Jets & Heavy Flavors in HIC from a Partonic Transport Approach and a Multistage Approach

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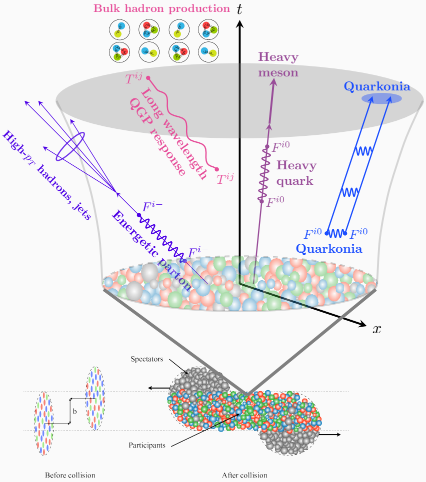
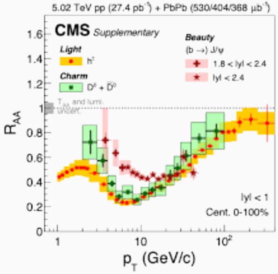
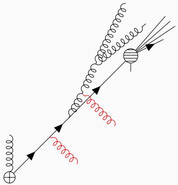
Weiyao Ke, Los Alamos National Laboratory



- Jet transport parameter $\hat{q}$.
- Heavy quark momentum diffusion parameters κ.

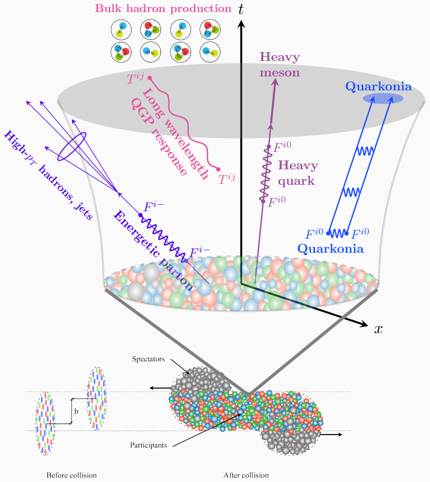
Intermediate to high-p_T HF modifications





- Energy loss from soft rad. & collisions, $\omega \sim T$.
- Medium-modified fragmentation and mass effects.
- Non-perturbative input and models: fragmentation, recombination, etc.

Characterizing quark-gluon plasma from jets and heavy flavors



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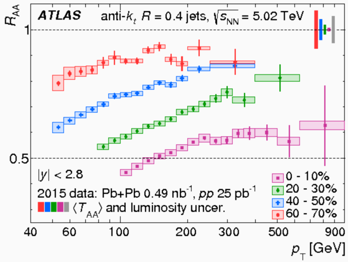
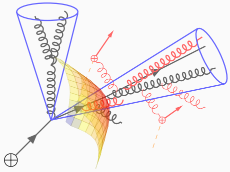
From jet modifications to $\hat{q}$





- Angular-dependent energy transport by parton shower in the medium.
- Medium excitations induced by energy loss

Outline

- Study of HF & jet in the LIDO partonic transport approach.
- Progresses in JETSCAPE multistage jet evolution: modified DGLAP + transport.
- Jets: inferring QGP $\hat{q}$ from jet & hadron suppression at both RHIC and LHC.
- Heavy flavors: towards a consistent description of light and heavy quenching
  new information from HF-tagged jets.
- Impact of future high precision data at RHIC.

Space-time evolution of on-shell hard partons in the medium

Transport equations of hard partons $f_H = f(t, x, p)\Theta(p \cdot u > E_{\min})$,

$$(\partial_t - v \cdot \partial_x) f_H(t, x, p) \quad = \quad \Theta(p \cdot u > E_{\min}) \left\{ \mathcal{C}_{nn} f_H + \mathcal{C}_{n(n+1)} f_H \right\}$$

- Collisional processes: number of hard partons does not change $n \to n$.
- Medium-induced radiative & semi-hard recoil processes: $n \to n+1$.
- (In most studies) medium is assumed to be a locally thermal gas of massless partons: $f_{q,g}(p) = [e^{p \cdot u/T} + 1]^{-1}$. QGP flow and temperature obtained in bulk medium simulations.

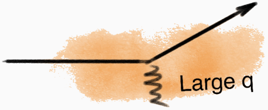
LIDO: Linearized Boltzmann + Diffusion Partonic Transport Model

[PRC100(2019)064911, JHEP05(2021)041]

$$\frac{df_H}{dt} = \mathcal{D}f_H + \mathcal{D}_{12}f_H + \mathcal{C}_{22}f_H + \mathcal{C}_{23}f_H$$

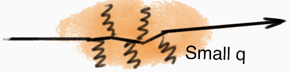
Large-angle collisions with thermal partons $f_s(p') = e^{-p'\cdot u/T}$

$$\frac{d\sigma}{d^2\mathbf{q}} \propto \frac{\alpha_s^2}{\mathbf{q}^4}\Theta(\mathbf{q}_\perp^2 - Q_c^2),\ \mathcal{C}_{22}f_H(p) = \int_{\mathbf{q},p'} f_s(p')\left\{\frac{d\sigma}{d^2\mathbf{q}}f_H(\mathbf{p}-\mathbf{q}) - \frac{d\sigma}{d^2\mathbf{q}}f_H(\mathbf{p})\right\}$$



Small-angle collisions absorbed in a diffusion component[1]:

$$\mathcal{D}f_H(p) = -\left\{\eta\nabla_p + \nabla_{p^i}\frac{\kappa_{s,ij}}{2}\nabla_{p^j}\right\} f_H(p).$$



The jet transport parameter combines both small & large-angle contribution

$$\hat{q}_F(T,p) \equiv \frac{d\langle\Delta k_T^2\rangle}{dt} = \underbrace{\alpha_s C_F T m_D^2 \ln\frac{Q_c^2}{m_D^2}}_{\hat{q}_s = \kappa_{s,xx}+\kappa_{s,yy}} + \int_{p'} f_s(p')\left\{2(N_c^2-1)\frac{d\sigma_{qg}}{d^2\mathbf{q}_\perp} + 4N_f N_c\frac{d\sigma_{qq}}{d^2\mathbf{q}_\perp}\right\}\Theta(\mathbf{q}_\perp^2 - Q_c^2)\mathbf{q}_\perp^2 d^2\mathbf{q}_\perp$$

[1] In J. Ghiglieri, G. D. Moore, D. Teaney JHEP 03, 095(2016), separation requires $m_D \ll Q_c \ll T$. we take $Q_c = 2m_D$

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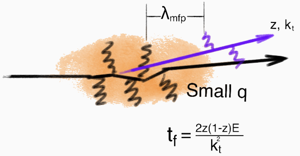
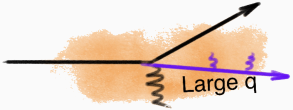
Diffusion-induced 1 *to* 2 radiation:

$$\mathcal{D}_{12}f_H(x,\mathbf{p}) = \int_{\mathbf{k}} \frac{\alpha_s P_{ij}(z)}{2\pi^2\mathbf{k}^2}\frac{\hat{q}_s}{\mathbf{k}^2} f_H(\frac{x}{z},\mathbf{p}+\mathbf{k})\frac{dz}{z} + \ldots$$



Large-q collision-induced 2 *to* 3 radiation:

$$\mathcal{C}_{23}f_H(x,\mathbf{p}) = \int_{\mathbf{k},\mathbf{q},p'} \frac{d\sigma_{23}}{dzd^2\mathbf{k}d^2\mathbf{q}} f_s(p')f_H(\frac{x}{z},\mathbf{p}+\mathbf{k}-\mathbf{q})\frac{dz}{z} + \ldots$$



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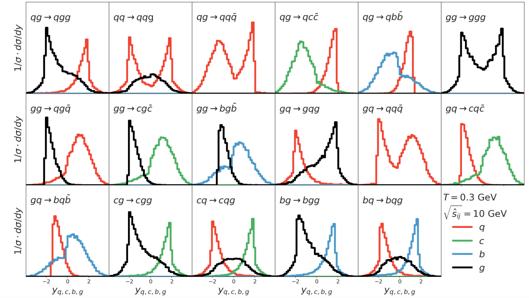
$2 \to 3$ cross-sections in the limit $\sqrt{z(1-z)\hat{s}_{ij}} \gg \mathbf{q}, \mathbf{k}$



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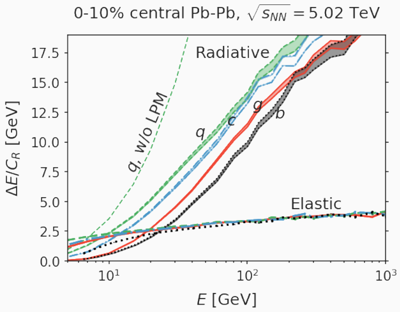
(Deep)Landau-Pomeranchuk-Midgal effect: suppressing radiation with $\#\lambda_{\mathrm{mfp}}/\tau_f$. Energy loss: ΔE_{rad} only dominates ΔE_{el} by $\alpha_s \ln E$.



For jet study: a simple model for medium excitation

- Energy-momentum deposition to soft sector:

$$\frac{d\delta p^\mu}{dt}(t,x) = \int_{\mathbf{p}} \Theta(p\cdot u < E_{\min}) p^\mu \frac{d}{dt} f_H(t,x,p)$$

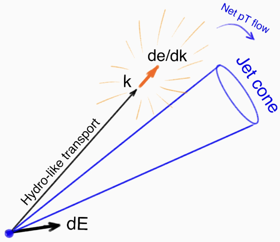
- An ideal-hydro response:

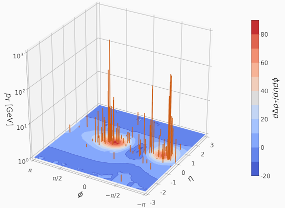
$$\frac{de}{d\Omega_{k'}} = \frac{\delta p^0 + \hat{k}'\cdot\delta\vec{p}/c_s}{4\pi}, \quad \frac{d\vec{p}}{d\Omega_{k'}} = \frac{3(c_s\delta p^0 + \hat{k}'\cdot\delta\vec{p})\hat{k}'}{4\pi}$$

- Freeze-out to massless particles w/ radial flow $v_\perp$ $\Rightarrow$ corrections to momentum density in the cone:

$$\frac{d\Delta p_T}{d\phi d\eta} = \int \frac{3}{4\pi} \frac{\frac{4}{3}\sigma u_\mu - \hat{p}_\mu}{\sigma^4} \delta p^\mu(\hat{k}) \frac{d\Omega_{\hat{k}}}{4\pi}$$

$$\sigma = \gamma_\perp \left[\cosh(\eta - \eta_s - \eta_{\hat{k}}) - v_\perp \cos(\phi - \phi_{\hat{k}})\right]$$



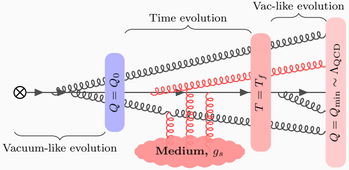


Other methods: recoiled partons (JEWEL), recoiled parton + rescatterings (LBT), coupled jet-hydro evolution (CoLBT, JETSCAPE), Hybrid model (next talk).

LIDO: joining partonic transport & the scale evolution

In LIDO simulations:

- Pythia generates vacuum shower down to transition scale Q_0.
- LIDO for time-evolution of shower in QGP in regions $T > T_c$.
- Pythia8 handles vacuum shower and fragmentation when $T < T_c$.



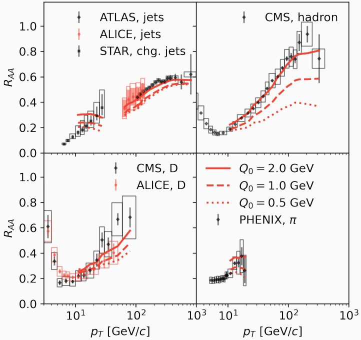
Results depend on Q_0.

- Q_0 can be tuned to data. Note that jet and HF R_{AA} are less sensitive to Q_0.
- Physical expectation: $Q_0 \approx$ momentum broadening.

- For example: in Björken medium with $\hat{q} = 5T^3$

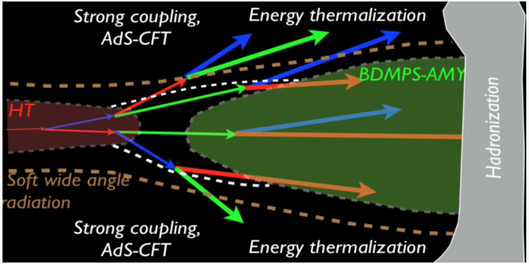
Systems	Pb-Pb 5 TeV		Au-Au 0.2 TeV
	0-5%	40-50%	0-5%
$5t_0 T_0^3$ [GeV^2]	1.1	0.55	0.46

Q_0 can be a function of beam energy and centraltiy.



JETSCAPE framework: the multistage in-medium jet evolution approach

A program envelop coupling jet shower and medium evolution + statistical inference package.



Philosophy for the jet sector:
applying different models to different phase space regions of parton energy E, virtuality Q and T.

The multistage method [PRC96(2017)024909, 1903.07706]

At high-virtuality $Q^2 = \frac{\mathbf{k}_\perp^2}{x(1-x)} > Q_0^2$: medium-modified DGLAP evolution (MATTER [PRC88(2013)014909])

$$P(Q'; Q) = \exp\left\{ -\int_{Q'^2}^{Q^2} \int dx \frac{dN_{ij}}{dx dQ^2} dQ^2 \right\}$$

At low-virtuality $Q < Q_0$, the time-ordered transport equation (e.g. LBT [PRC91(2015)054908])

$$P(t_2; t_1) = \exp\left\{ -\int_{t_1}^{t_2} \int dx \frac{dN_{ij}(t)}{dx d\mathbf{k}_\perp^2 dt} dx d\mathbf{k}_\perp^2 dt \right\}$$

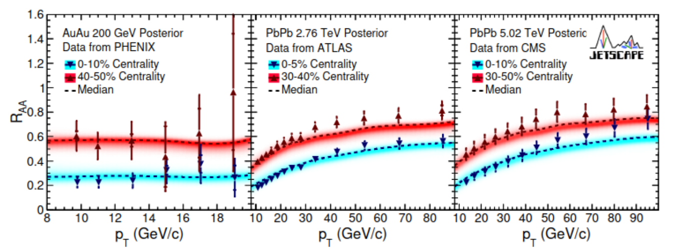
JETSCAPE extraction of $\hat{q}$ from hadron suppression

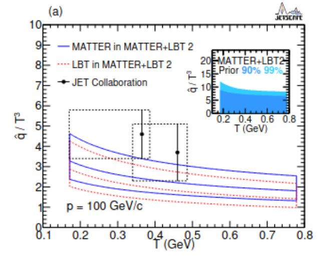
In this approach, $\hat{q}$ depends on E, T, and Q [JETSCAPE PRC 104 (2021) 024905]

$$\left[\frac{\hat{q}}{T^3}\right]_{\mathrm{LBT}} = \#\left\{a\frac{\ln(E/\Lambda)-\ln b}{\ln^2(E/\Lambda)} + c\frac{\ln(E/T)-\ln d}{\ln^2(ET/\Lambda^2)}\right\}$$

$$\left[\frac{\hat{q}}{T^3}\right]_{\mathrm{Matter}} = \#\left\{\Theta(Q-Q_0)a\frac{\ln(Q/\Lambda)-\ln(Q_0/\lambda)}{\ln^2(Q/\Lambda)} + c\frac{\ln(E/T)-\ln d}{\ln^2(ET/\Lambda^2)}\right\}$$

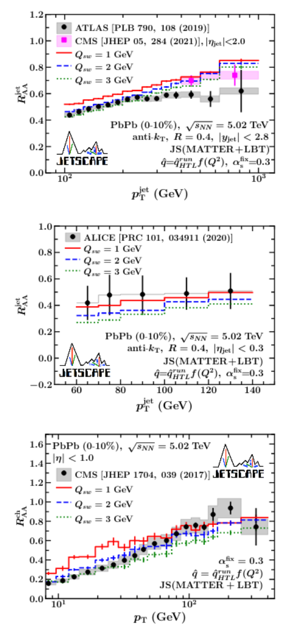
A Bayesian analysis is performed with inclusive hadron R_{AA} at both RHIC and LHC.





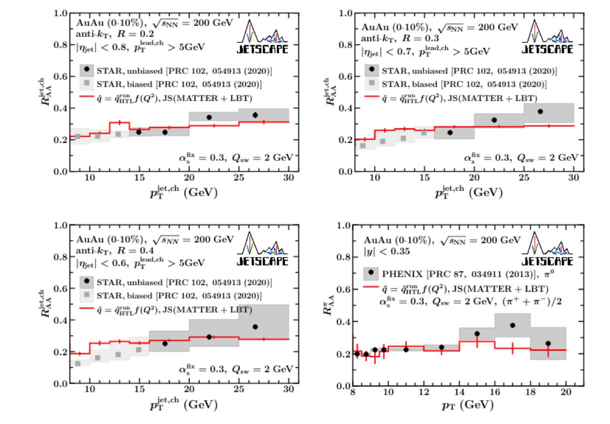
Model choices: MATTER (modified DGLAP) + LBT (transport), both use the higher-twist formula for induced parton radiation.

Recent hadron & jet studies within the JETSCAPE framework [2204.01163]



◁ Weaker Q_0 dependence in the multi-stage approach.

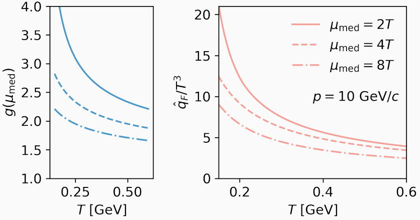
▽ Simultaneous description of hadron and jet R_{AA} at RHIC energy



LIDO: extract $\hat{q}$ from hadron+jet data in central Au-Au & Pb-Pb [JHEP05(2021)041]

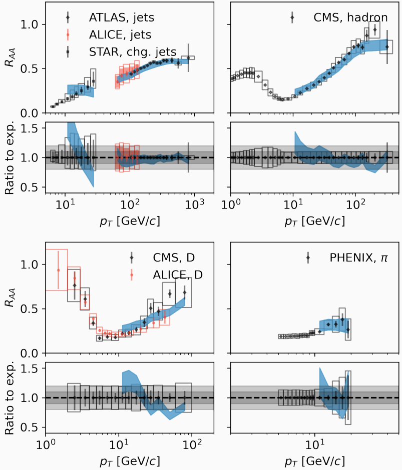
Objective: determine "jet-medium coupling $\alpha_s(\mu_{\rm med}) = g_s^2(\mu_{\rm med})/4\pi$", then the $\hat{q}$

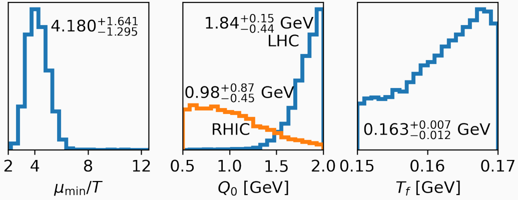
$$\hat{q}_F(T,p) = \alpha_s(\mu_{\rm med}) C_F T m_D^2 \ln\frac{Q_c^2}{m_D^2} + \int_{p'} f_s(p')\left\{2(N_c^2-1)\frac{d\sigma_{qg}}{d^2\mathbf{q}_\perp} + 4N_f N_c \frac{d\sigma_{qq}}{d^2\mathbf{q}_\perp}\right\}\Theta(\mathbf{q}_\perp^2 - Q_c^2)\mathbf{q}_\perp^2 d^2\mathbf{q}_\perp$$



- $0.7\pi T < \mu_{\rm med} < 4\pi T$: controls in-medium g_s:
  $$\frac{g_s^2(\mathbf{k}_\perp)}{4\pi} = \frac{4\pi}{\beta_0}\ln^{-1}\left[\frac{\max\{\mathbf{k}_\perp^2, \mu_{\rm med}^2\}}{\Lambda^2}\right]$$
- $0.5 < Q_0 < 2.0$ GeV: separates vacuum-like and transport evolution.
- $0.15 < T_f < 0.17$ GeV, sudden transition to confinement below $T < T_f$.

LIDO Bayesian analysis of $\hat{q}$ from hadron and jet

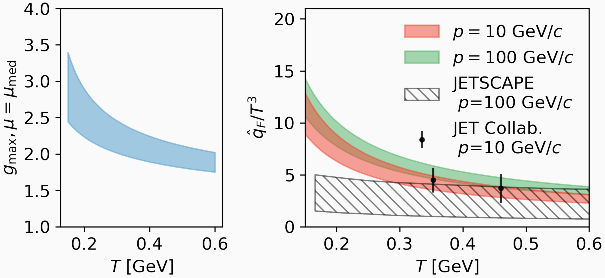




- $Q_0^{\rm LHC}$ varies independently from $Q_0^{\rm RHIC}$.
- Favors higher T_f than the pseudo-critical T_c.
- Running of g_s in medium saturates around $\mathbf{k}_\perp > \mu_{\rm med} \approx 4.2T$ (or $1.3\pi T$).

[Data: STAR PRC102(2020)054913; ALICE PRC101(2020)034911; ATLAS PLB 790(2019)108-128; CMS JHEP04(2017)039, PLB287(2018)474-496; PHENIX PRC 87(2013)034911.]

Results: jet-medium coupling g and jet transport parameter $\hat{q}$

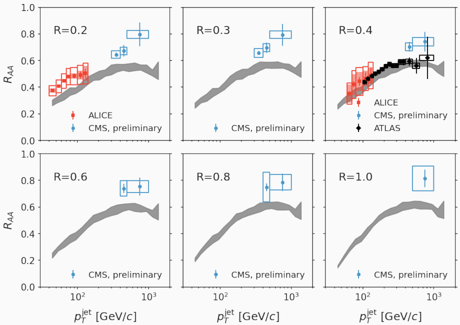


Left: maximum coupling at different temperature $g_s(\mu_{\mathrm{med}})$
Right: $\hat{q}$ at $p = 10$ and 100 GeV for a quark. [JHEP05(2021)041]

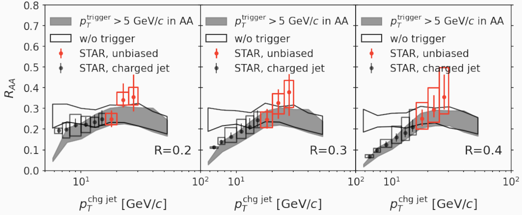
Compared to [JET Collab: PhysRevC.90.014909 (2014), JETSCAPE : PRC 104, 024905 (2021)] using inclusive hadrons.

- Results consistent with JET collaboration. (using inclusive hadron suppression)..
- Higher than the recent JETSCAPE Collaboration analysis (using inclusive hadron suppression).
  A possible explanation could be the use of medium-modified DGLAP evolution for $Q > Q_0$.

The cone-size dependence of jet R_{AA} from LIDO



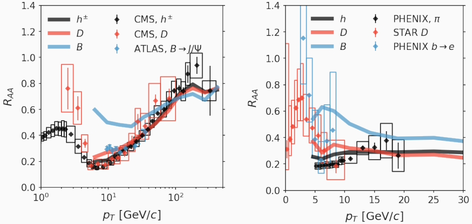
[CMS: JHEP 05, 284(2021)]



△ Unbiased region (red) are in sensitive to the high-p_T hadron trigger. [STAR: PRC 102, 054913(2020)]

- LHC: LIDO predicts R_{AA} increased by 10% from $R = 0.2$ to $R = 1.0$ at $p_T^{\mathrm{jet}} = 500$ GeV.
- RHIC: Weak R-dependence in the unbiased region. Trigger bias understood from simulation.

LIDO: $R_{AA}^{\pi,D,B}$ in 0-10% Au-Au@0.2 TeV



[ATLAS EPJC78(2018)9 762; CMS PLB782(2018)474, JHEP04(2017)039; PHENIX PRL101(2008)232301, PRC93(2016)034904 ; STAR PRC99(2019)034908.]

- Same $\hat{q}$ (median) as calibrated to $R_{AA}^{\rm jet}$ and R_{AA}^{h}. *Previous works [PRC98(2018)06490] only used heavy-flavor data.
- Consistent $\hat{q}$ for q, c, b overestimates the flavor separation.
- Similar problem in a recent QCD-evolution based calculation [2204.00634]. • Need interactions in the hadronic stage? A large NP contribution from $g \to D, B$?

Recent progress from the JETSCAPE multi-stage evolution

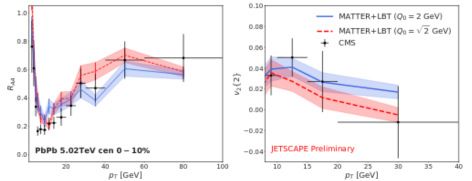
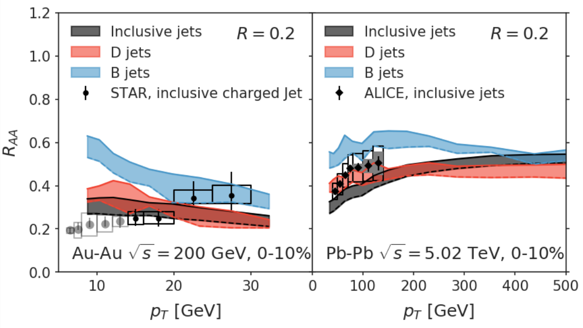


Figure 1: Comparison of D^0 meson nuclear modification factor R_{AA} and azimuthal anisotropy $v_2\{2\}$ using the multi-stage energy loss approach (MATTER + LBT) with CMS data for central Pb + Pb collisions at $5.02 TeV$. (Left) D^0 meson R_{AA}. (Right) D^0 meson $v_2\{2\}$. Computed with two switching virtuality $Q_0 = 2GeV$ and $Q_0 = \sqrt{2}GeV$.

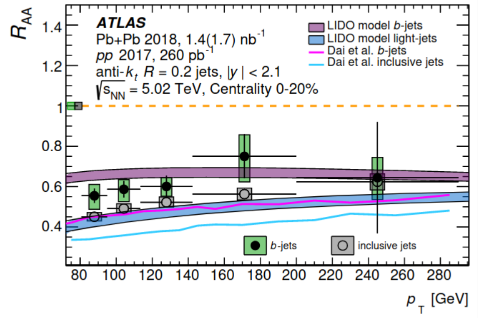
[PoS(HardProbes2020)067 / 2009.04946]

- A consistent study of both charm and light flavor to appear soon.
- Check if similar problem exists for the multi-stage approach with h, D & B.

What can be learned from heavy-flavor jets?



[PoS(HardProbes2020)060 / 2008.07622]

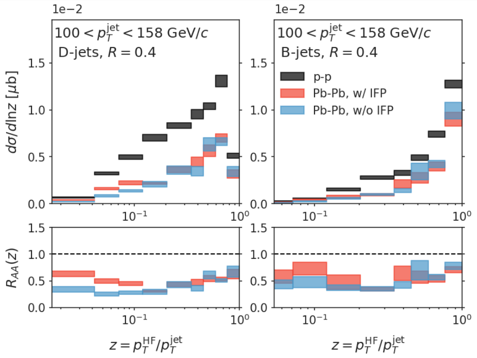


[ATLAS 2204.13530]

HF-jet suppression in LIDO (in preparation)

- A clear mass dependence recently suggested by ATLAS measurements at 5.02 TeV.
- LIDO seem to result in too large a mass separation of $R_{AA}^{b\text{-jet}}$ and R_{AA}^{jet}
- Heavy jet continued to be highly suppressed at high p_T.

More information contained in the fragmentation / HF-jet correlation



Suppression of inclusive HF spectra is only probing the HF modification near $z \approx 1$ (energy loss limit).

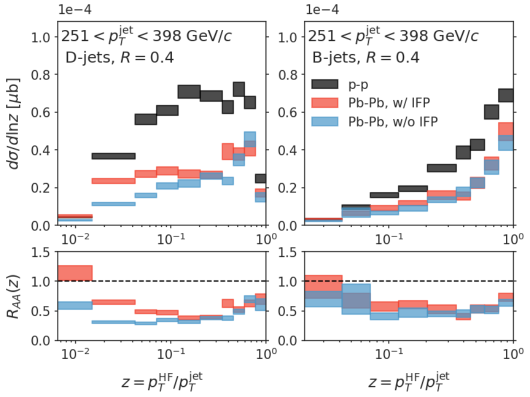
$$\frac{d\sigma_{AA\to Q}}{dq_T} \propto 1/q_T^N$$

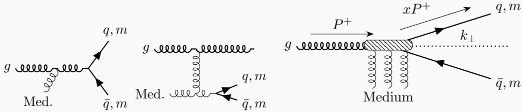
$$\frac{d\sigma_{AA\to HF}}{dp_T} = \frac{d\sigma_{AA\to Q}}{dq_T} \otimes D_{AA}(z) \propto \int z^{N-1} D_{AA}(z) dz$$

Heavy-flavor in jet fragmentation tests the full-z dependence.

- The shape is a mixture of $Q \to$ HF, $g \to$ HF, $q \to$ HF
- Study the NP contribution from $g \to$ HF meson, e.g., D-meson fragmentation function from hadron-in-jet analysis in p+p [PRD96(2017)034028].

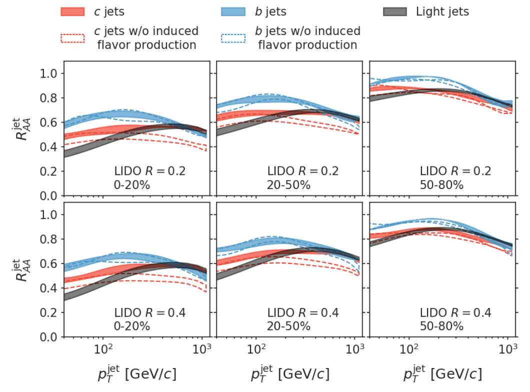
(Perturbative) Medium-induced charm flavor production

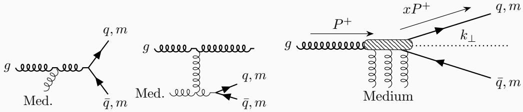




- LO collisional processes and induced $g \to c + \bar{c}$.
- $\hat{q}\Delta\tau \lesssim m_c^2 \ll m_b^2$.

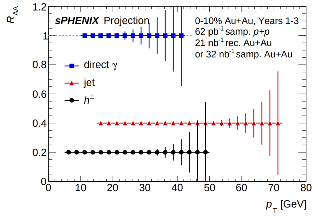
(Perturbative) Medium-induced charm flavor production

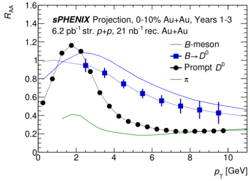


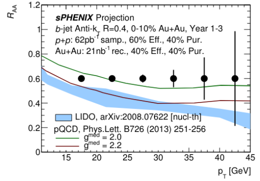


- LO collisional processes and induced $g \to c + \bar{c}$.
- $\hat{q}\Delta\tau \lesssim m_c^2 \ll m_b^2$.
- Can be important for $R_{AA}^{c\text{-jets}}$ at high p_T.

Impact of future high-precision jet & HF measurement at RHIC





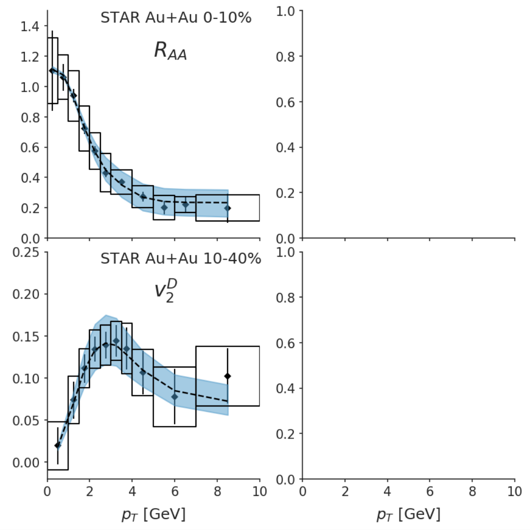


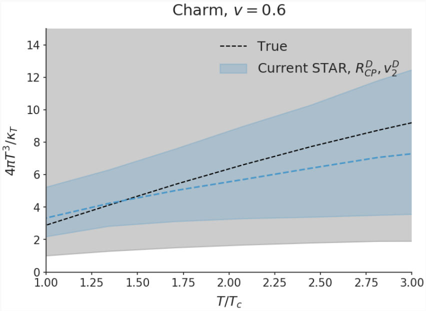
[sPHENIX Beam Use Proposal]

- High precision HF, jet measurements with much higher reach of jet p_T.
- However, the dominant uncertainty in current Bayesian analysis is theory/interpolation uncertainty ($\sim$ 10%).
- The gain of information will be limited by theory / model...

Impact of future sPHENIX heavy-flavor data

Pseudodata: R_{AA}^D, v_2^D from simulations w/ "true" parameters + **current** uncertainties.

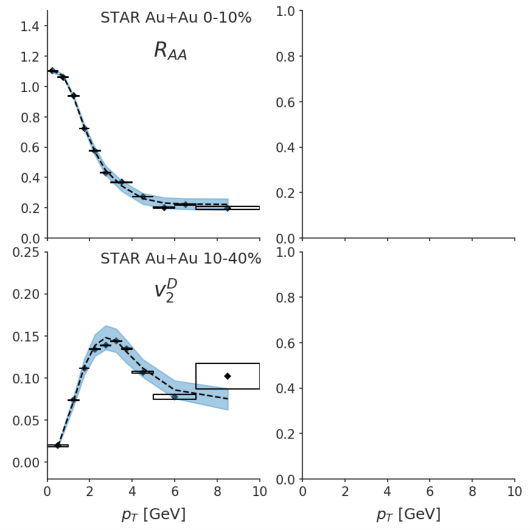


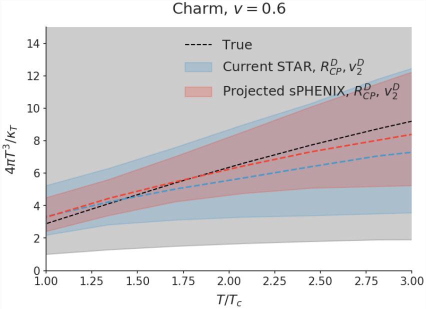


Current level of uncertainties in the charm diffusion constant using STAR uncertainty level.

Impact of future sPHENIX heavy-flavor data

Pseudodata: R_{AA}^D, v_2^D from simulations w/ "true" parameters + **projected** uncertainties.





Uncertainties in the charm diffusion constant using the projected sPHENIX data.

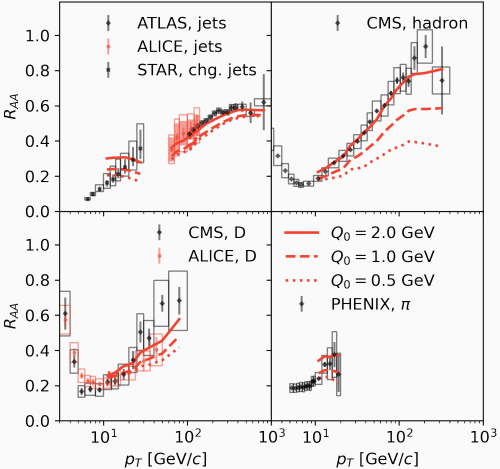
Note that the residue uncertainty band comes from theory and interpolation uncertainty.

Summary and outlook for HF and jet in HIC

- The pure LIDO transport approach:
  - Vacuum shower + LIDO (collisional + radiative)
  - $\hat{q}$ determined from hadron and jet R_{AA} at RHIC and LHC.
- The JETSCAPE multistage approach:
  - Medium-modified high-virtuality shower + time-evolution of low-virtuality partons in QGP.
  - Expected to further reduce model uncertainties in the future.
- Heavy flavor: using same $\hat{q}$ in LIDO overestimate the flavor suppression between $R_{AA}^{h,D,B}$.
- Heavy-flavor jets can provide more information:
  - The full-z dependence of modified HF fragmentation
  - Perturbative & NP contributions of $g \to$ HF.
- With future high-precision sPHENIX data on HF:
  - One expects the uncertainty on $\hat{q}, \kappa$ to decrease.
  - But currently limited by theory / interpolation uncertainties in statistical analysis.

Questions?

Uncertainties of Q_0: advantage of using jet R_{AA} to calibrate $\hat{q}$



Experimental data:

[STAR charged jet: PRC 102, 054913(2020)]

[ALICE jet: PRC 101 034911(2020)]

[ATLAS jet: PLB 790 108-128(2019)]

[CMS D: PLB 287 474-496(2018)]

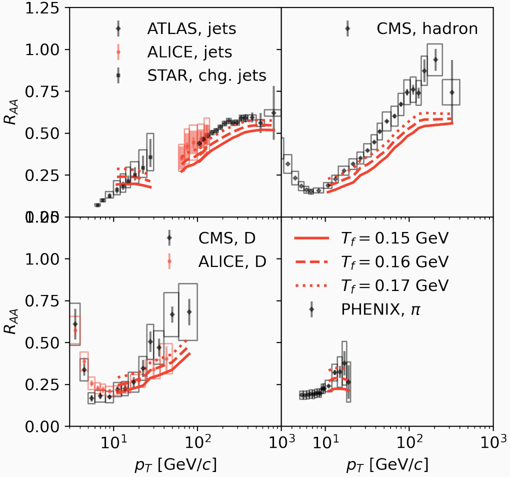
[CMS h: JHEP 04, 039(2017)]

[PHENIX π: PRC 87, 034911(2013)]

Test the variation of $Q_0 = 0.5, 1.0, 2.0$ GeV.

- Light hadron R_{AA} are very sensitive to Q_0.
- Jet and heavy-flavor R_{AA} at the LHC energy are the least sensitive.

Uncertainties: the QGP termination temperature T_f



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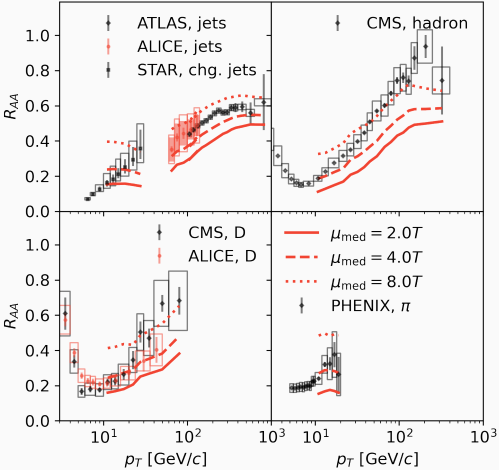
[PHENIX π: PRC 87, 034911(2013)]

Change $T_f = 0.15, 0.16, 0.17$ GeV. $\Leftrightarrow$ effectly change color density near T_c.

Uncertainties: $\mu_{\rm med}$ or $g_s(\max\{k_T, \mu_{\rm med}\})$



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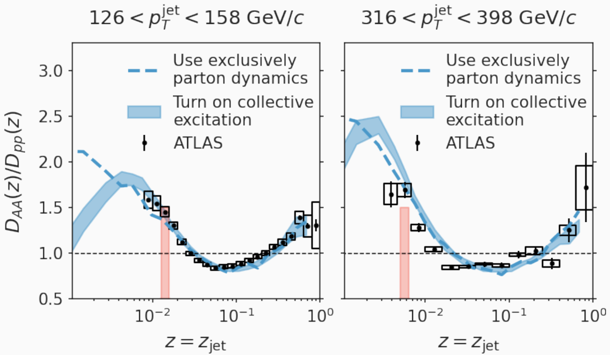
[PHENIX π: PRC 87, 034911(2013)]

Changing the coupling strength by varying $\mu_{\rm med} = 2T, 4T, 8T$ GeV

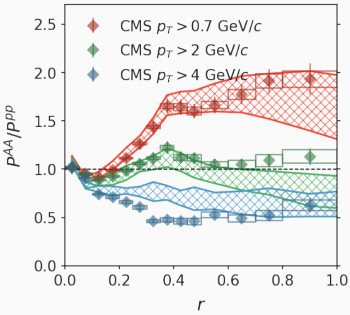
Test the transport of energy: fragmentation function



[ATLAS: PRC 98, 024908(2018)]

- Calculations that *treats everything with partonic dynamics* well describes the fragmentation at $zp_T^{jet} > 2$ GeV (red bands).
- *Use collective excitations to redistribution soft particles* improves at $p_T \lesssim 2$ GeV.

Test the transport of energy: a detailed look at low-p_T particles



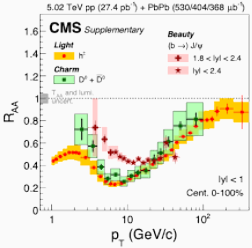
[CMS: JHEP05, 006(2018)]

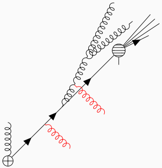
◁ Jet shape with different minimum hadron p_T

- Energy is shifted to particles at lower p_T and larger r.
- Discrepancy appears wihtin the cone for $p_{T,cut} = 4$ GeV
  - Can this be fixed by fine-tuning of parameters?
  - Suggest missing physics? Such as coalescence shifting intermediate-p_T hadrons to higher p_T.

Dynamics of HF & jet from intermediate to high p_T

Intermediate to high-p_T HF production

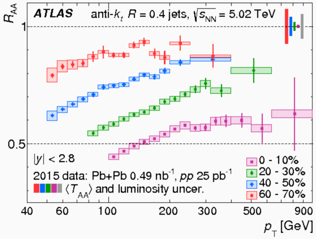


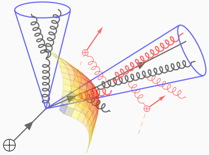


Probe modification/eloss of large-z partons

- Energy loss from soft rad. & collisions, $\omega \sim T$.
- Medium-modified fragmentation and mass effects.
- Non-perturbative input and models: fragmentation, recombination, etc.

Jet modifications





Also sensitive to energy redistribution

- Collisions, induced radiations.
- Collective excitations.

Useful for studying the modified HF fragmentation.