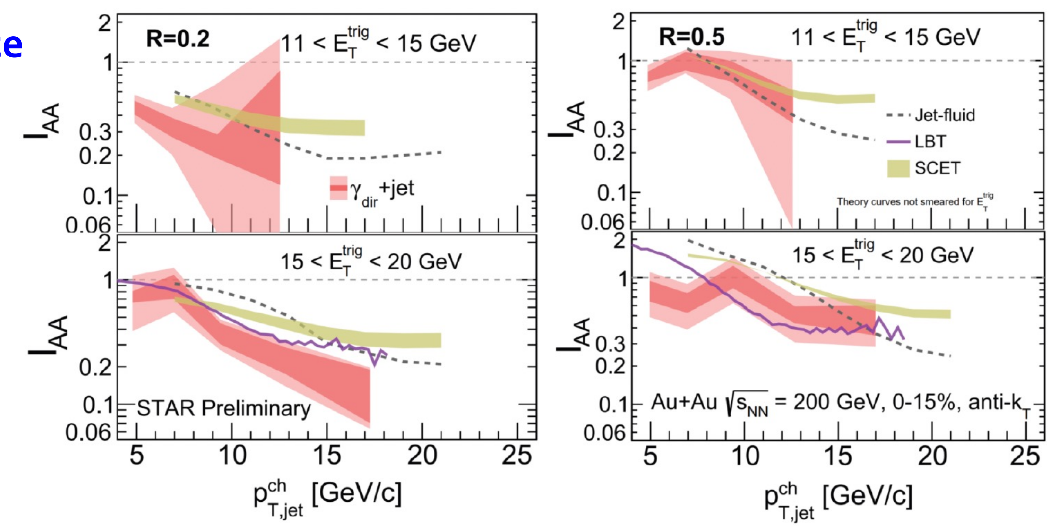
Similar physics, different flavor composition and underlying cross section

$$\frac{1}{\langle N_{bin}\rangle}\frac{d\sigma^{AA}}{dp_{T_\gamma}dp_{T_{\rm jet}}} = \sum_{q,g}\int_0^1 d\epsilon \frac{P_{q,g}(\epsilon)}{1-[1-f(R)]\epsilon} \times R_{q,g}\,\frac{d\sigma^{CNM}\left(p_{T_\gamma}, \frac{p_{T_{\rm jet}}}{1-[1-f(R)]\epsilon}\right)}{dp_{T_\gamma}dp_{T_{\rm jet}}}\,.$$

- **Gamma-jets give cleaner constraints on the E-loss of jets**
- **Transition from enhancement to suppression or different p_T dependence**



W. Dai et al. (2012)



STAR / N. Shahoo. et al. (2022)

Indication of different shape and of R dependence

Gamma-jet momentum imbalance

While we now have photon/pion tagged jet I_{AA}s, the momentum imbalance at RHIC has not been measured even in preliminary form – an area where sPHENIX can gave an impact

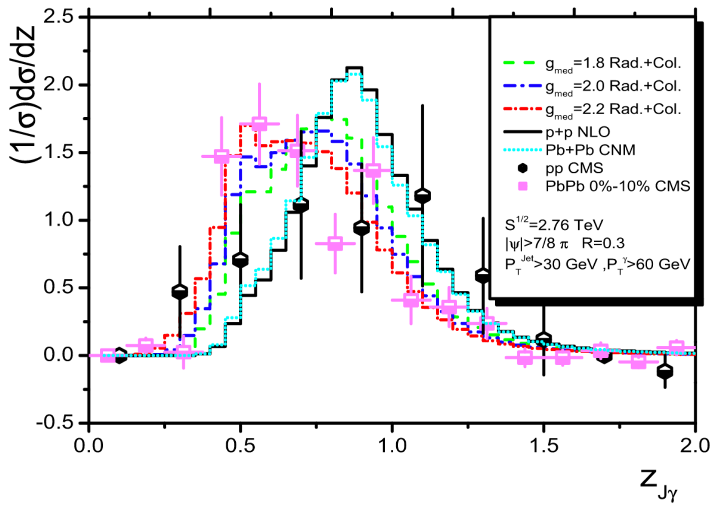
- **Define average momentum imbalance and direct constraints in energy loss**

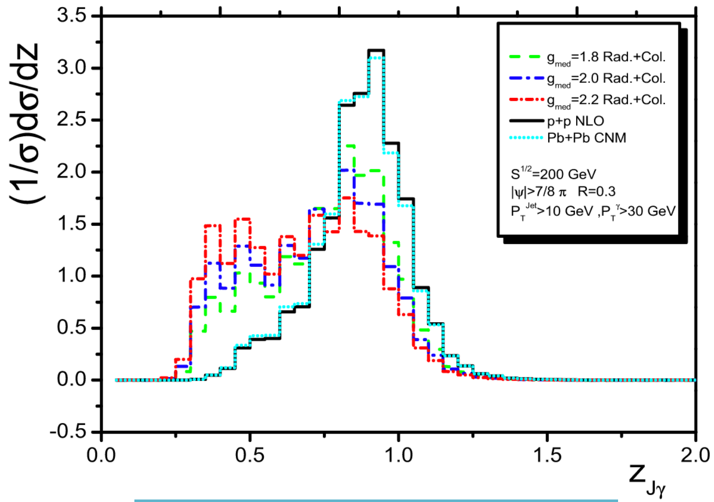
$$\frac{d\sigma}{dz_{J\gamma}} = \int_{p_{T_{\rm jet}}^{min}}^{p_{T_{\rm jet}}^{max}} dp_{T_{\rm jet}} \frac{p_{T_{\rm jet}}}{z_{J\gamma}^2} \frac{d\sigma[z_{J\gamma}, p_{T_\gamma}(z_{J\gamma}, p_{T_{\rm jet}})]}{dp_{T_\gamma} dp_{T_{\rm jet}}}$$

- **Define average momentum imbalance and direct constraints in energy loss**

$$\langle z_{J\gamma} \rangle = \int dz_{J\gamma} z_{J\gamma} \frac{1}{\sigma} \frac{d\sigma}{dz_{J\gamma}}$$

System	$\langle z_{J\gamma}\rangle_{\rm LHC}$	$\langle z_{J\gamma}\rangle_{\rm RHIC}$
p+p	0.94	0.90
A+A, CNM	0.94	0.89
A+A, $g_{med} = 1.8$,Rad.+Col	0.84	0.78
A+A, $g_{med} = 2.0$,Rad.+Col	0.80	0.74
A+A, $g_{med} = 2.2$,Rad.+Col	0.71	0.70



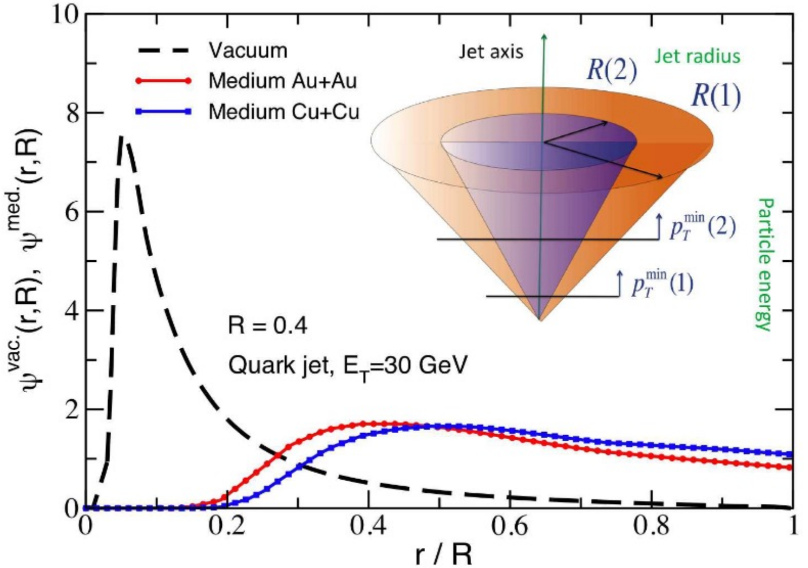


W. Dai et al. (2012)

Light jet substructure – jet shape and width

Jet shape – most closely related to the jet cross sections

$$\psi_{\rm tot.}(r/R) = \frac{1}{\rm Norm}\int_{\epsilon=0}^{1} d\epsilon \sum_{q,g} P_{q,g}(\epsilon)\frac{1}{(1-(1-f_{q,g})\cdot\epsilon)^3} \times \frac{\sigma_{q,g}^{NN}(R,\omega^{\rm min})}{d^2E_T' dy}\left[(1-\epsilon)\,\psi_{\rm vac.}^{q,g}(r/R) + f_{q,g}\cdot\epsilon\,\psi_{\rm med.}^{q,g}(r/R)\right]$$



We can define an observable that characterizes the mean width of the energy flow

Note that the vacuum + medium distributions are not combined yet in the figure

$$\langle r/R\rangle = \int_0^1 d(r/R)(r/R)\psi\,(r/R)$$

$$\Delta\langle r/R\rangle = (\langle r/R\rangle_{\rm tot.} - \langle r/R\rangle_{\rm vac.})/\langle r/R\rangle_{\rm v}$$

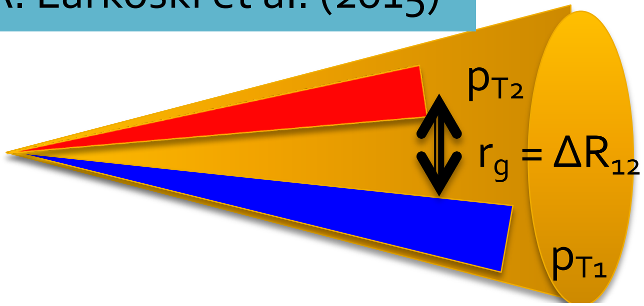
I.V et al (2009)

$\langle r/R\rangle$	Vacuum	Medium	Total	Δ
Au+Au	0.271	0.601	0.283	4%
Cu+Cu	0.271	0.640	0.272	0.4%

Observables that characterize mean intra-jet properties are modified very little. Larger modification can be seen in the periphery of energy and particle flow distributions

Light jet substructure – jet splitting functions

A. Larkoski et al. (2015)



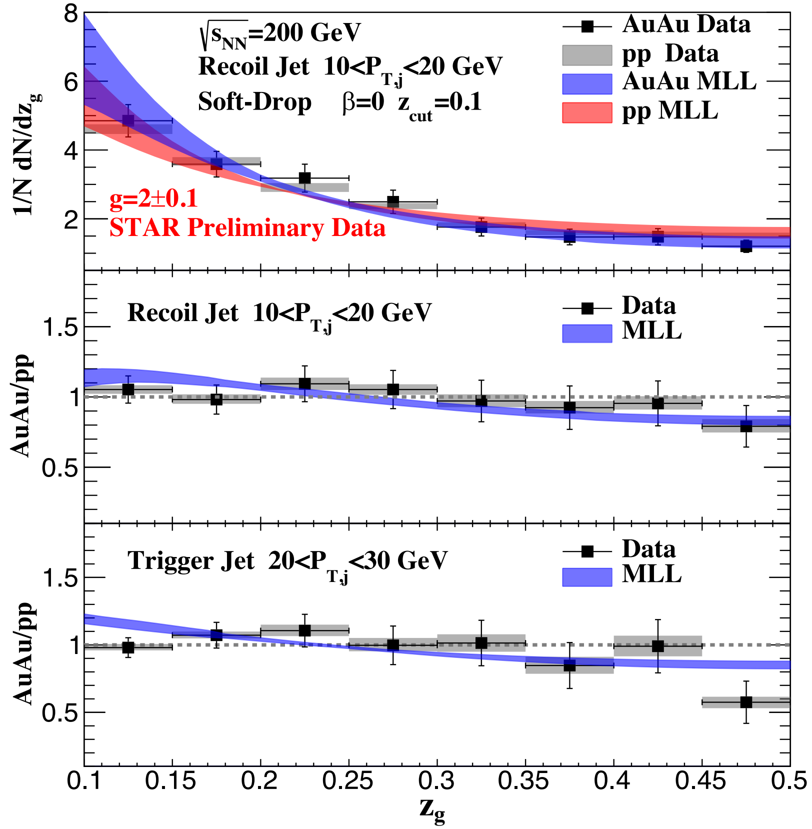
$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

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

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

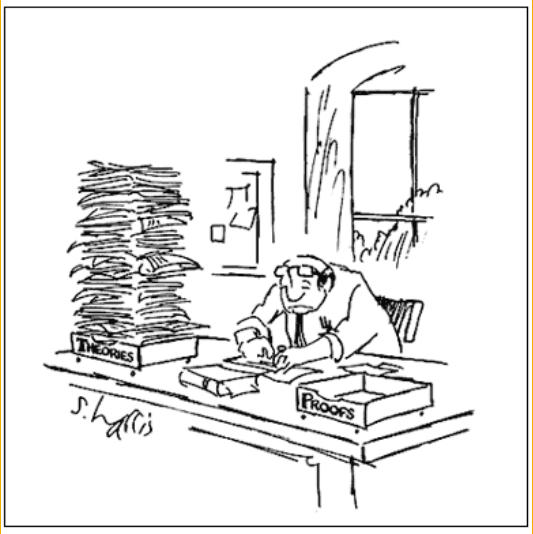
We find only small modification

Groomed, soft dropped momentum sharing distributions - directly proportional to the splitting functions, + resummation for small angles



H. Li et al . (2018)

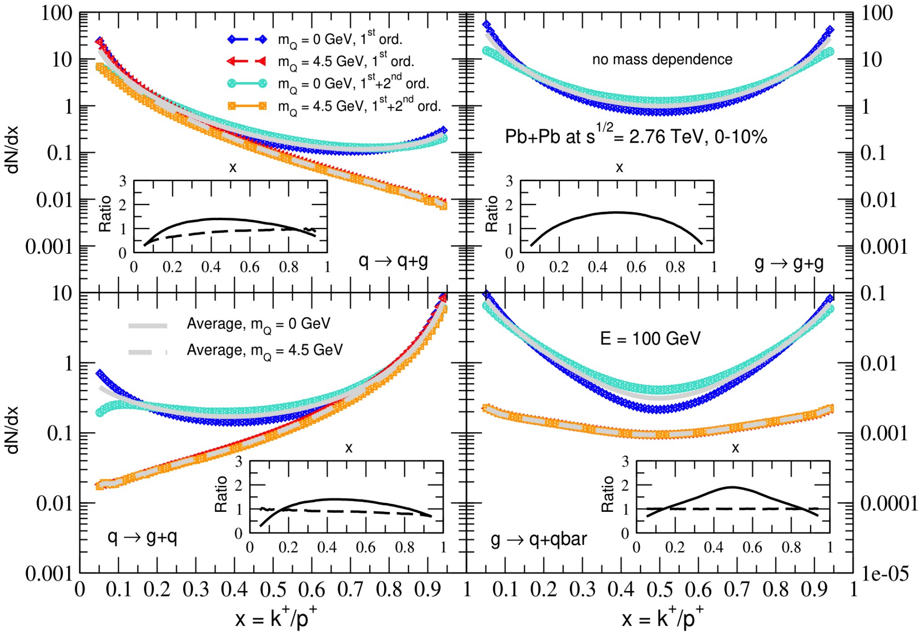
III. Heavy flavor jets, dijet mass, and substructure

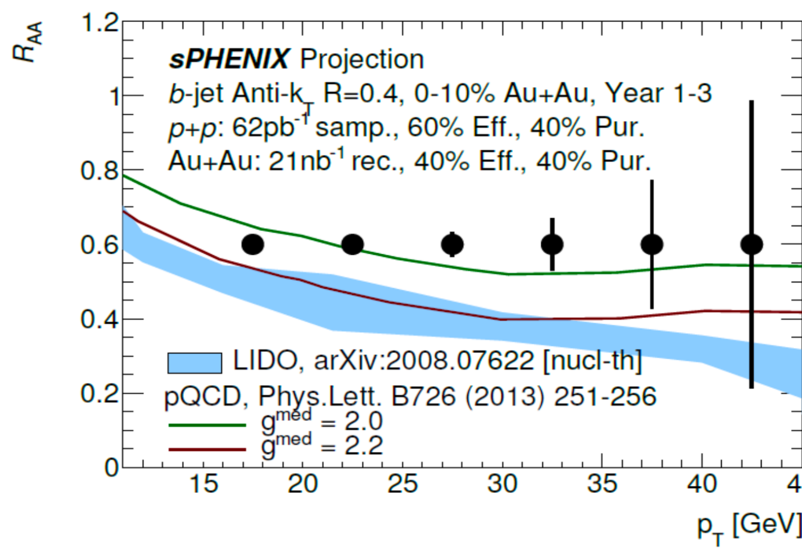


Differential branching distributions for heavy quarks

- There are significant differences due to the **heavy quark mass** between massless and massive splitting functions
- Higher orders in opacity **have minimal effect on heavy flavor splitting**
- **Different dead cone effect for different splittings**

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



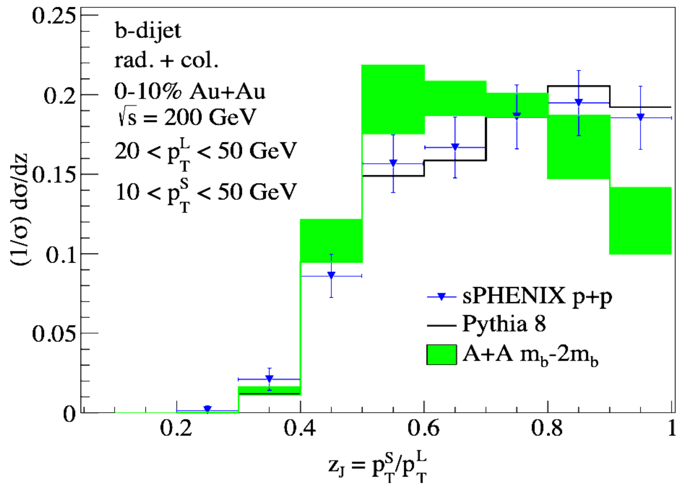


Enhancing the heavy quark mass effect

Z. Shi et al. / sPHENIX (2021)

- We can look at the di b-jets and their momentum imbalance but it is relatively small

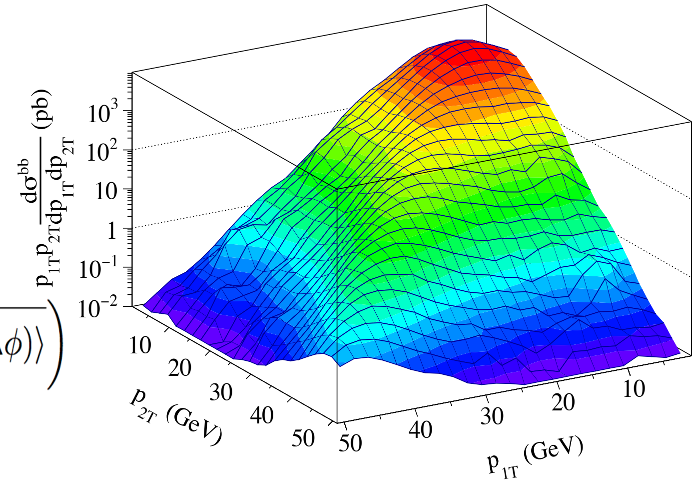
Kinematics	dijet flavor	$\langle z_J \rangle_{pp}$	$\langle z_J \rangle_{AA}$	$\Delta\langle z_J \rangle$
CMS [25]	b-tagged	0.661 ± 0.003	0.601 ± 0.023	0.060 ± 0.025
Experiment	inclusive	0.669 ± 0.002	0.617 ± 0.027	0.052 ± 0.024
LHC	b-tagged	0.685	0.626 ± 0.013	0.059 ± 0.013
theory	inclusive	0.701	0.605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



Quantitative differences quite small (we react to differences in shape)

- Examine instead the dijet mass, where effects are additive

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



Individual mass modification is negligible, no change

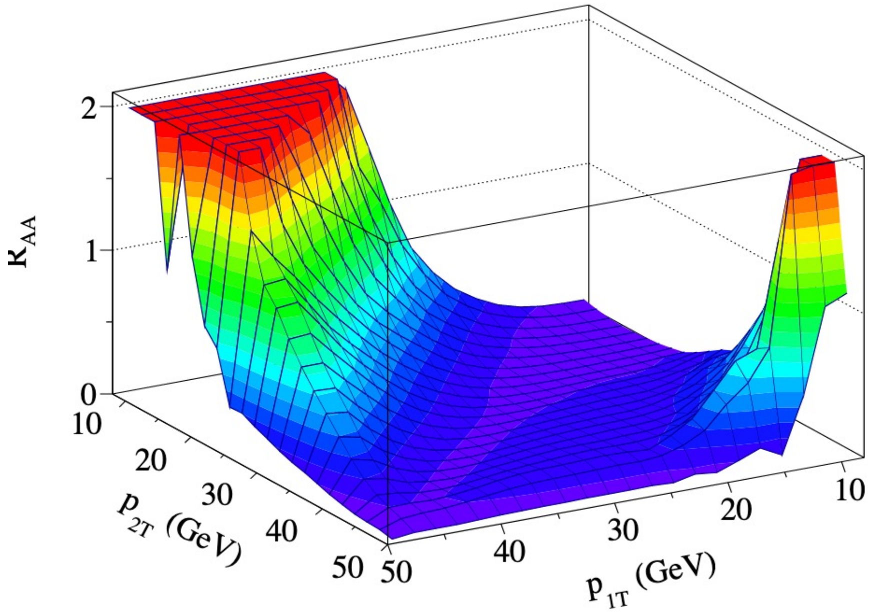
Z. Kang et al . (2018)

Di b-jet distribution in PYTHIA

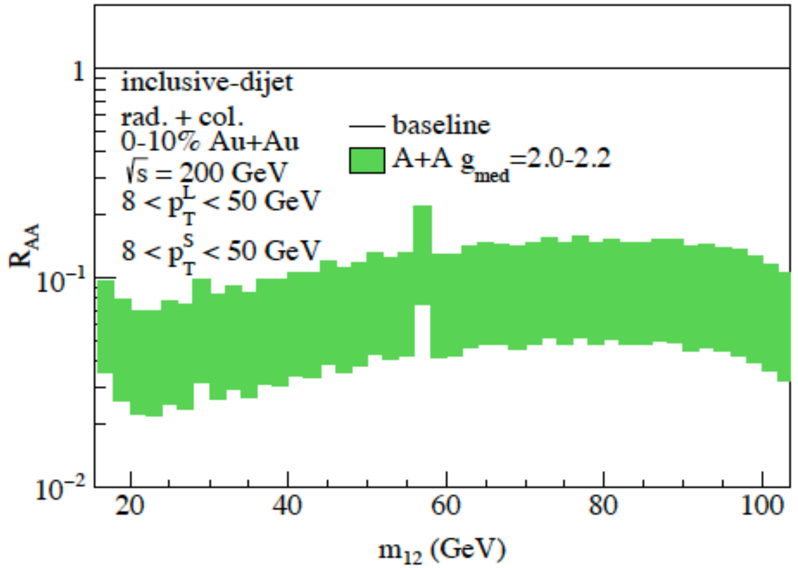
Dijet mass modification

- 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)

Two dimensional suppression

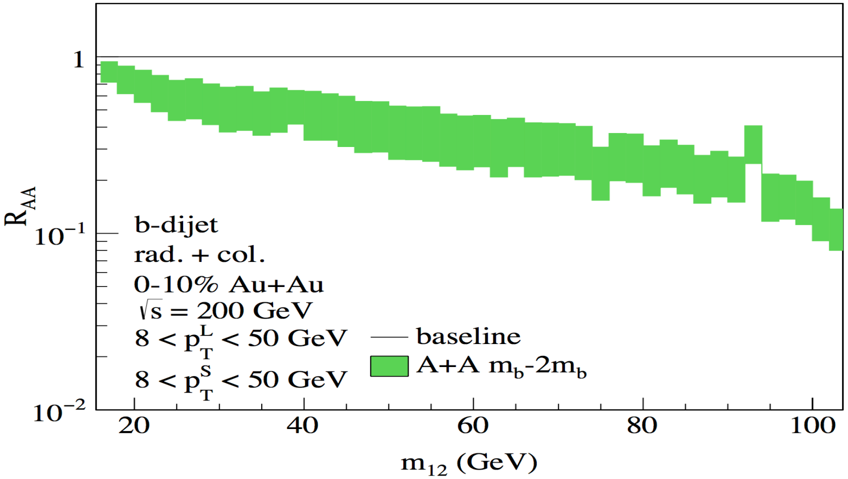


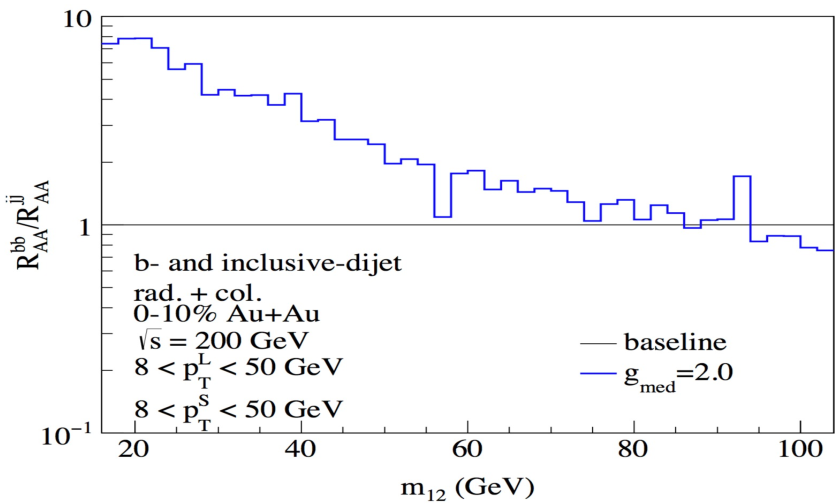
$$R_{AA}(m_{12}, |\mathbf{b}_\perp|) = \frac{1}{\langle N_{\rm bin}\rangle} \frac{d\sigma^{AA}(|\mathbf{b}_\perp|)/dm_{12}}{d\sigma^{pp}/dm_{12}}$$



Ideal measurement to make at RHIC. Suppression of the inclusive di jet mass distribution by an order of magnitude

Heavy flavor di jet measurements at RHIC





Z. Kang et al . (2018)

Great way to study the effect of mass on parton energy loss

- **Light and heavy flavor di jet mass show different m_{12} dependence. At the LHC for $m_{12} > 100$ GeV we find the same dependence**
- **Differences between light and heavy di jet mass modification can reach nearly a factor of 10. At the LHC they are very small, if any.**

sPHENIX will heave excellent reach to measure heavy flavor jets. It will be very important to complement such measurements with heavy flavor jet substructure that will be described next

Inverting the mass hierarchy of jet quenching effects

A regime where splitting function-dependent dead cone effect alters the longitudinal structure of the shower

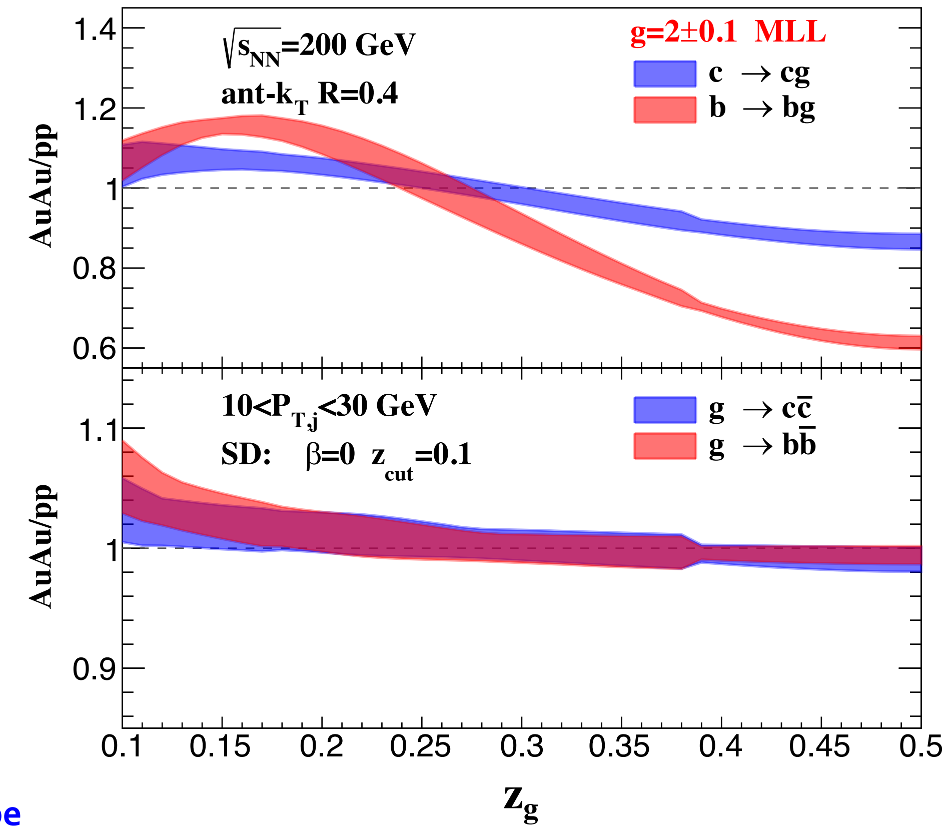
$$\left(\frac{dN^{\rm vac}}{dzd^2\mathbf{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2}\frac{C_F}{\mathbf{k}_\perp^2+z^2m^2} \times\left(\frac{1+(1-z)^2}{z}-\frac{2z(1-z)m^2}{\mathbf{k}_\perp^2+z^2m^2}\right)$$

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

- At RHIC jet energies, and at lower jet energies at the LHC there is a unique reversal of the mass hierarchy effects on b > c >= u,d. (Single B,D meson tag)
- Modification of the double B,D meson tag is small. Allows us to get a new handle on mass correction

One example, but expect that jet substructure will be more significantly modified for heavy flavor jets (especially b-jets)

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



H. Li et al . (2018)

Conclusions

- Important progress has been made in the theory of hard probes (QCD, SCET, NRQCD) – precise high order and resumed calculations standard. A+B collisions provide new opportunities to study many-body QCD, an have led to emergence of EFTs in matter. Progress toward medium motion effects, gradient corrections – leading subeikonal effects can be studied at RHIC
- Hadron production has been instrumental in the discovery of jet quenching and jet tomography at RHIC. First to benefit from modern QCD / SCET techniques in matter (evolution, NLO). An important question is whether QGP can be produced in small (p-sized) systems, jet quenching does not support that hypothesis at present. This can be tested with small symmetric vs asymmetric systems at LHC and should be explored if at all possible at RHIC
- Jet production and substructure are a step forward in jet quenching studies. Require precise theoretical control on parton showers. Predictions are for flat suppression of inclusive jets (significant) and distinct radius dependence, but very small modification of light jet substructure. Photon-tagged jets show different p_T-dependent suppression driven by the trigger and exhibit significant momentum imbalance similar to the one seen at LHC
- Heavy flavor provides a new mass scale ("dead cone effect") RHIC led to many of the important developments in HF physics and is ideally suited to study the mass effect. Predictions for heavy flavor jets quenching and di jet imbalance , but more importantly heavy jet substructure modification (momentum sharing distributions) can show different mass hierarchy of nuclear effects at moderate p_T . Di-jet mass calculations have shown that this observable can enhance otherwise more subtle jet quenching effects.

The exploration of the extreme phases of matter has also fascinated the general public. RHIC should make the most out of the remaining years of running

Jet charge in A+A in HIC

The jet charge

R. Field *et al.* (1978)

$$Q_{\kappa,\,\mathrm{jet}} = \frac{1}{\left(p_T^{\mathrm{jet}}\right)^{\kappa}} \sum_{\mathrm{h\ in\ jet}} Q_h \left(p_T^h\right)^{\kappa} \qquad \langle Q_{\kappa,q}\rangle = \frac{\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu)}{J_q(E,R,\mu)} \tilde{D}_q^Q(\kappa,\mu)$$

$$\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu) = \int_0^1 dz\ z^{\kappa} \mathcal{J}_{qq}(E,R,z,\mu)\ ,$$

$$\tilde{D}_q^Q(\kappa,\mu) = \int_0^1 dz\ z^{\kappa} \sum_h Q_h D_q^h(z,\mu)$$

The components of he factorization formula receive in-medium corrections

$$\langle Q^{\mathrm{pp}}_{q,\kappa}\rangle \left(1 + \tilde{\mathcal{J}}^{\mathrm{med}}_{qq} - J^{\mathrm{med}}_q\right) \exp\left[\int_{\mu_0}^{\mu} \frac{d\bar{\mu}}{\bar{\mu}} \frac{\alpha_s(\bar{\mu})}{\pi} \tilde{P}^{\mathrm{med}}_{qq}\right] + \mathcal{O}\left(\alpha_s^2, \chi^2\right)$$

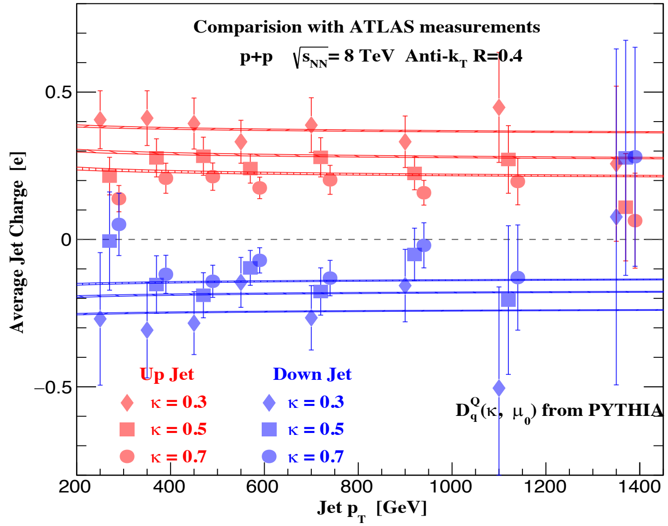
$$\tilde{\mathcal{J}}^{\mathrm{med}}_{qq} - J^{\mathrm{med}}_q = \frac{\alpha_s(\mu)}{2\pi^2} \int_0^1 dx\,(x^{\kappa} - 1) \int_0^{2Ex(1-x)\tan R/2} \frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2} P^{\mathrm{med,real}}_{q\to qg}(x, \mathbf{k}_\perp)$$

- Medium-induced scaling violation of the individual flavor and average jet charge
- The CMS collaboration has inverted the problem to determine quark/gluon jet fraction and found no significant difference between pp and AA

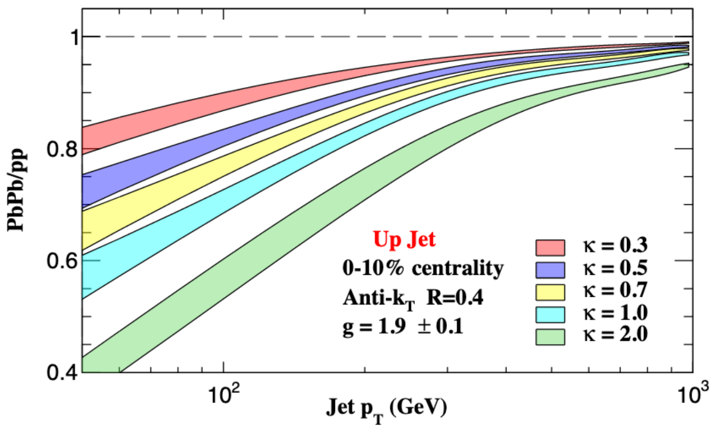
A. Sirunyan *et al.* (2020)

SCET approach

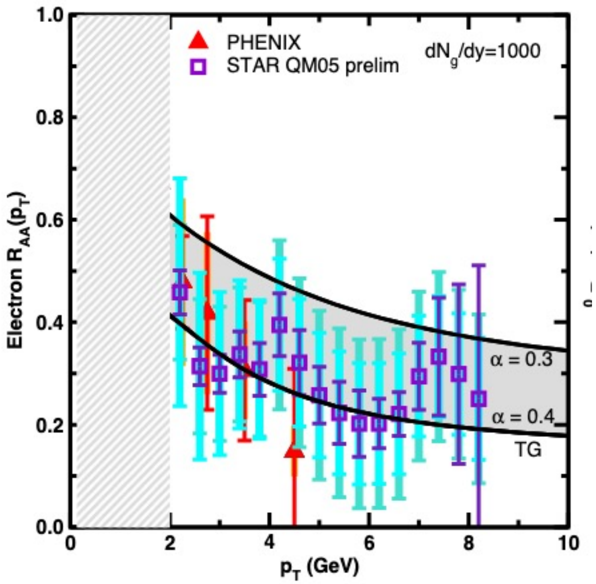
D. Krohn et al. (2012)



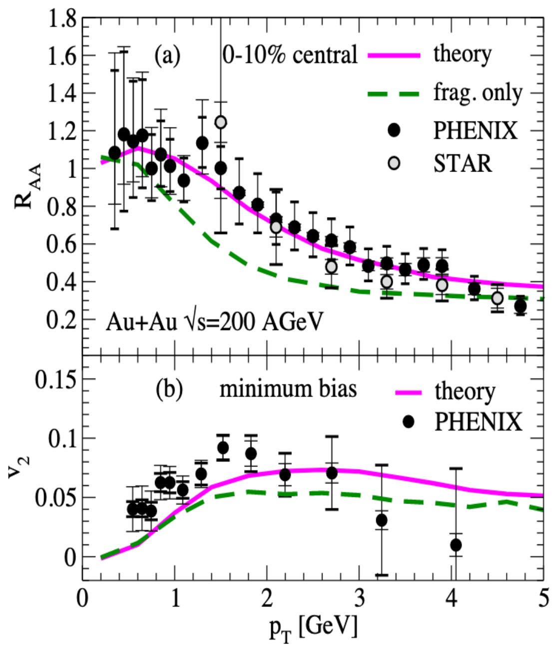
H. Li *et al.* (2019)



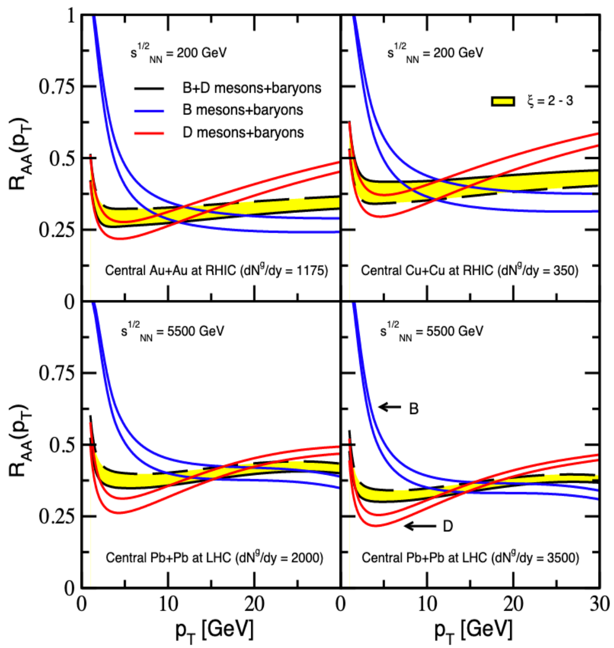
The crucial role of heavy quarks



S. Wicks et al. (2007)



V. Greco et al. (2008)



A. Adil et al. (2006)

Radiative energy loss is not dominant below 10 GeV for heavy quarks/heavy mesons. Especially when bottom quarks are included

- There have been evolving measurements at RHIC – from ones suggesting equal D and B meson suppression to ones inferring measurable differences.

Taking a closer look at the dijet mass

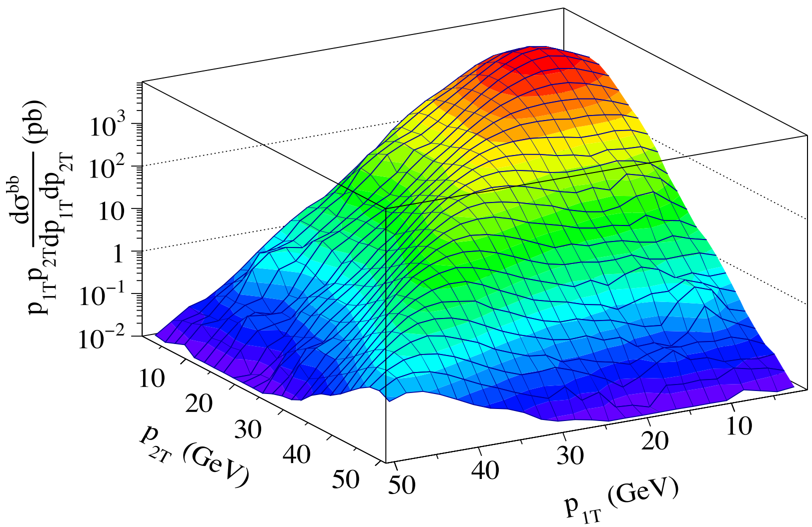
- Approximating the dijet cross section with individual jet pT, rapidity, mass and angular distributions (which we simulate from PYHIA)
- We have checked that aby difference are < 10%, also cancel in R_{AA} ratios

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

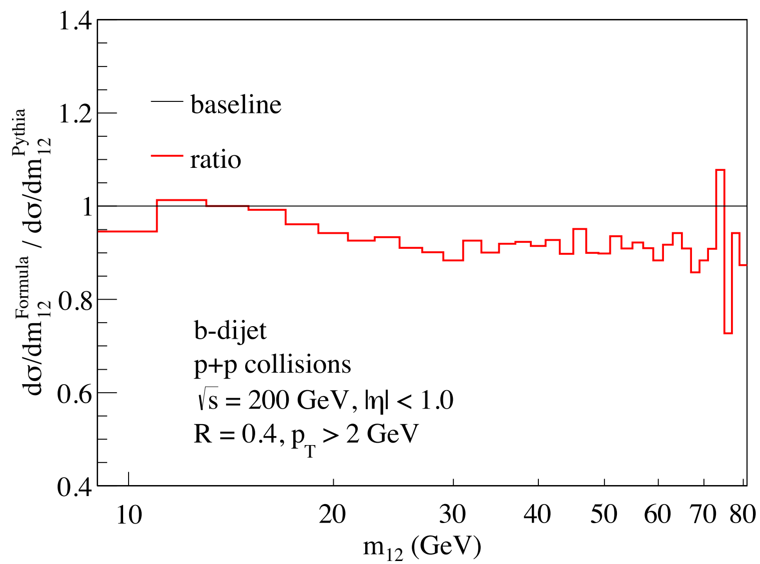
2-D nuclear modification factor needed

inclusive jet mass remains the same

angular information remains the same

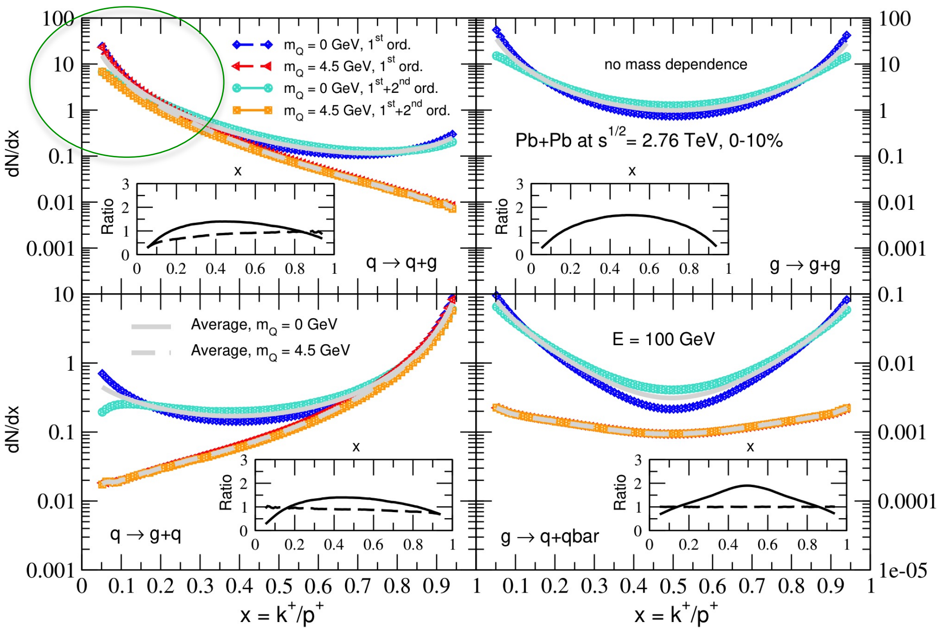


2D distributions for inclusive dijets and Di-bjets

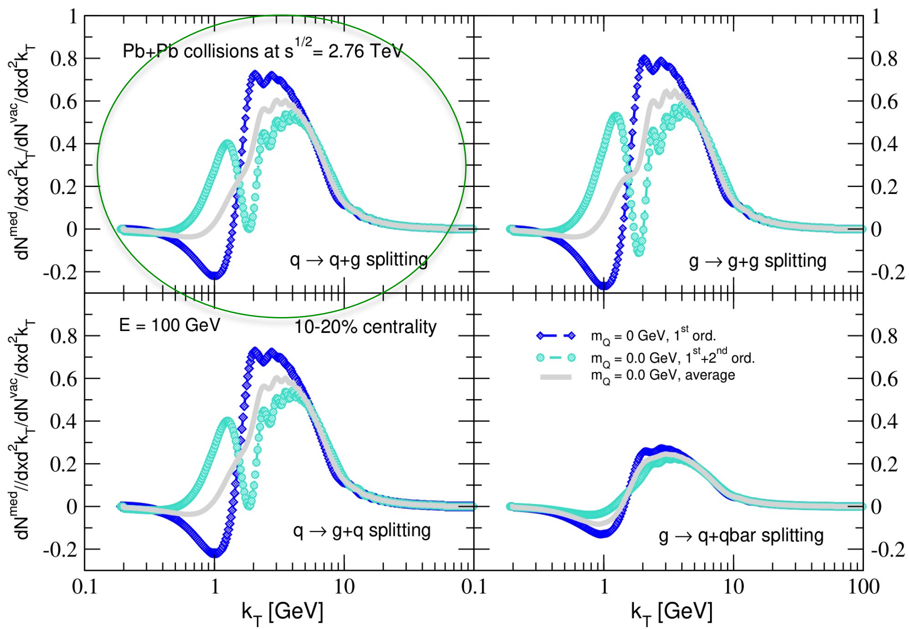


Differences very small

Differential branching spectra



- Production of hadrons and jets can be understood from the broader and softer splitting functions
- Holds to higher orders in opacity



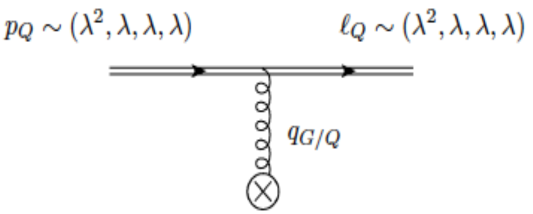
Most importantly – additional medium-induced contribution to factorization formulas (final-state) – Additional scaling violation due to the medium-induced shower. Additional component to jet functions

NRQCD in the medium

- At the level of the Lagrangian

$$\mathcal{L}_{\mathrm{NRQCD}_G} = \mathcal{L}_{\mathrm{NRQCD}} + \mathcal{L}_{Q-G/C}(\psi, A^{\mu,a}_{G/C}) + \mathcal{L}_{g-G/C}(A^{\mu,b}_{s}, A^{\mu,a}_{G/C}) + \psi \longleftrightarrow \chi$$

Y. Makris et al . (2019)

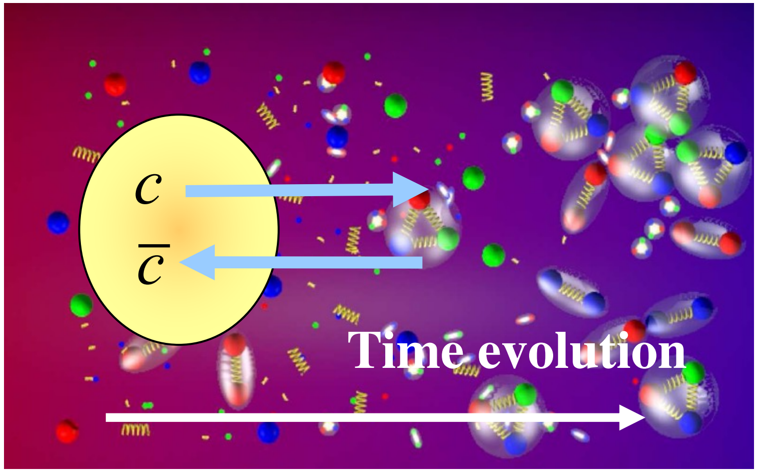


Possible scaling for the virtual gluons interacting with the heavy quarks

	0 1 2 3	+ − ⊥
(1)	$q_G \sim (\lambda^2, \lambda^1, \lambda^1, \lambda^2)$	$\sim (\lambda^2, \lambda^2, \boldsymbol{\lambda}_\perp)_n$
(2)	$q_C \sim (\lambda^2, \lambda^1, \lambda^1, \lambda^1)$	$\sim (\lambda^1, \lambda^1, \boldsymbol{\lambda}_\perp)_n$

- Energy component must always be suppressed
- Glauber gluons - transverse to the direction of propagation contribution
- Coulomb gluons - isotropic momentum distribution

- Depends on the type of the source of scattering in the medium



Leading medium corrections

$$\mathcal{L}^{(0)}_{Q-G/C}(\psi, A^{\mu,a}_{G/C}) = \sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\left(-gA^0_{G/C}\right)\psi_{\mathbf{p}} \quad (collinear/static/soft).$$

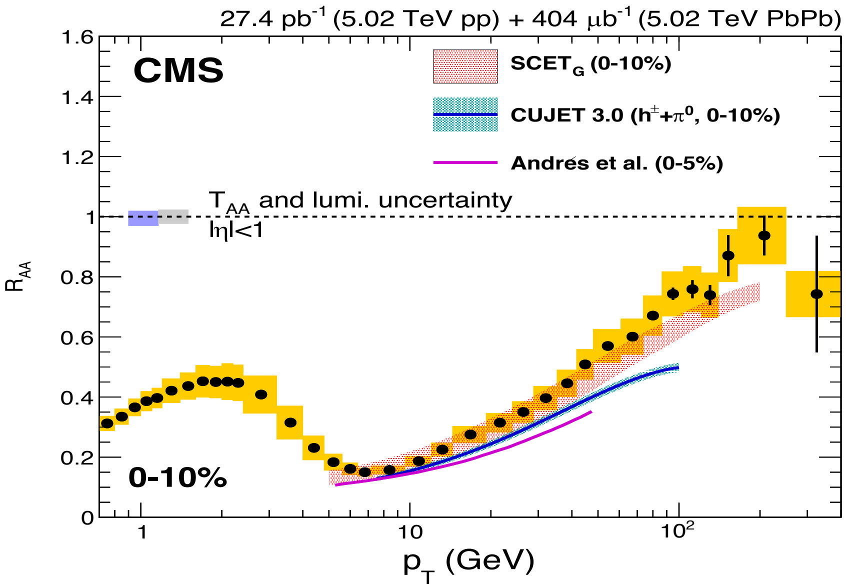
Sub-leading medium corrections

$$\mathcal{L}^{(1)}_{Q-G}(\psi, A^{\mu,a}_{G}) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\left(\frac{2A^{\mathbf{n}}_G(\mathbf{n}\cdot\boldsymbol{\mathcal{P}}) - i\left[(\boldsymbol{\mathcal{P}}_\perp \times \mathbf{n})A^{\mathbf{n}}_G\right]\cdot\boldsymbol{\sigma}}{2m}\right)\psi_{\mathbf{p}} \quad (collinear)$$

$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_{C}) = 0 \quad (static)$$

$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_{C}) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\left(\frac{2\mathbf{A}_C\cdot\boldsymbol{\mathcal{P}} + [\boldsymbol{\mathcal{P}}\cdot\mathbf{A}_C] - i\left[\boldsymbol{\mathcal{P}}\times\mathbf{A}_C\right]\cdot\boldsymbol{\sigma}}{2m}\right)\psi_{\mathbf{p}} \quad (soft)$$

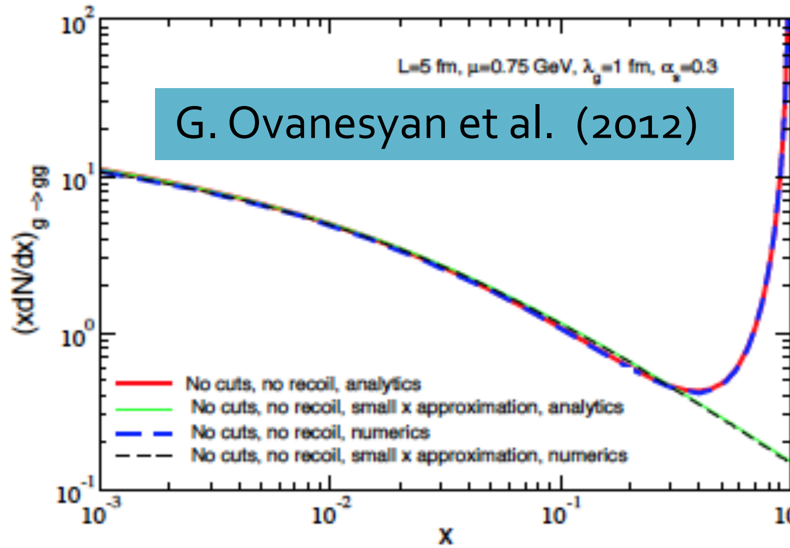
QCD evolution in the soft gluon energy loss limit and beyond



$$\frac{df_q(x,Q)}{d\ln Q} = P_{q\to qg}\otimes f_q + P_{g\to q\bar{q}}\otimes f_g$$

$$\frac{df_g(x,Q)}{d\ln Q} = P_{g\to gg}\otimes f_g + \sum_{q,\bar{q}} P_{q\to gq(\bar{q})}\otimes f_q$$

Advances in understanding in-medium parton showers. Beyond energy loss



$$P_{q\to qg} = \frac{2C_F}{x_+} + \left(\frac{2C_F}{x}\, g[x,Q,L,\mu]\right)_+ ,$$

- If a connection is to be found between the energy loss and the evolution approach, it is in the soft gluon limit

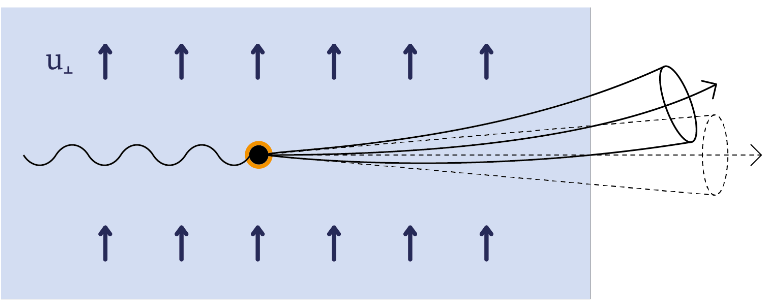
Z. Kang et al. (2014)

Analytic solution to DGLAP evolution

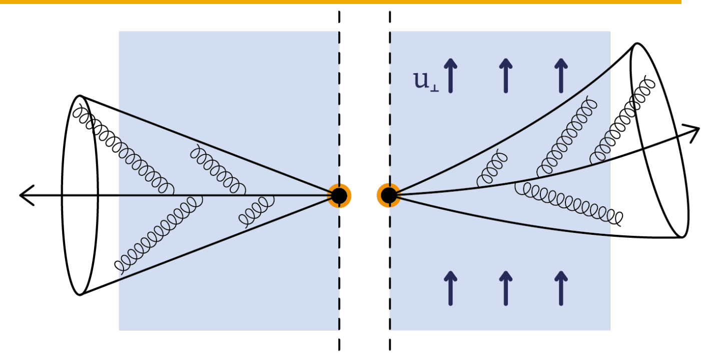
$$D_{h/c}^{\text{med.}}(z,Q) = D_{h/c}(z,Q)\, e^{-[n(z)-1]\langle\frac{\Delta E}{E}\rangle_z - \langle \tilde{N^g}\rangle_z} .$$

Effect of medium motion and inhomogeneities

- In the QGP - transverse and longitudinal expansion, rotation at non-zero impact parameter, fluctuations
- Cold nuclear matter – orbital motion of nucleons, breakup of the nucleus, color charge fluctuations



Effects on broadening and radiation



- Several selected results

Scattering

$$\langle \boldsymbol{p}_\perp \rangle = 3 \frac{\boldsymbol{u}_\perp}{(1-u_z)} \frac{L}{\lambda} \frac{\mu^2}{E} \ln \frac{E}{\mu}$$

$$E \frac{dN^{(1)}}{d^2k_\perp \, dx \, d^2p_\perp \, dE} = \frac{\alpha_s N_c}{\pi^2 x} \left(E \frac{dN^{(0)}}{d^2p_\perp \, dE} \right) \int_0^L dz \, \rho \int d^2 q_\perp \bar{\sigma}(q_\perp^2)$$
$$\times \left\{ \frac{2\boldsymbol{k}_\perp \cdot \boldsymbol{q}_\perp}{k_\perp^2 (k-q)_\perp^2} \left(1 - \cos\left(\frac{(k-q)_\perp^2}{2xE} z \right) \right) + \frac{q_\perp^2}{k_\perp^2 (q_\perp^2 + \mu^2)} \frac{\boldsymbol{u}_\perp \cdot \boldsymbol{k}_\perp}{2(1-u_z) x E} \right\}$$

Radiation

$$\left\langle \frac{\boldsymbol{k}_\perp}{k_\perp^2} \right\rangle = \frac{N_c}{C_F} \frac{L}{\lambda} \frac{\boldsymbol{u}_\perp}{8(1-u_z) x E}$$

Should appear on the ArXiv tonight, I think

A. Sadofyev et al . (2021)

Jet production with SiJF

Factorization formula

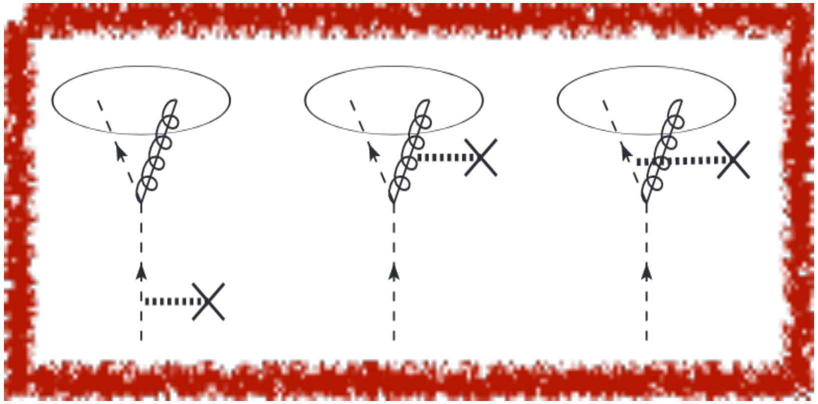
$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^{1}\frac{dx_a}{x_a}f_a(x_a,\mu)\int_{x_b^{\min}}^{1}\frac{dx_b}{x_b}f_b(x_b,\mu)\int_{z_c^{\min}}^{1}\frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab}^{c}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{dvdz}J_c(z_c,\omega_J,\mu)$$

$$\mu_J = \omega_J \tan\frac{\mathcal{R}}{2} = (2p_T\cosh\eta)\tan\left(\frac{R}{2\cosh\eta}\right)\approx p_T R$$

A useful modern way (though not unique) to calculate jet cross sections

In-medium jet functions

$$J_q^{\text{med},(1)}(z,\omega R,\mu) = \left[\int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{qq}(z,q_\perp)\right]_+ + \int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{gq}(z,q_\perp)\,. \quad (15)$$



- Stable in numerical implementation
- Implemented at fixed order - NLO

Cross section contribution

Z. Kang et al. (2016)

$$d\sigma_{\text{PbPb}}^{\text{jet,med}} = \sum_{i=q,\bar{q},g}\sigma_i^{(0)}\otimes J_i^{\text{med}}$$