Jet quenching theory overview

Sangyong Jeon

Department of Physics
McGill University
Montréal, QC, CANADA

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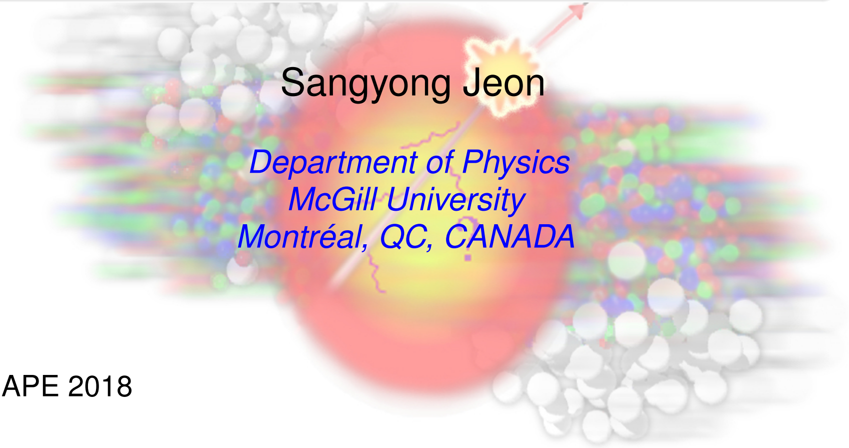
Jet-medium Interaction



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The issues I want to address

- How does the jet-energy loss influence the evolution of the QGP medium?
- Source term for the energy-momentum current
- Some results from the McGill team for
  - Medium Response to the Jet
  - Hadron-Jet correlations
  - Jets in pA

The Source

The hydro source term

- Formal statement of energy-momentum conservation without the source (that's hydro)

$$\partial_\mu T^{\mu\nu} = 0$$

- With the source

$$\partial_\mu T^{\mu\nu} = J^\nu$$

- When do you have the "energy-momentum" source?
  - When you have a "force"

$$F^\mu = \frac{dp^\mu}{d\tau}$$

- How do J^ν and F^ν connect?

Field-Particle Examples

Scalar field

- Lagrangian with a scalar source term J

$$\mathcal{L} = \mathcal{L}_\phi - J\phi = \frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - \frac{m^2}{2}\phi^2 - V(\phi) - J\phi$$

- Equation of motion

$$(\partial^2 + m^2)\phi + V'(\phi) = -J$$

- Stress-energy tensor

$$T_\phi^{\mu\nu} = (\partial^\mu\phi)(\partial^\nu\phi) - g^{\mu\nu}\mathcal{L}_\phi$$

- Energy-momentum flow

$$\begin{aligned} \partial_\mu T_\phi^{\mu\nu} &= \partial^\nu\phi\left(\partial^2\phi + m^2\phi + V'(\phi)\right) \\ &= -(\partial^\nu\phi)J \end{aligned}$$

Scalar field

- Classical particle dynamics with a *Lorentz scalar* field (e.g. nucleons and σ)

$$L = -(m+\phi)\sqrt{1-v^2}$$

- Euler-Lagrange equation

$$\frac{d}{d\tau}\left((m+\phi)\mathbf{u}\right) = -\nabla\phi$$

with $\mathbf{u} = \mathbf{v}\gamma$ and $u^0 = \sqrt{1+\mathbf{u}^2}$.

- With $p^\mu = (m+\phi)u^\mu$,

$$\frac{dp^\mu}{d\tau} = \partial^\mu\phi$$

Scalar field

- Energy momentum flow:

$$\partial_\mu T^{\mu\nu}_\phi = -J\partial^\nu \phi = -\frac{dp^\nu}{d\tau} J$$

- The source J can be interpreted as the scalar density of the particles.

$$J = \langle\sqrt{1-\mathbf{v}^2}\rangle = \langle m^*/E^*\rangle = m^* \int \frac{d^3p}{(2\pi)^3 E^*_p} f(t, \mathbf{x}, \mathbf{p})$$

where $m^* = m + \phi$ and $E^*_p = \sqrt{\mathbf{p}^2 + (m^*)^2}$.

Recall that $L = -(m+\phi)\sqrt{1-v^2}$.

Non-Abelian gauge field

- Lagrangian

$$\mathcal{L} = \mathcal{L}_G - J^\mu_a A^a_\mu$$

[Caveat: This is not gauge invariant.]
where

$$\mathcal{L}_G = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

with

$$G_{\mu\nu} = \frac{1}{ig}[D_\mu, D_\nu] \quad \text{and} \quad D_\mu = \partial_\mu + igA_\mu$$

Coloured object notation: $G_{\mu\nu} = G^a_{\mu\nu} T_a$ with $[T_a, T_b] = if_{abc} T_c$

Non-Abelian gauge field

- Equation of motion

$$[D_\mu, G^{\mu\nu}] = J^\nu$$

- Stress-energy tensor

$$T_G^{\mu\nu} = G_a^{\mu\alpha} G_\alpha^{a\,\nu} + \frac{g^{\mu\nu}}{4} G_a^{\alpha\beta} G^a_{\alpha\beta}$$

- Energy momentum flow

$$\partial_\mu T_G^{\mu\nu} = J_\mu^a G_a^{\mu\nu}$$

Classical coloured particle

- Wong Equations: Non-Abelian Lorentz force

$$\frac{dp^{\nu}_{\rm Kin}}{d\tau} = gQ_a G_a^{\nu\mu} u_\mu$$

and the color precession

$$\frac{dQ}{d\tau} = -ig[Q, u_\mu A^\mu]$$

where $p^{\mu}_{\rm Kin} = mu^\mu$ with $u^\mu = dx^\mu/d\tau$.

- Equivalently,

$$\frac{dp^{\nu}_{\rm Kin}}{dt} = gQ_a G_a^{\nu\mu} v_\mu$$

and

$$\frac{dQ}{dt} = -ig[Q, v_\mu A^\mu]$$

where $v^\mu = dx^\mu/dt$.

Energy-momentum flow

- Non-Abelian gauge field with a source

$$\partial_\mu T_G^{\mu\nu} = J_\mu^a G_a^{\mu\nu} = -G_a^{\nu\mu} J_\mu^a$$

- The current made up of Wong's particles

$$J_\mu^a(x) = \sum_q g Q_a v_{q,\mu}(t) \delta^{(3)}(\mathbf{x} - \mathbf{x}_q(t))$$

which gives

$$-G_a^{\nu\mu} J_\mu^a = -\sum_q G_a^{\nu\mu}(x) g Q_a v_{q,\mu}(t) \delta^{(3)}(\mathbf{x} - \mathbf{x}_q(t))$$

$$= -\sum_q \frac{dp_{\mathrm{Kin}}^{q,\nu}}{dt} \delta^{(3)}(\mathbf{x} - \mathbf{x}_q(t))$$

where q labels particles.

- More generally, the source term is

$$-S^\nu(x) = \sum_q \int d\lambda\, \delta^{(4)}(x - x_q(\lambda)) \frac{dp_q^\nu}{d\lambda}$$

Kinetic Theory Approach

- Energy momentum conservation

$$\partial_\mu T^{\mu\nu} = \partial_\mu \left(T^{\mu\nu}_{\rm soft} + T^{\mu\nu}_{\rm hard} \right) = 0$$

- Jet particle stress-energy tensor

$$T^{\mu\nu}_{\rm hard} = \int \frac{d^3p}{(2pi)^3 E_p} p^\mu p^\nu f_{\rm hard}(x, \mathbf{p})$$

- The source term for the medium evolution

$$\begin{aligned} S^\nu &= -\partial_\mu T^{\mu\nu}_{\rm hard} \\ &= -\int \frac{d^3p}{(2\pi)^3 E_p} p^\nu p^\mu \partial_\mu f_{\rm hard}(x, \mathbf{p}) \end{aligned}$$

Kinetic Theory Approach

- Considering only the scatterings (no Vlasov terms)

$$p^\mu \partial_\mu f_{\rm hard} = C_{\rm hard}[f_{\rm hard}, f_{\rm soft}]$$
$$k^\mu \partial_\mu f_{\rm soft} = C_{\rm soft}[f_{\rm hard}, f_{\rm soft}]$$

- Relationship between $C_{\rm hard}$ and $C_{\rm soft}$. is provided by energy-momentum conservation

$$\partial_\mu T^{\mu\nu} = \partial_\mu \left(T^{\mu\nu}_{\rm soft} + T^{\mu\nu}_{\rm hard}\right) = \partial_\mu \int d\Gamma_k k^\nu k^\mu f_{\rm soft}(k) + \partial_\mu \int d\Gamma_p p^\nu p^\mu f_{\rm hard}(p) = 0$$

Here $d\Gamma_p = d^3p/(2\pi)^3\omega_p$.

Kinetic Theory Approach

- Example: $2 \leftrightarrow 2$, Boltzmann

$$C_{\rm hard}[f_{\rm hard}, f_{\rm soft}](p) = \int d\Gamma_{k34} |M_{pk\leftrightarrow 34}|^2 (2\pi)^4 \delta^{(4)}(p + k - p_3 - k_4) \times (f_{\rm hard}(p_3) f_{\rm soft}(k_4) - f_{\rm hard}(p) f_{\rm soft}(k))$$

$$C_{\rm soft}[f_{\rm hard}, f_{\rm soft}](k) = \int d\Gamma_{p34} |M'_{pk\leftrightarrow 34}|^2 (2\pi)^4 \delta^{(4)}(p + k - p_3 - k_4) \times (f_{\rm hard}(p_3) f_{\rm soft}(k_4) - f_{\rm hard}(p) f_{\rm soft}(k))$$

- Need

$$M_{pk\leftrightarrow 34} = M'_{pk\leftrightarrow 34}$$

Kinetic Theory Approach

- Energy-momentum conservation

$$\partial_\mu T^{\mu\nu}_{\rm soft} = -\partial_\mu T^{\mu\nu}_{\rm hard}$$

- The "source term"

$$\begin{aligned}
-\partial_\mu T^{\mu\nu}_{\rm hard} &= -\int d\Gamma_p p^\nu p^\mu \partial_\mu f_{\rm hard}(p) \\
&= -\frac{1}{2}\int d\Gamma_{p234} |M_{p2\leftrightarrow 34}|^2 (2\pi)^4 \delta^{(4)}(p + k_2 - p_3 - k_4) \\
&\quad \times (p^\nu - p_3^\nu)\left(f_{\rm hard}(p_3) f_{\rm soft}(k_4) - f_{\rm hard}(p) f_{\rm soft}(k_2)\right) \\
&\sim \frac{\langle \Delta p^\nu \rangle_{\mathbf{x}}}{\tau_{\rm rel}} \delta^{(3)}(\mathbf{x} - \mathbf{x}_{\rm hard}(t))
\end{aligned}$$

assuming $f_{\rm hard}(p) \sim (2\pi)^3 \delta^{(3)}(\mathbf{p} - \mathbf{p}_{\rm hard}(t))\delta^{(3)}(\mathbf{x} - \mathbf{x}_{\rm hard}(t))$

- E-by-E interpretation possible

Kinetic Theory Approach - II

- Approximate the collision integral

$$p^\mu \partial_\mu f_{\rm hard}(x, \mathbf{p}) = \omega_p \left(\hat{e} \frac{\partial}{\partial \omega_p} + \frac{\hat{q}}{4} \nabla_{p_\perp^2} \right) f_{\rm hard}(x, \mathbf{p})$$

where $\hat{e}$ is the energy loss rate and $\hat{q}$ is the $\mathbf{p}_\perp$ diffusion rate.

- If $\omega_p \gg \mathbf{p}_\perp$, $\mathbf{p}_{\rm jet}$ hardly changes

$$f_{\rm hard}(x, \mathbf{p}) \approx \delta^{(3)}(\mathbf{x} - \mathbf{x}_0 - \frac{\mathbf{p}_{\rm jet}}{\omega_p} t)(2\pi)^3 \delta^{(3)}(\mathbf{p} - \mathbf{p}_{\rm jet})$$

then

$$\partial_\mu T^{\mu\nu}_{\rm hard} = \int \frac{d^3p}{(2\pi)^3 \omega_p} p^\nu p^\mu \partial_\mu f_{\rm hard}$$
$$\propto p^\nu_{\rm jet} \sim \frac{dp^\nu_{\rm jet}}{d\tau}$$

which makes sense only if the energy loss is mostly due to the collinear radiation

Simulation procedure

- MUSIC solves

$$\partial_\mu T^{\mu\nu} = S^\nu$$

in two parts. With $T^{\mu\nu} = T^{\mu\nu}_{\rm id} + \delta T^{\mu\nu}$, First solve

$$\partial_\mu T^{\mu\nu}_{\rm id} = -\partial_\mu \delta T^{\mu\nu} + S^\nu$$

Then solves (in the fluid rest frame)

$$\partial_t \delta T^{ij} = -\frac{1}{\tau_R}\left(\delta T^{ij} - \sigma^{ij}\right)$$

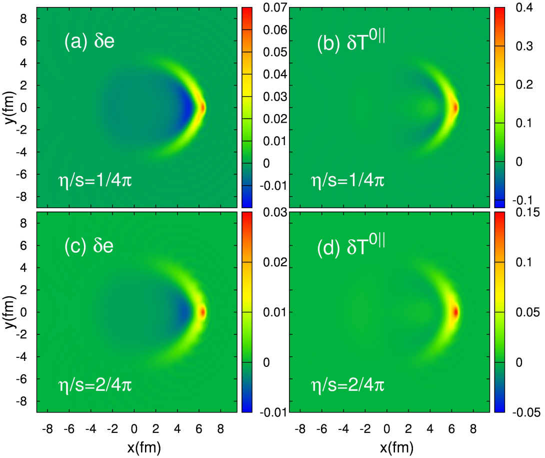
where

$$\sigma_{ij} = -\frac{1}{2}\left(\partial_i u_j + \partial_j u_i - \frac{2g_{ij}}{3}\partial_k u^k\right)$$

Some results

Medium response – Semi-analytic solution

[1707.09515, *Li Yan,* S. Jeon and C. Gale]



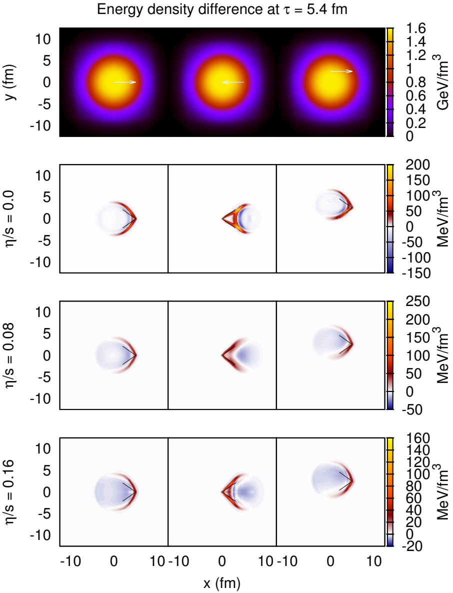
$\tau_0 = 0.5\,\text{fm}, \tau = 6.0\,\text{fm}$

- 2D Gubser background with non-zero η/s
- 2D "Jet" (a 1-D object, like a wire going through the medium)
- Perturbative calculation with the l, m decomposition – Up to $l = 30$
- Jet starts from $(1, 1)$ and moves outward (short medium side)
- The strength and the angle of the bow wave depends on η/s

Simulation results

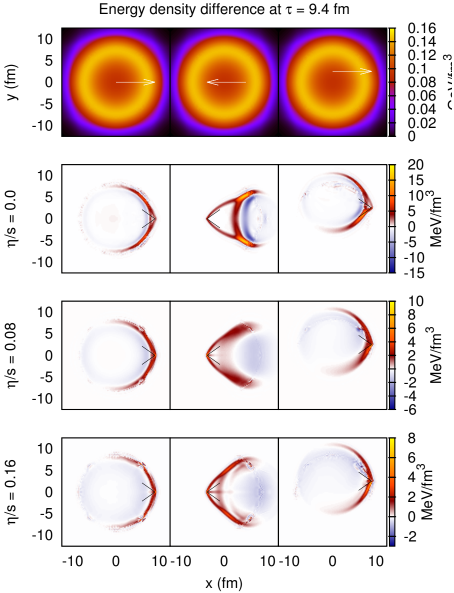
- Results shown:
  - All plots are *preliminary*.
  - IP-Glasma initial condition by *Scott McDonald*
  - MUSIC including medium response by *Mayank Singh*
  - MARTINI by *Chanwook Park*
  - With the help of B. Schenke and C. Shen
  - Number of events $\sim 1,000$ per plot

Medium response



- At $\tau = 5.4\,\mathrm{fm}$
- $\delta\epsilon/\epsilon \sim 10\,\%$
- Diffusion wake clearly visible – The higher η/s, the stronger the wake.
- The strength and the angle of the shock depends on η/s – Note that $\eta/s = 1/4\pi$ has *higher* temperature – Reheating

Medium response



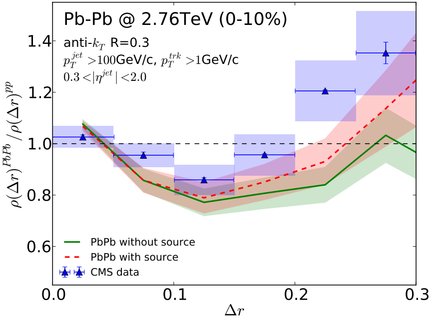
- Later time at $\tau = 9.4\,\mathrm{fm}$
- $\delta\epsilon/\epsilon \sim 10\,\%$
- The strength and the angle of the shock depends on η/s – The higher η/s, the weaker the shock wave – Dissipation wins

Jet-Shape function w/ Medium response

Jet-shape function

$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jets}} \frac{\sum_{\text{tracks}\in[r_a,r_b)} p_T^{\text{track}}}{p_T^{\text{jet}}}$$

with $r_a = r - \delta r/2$ and $r_b = r + \delta r/2$

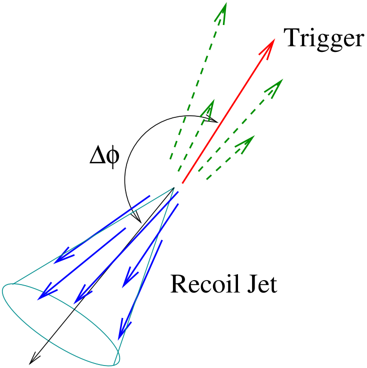


- In this plot: $\Delta r = r$.
- With and without the medium response
- Medium response is crucial in understanding the jet-shape change

Hadron-Jet Correlation (w/o Medium reponse)

- Semi-Inclusive recoil jet distribution

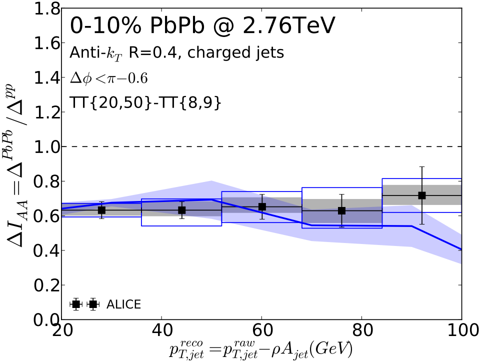
$$H_{TT}(p_{T,\mathrm{jet}}, \eta_{\mathrm{jet}}) \equiv \frac{1}{N^{AA}_{\mathrm{trig}}} \frac{d^2 N^{AA}_{\mathrm{jet}}}{dp^{\mathrm{ch}}_{T,\mathrm{jet}} d\eta_{\mathrm{jet}}}\Bigg|_{p_{T,\mathrm{trig}} \in \mathrm{TT}}, \qquad V_{TT}(\Delta\phi) \equiv \frac{1}{N^{AA}_{\mathrm{trig}}} \frac{d^2 N^{AA}_{\mathrm{jet}}}{dp^{\mathrm{ch}}_{T,\mathrm{jet}} d\Delta\phi}\Bigg|_{p_{T,\mathrm{trig}} \in \mathrm{TT}}$$



- Spectrum of recoil jets provided that a hard hadron is found in TT (Trigger Tracks). Includes no-jet cases.
- TT represents the trigger range. For example, $H_{8,9}(p_T, \eta)$ represents the jet spectrum with the trigger hadron within $(8\,\mathrm{GeV}, 9\,\mathrm{GeV})$

Hadron-Jet Correlation (w/o Medium reponse)

$$\Delta = H_{20,50}(p_T,\eta) - H_{8,9}(p_T,\eta)$$

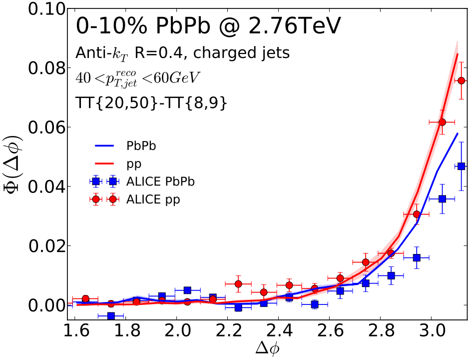


- Experimental feature roughly reproduced
- $\rho = \text{median}\left\{ \frac{p^{i,\text{raw}}_{T,\text{jet}}}{A^i_{\text{jet}}} \right\}$ with the highest two jet p_T's excluded.
- High p_T: Need more statistics

$$H_{TT}(p_{T,\text{jet}},\eta_{\text{jet}}) \equiv \frac{1}{N^{AA}_{\text{trig}}} \frac{d^2 N^{AA}_{\text{jet}}}{dp^{\text{ch}}_{T,\text{jet}}\, d\eta_{\text{jet}}}\bigg|_{p_{T,\text{trig}} \in \text{TT}},$$

Hadron-Jet Correlation (w/o Medium reponse)

$$\Phi(\Delta\phi) = V_{20,50}(\Delta\phi) - V_{8,9}(\Delta\phi)$$



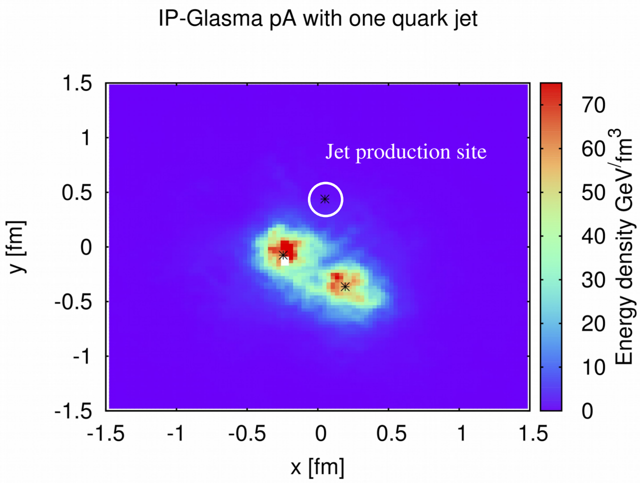
- High trigger (HT): Trigger p_T and the recoil jet direction tends to align
- Low trigger (LT): Trigger direction and the recoil jet direction are less correlated
- (HT) − (LT) still retains $\Delta\phi = \pi$ peak
- Medium interaction deflects jets: The trigger-jet correlation is degraded

$$V_{TT}(\Delta\phi) \equiv \left(1/N_{\rm trig}^{AA}\right) d^2N_{\rm jet}^{AA}/dp_{T,\rm jet}^{\rm ch}d\Delta\phi\Big|_{p_{T,\rm trig}\in {\rm TT}}$$

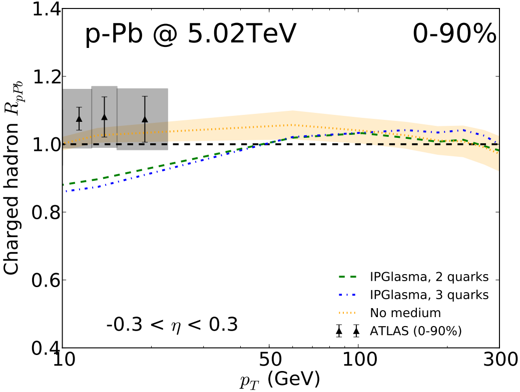
Extra: Jets in small systems

pA

- Energy distribution: IP-Glasma with 3 valence quarks
- If one quark generates a jet, it won't deposit energy



R_{pA} with or without the missing hot-spot



- No medium: Includes the nuclear PDF effects
- The missing hot-spot does make a difference, but not big.
- What about correlations? – In the works.

Conclusions

- Medium response to jet quenching maturing
  - Phenomenology is being explored
  - Bench-marking results for year 2 JETSCAPE release
- Hadron-Jet Correlation – Needs media response included
- Jets in small systems being explored – (In)Sensitive to the possible presence of QGP droplets?
- In the works: Groomed Jet