Probing transport properties with boson-jet correlations
in Heavy-Ion Collisions

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PLB 773 672
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NPB 933 306
CL, S.Y. Wei, H.Z. Zhang - in preparation

1. Introduction
   - the transport properties of Quark-Gluon Plasma
   - observables
2. Formalism
   - resummation
   - cross-section and Sudakov factor
   - hard factors
   - scales
3. Results
   - pp and smearing
   - AA and energy loss
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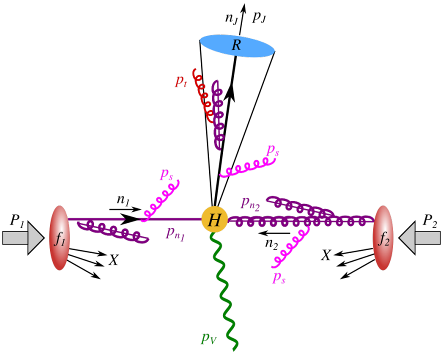
Introduction - QGP and $\hat{q}$

In RHIC and LHC, QGP is created.

beam view *top view*



Hard probes(jets) are used to study the QGP by comparing pp to AA collisions. Phenomena generally known as Jet Quenching.

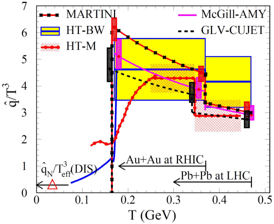
Jet Quenching, classified as:

- Transverse momentum broadening
- Jet energy loss

Transport property of the QGP

$$-\frac{dE}{dx} = \frac{\alpha_s N_c}{4}\hat{q}L, \quad \hat{q} \equiv \frac{d\langle q_\perp^2\rangle}{dL}$$

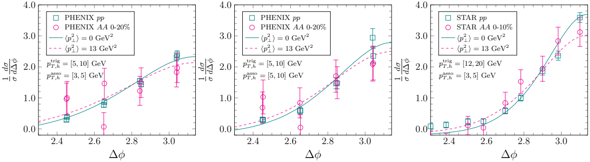
BDMPS NPB **483** (1997) 291, **484** (1997) 265, **531** (1998) 403



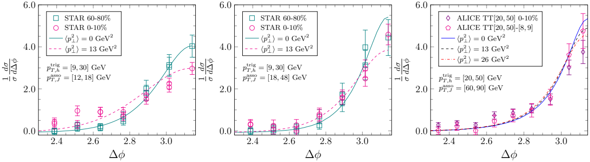
JET collaboration. PRC **90**, 014909 (2014)

INTRODUCTION - $\Delta\phi$ AND x_J

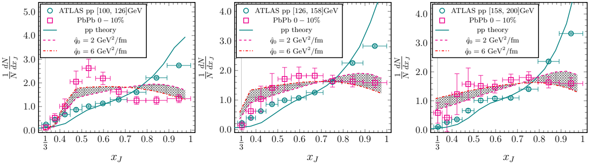
Di-hadron $\Delta\phi$



Hadron-jet $\Delta\phi$



Di-jet x_J



PLB **773** 672, PLB **782** 773

Formalism - resummation

pQCD vs Resummation:

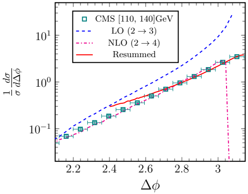
$$\sigma_0 \sum_{i=0}^{\infty} \alpha_s^i \left(L^i + C^{(i)} \right), \quad L^i \equiv \ln^{2i-1}\left(\frac{Q^2}{q_\perp^2}\right)$$

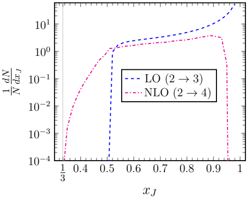
$$\sigma_0 \sum_{i=0}^{n-1} \alpha_s^i L^i \;\Big|\; \sigma_0 \sum_{i=0}^{n-1} \alpha_s^i C^{(i)} \quad \Leftarrow \text{pQCD}$$

$$\sigma_0 \sum_{i=n}^{\infty} \alpha_s^i L^i \;\Big|\; \sigma_0 \sum_{i=n}^{\infty} \alpha_s^i C^{(i)}$$

$\Uparrow$ resummation

$\nwarrow$ negligible



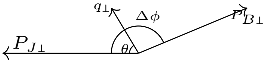


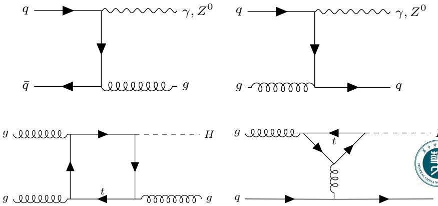
$$S_{\rm AA}(Q,b) = S_{\rm pp}(Q,b) + \frac{\langle \hat{q} L\rangle b^2}{4}$$

Mueller, Wu, Xiao, Yuan, 1608.07339, 1604.04250

$$\boxed{\frac{1}{\sigma}\frac{d\sigma}{dx_J}\Big|_{\rm Imp} = \frac{1}{\sigma_{\rm NLO}}\frac{d\sigma_{\rm NLO}}{dx_J}\Big|_{0<\Delta\phi<\phi_m} + \frac{1}{\sigma_{\rm Sud}}\frac{d\sigma_{\rm Sud}}{dx_J}\Big|_{\phi_m<\Delta\phi<\pi}}$$

Boson-jet Topology:





- Gamma-jet: photon neutral to QGP interaction, preserves momentum information of away-side jet.
- cross-section can discriminate individual jet species for energy loss implementation.
- Heavy-bosons: clean signature, encourages soft

Formalism - implementation

$$\frac{d^5\sigma}{dy_B dy_J dP_{J\perp}^2 d^2\vec{q}_\perp} = \sum_{ab}\sigma_0\left[\int \frac{d^2\vec{b}_\perp}{(2\pi)^2} e^{-i\vec{q}_\perp\cdot\vec{b}_\perp} W_{ab\to BJ}(x_1,x_2,b_\perp) + Y_{ab\to BJ}\right]$$

$$W_{ab\to BJ}(x_1,x_2,b_\perp) = x_1 f_a(x_1,\mu_{\rm fac})\; x_2 f_b(x_2,\mu_{\rm fac}) \times H_{ab\to BJ}(s,\mu_{\rm res}) e^{-S_{\rm Sud}(s,\mu_{\rm res})}$$

$$S_{\rm Sud}(s,\mu_{\rm res},b_\perp) = \int_{\mu_{\rm fac}^2}^{\mu_{\rm res}^2} \frac{d\mu^2}{\mu^2}$$

$$\times\left[\left(A^{(1)} + A^{(2)}\right)\ln\frac{s}{\mu^2} + B_1^{(1)} + B_2^{(1)} + D^{(1)}\ln\frac{1}{R^2}\right]$$

	quark	gluon
$A^{(1)}$	$C_F\left(\frac{\alpha_s}{2\pi}\right)$	$C_A\left(\frac{\alpha_s}{2\pi}\right)$
$A^{(2)}$	$KC_F\left(\frac{\alpha_s}{2\pi}\right)^2$	$KC_A\left(\frac{\alpha_s}{2\pi}\right)^2$
$B_1^{(1)}$	$-\frac{3}{2}C_F\left(\frac{\alpha_s}{2\pi}\right)$	$-2\beta_0 C_A\left(\frac{\alpha_s}{2\pi}\right)$
$B_2^{(1)}$	$\ln\frac{u}{t}C_F\left(\frac{\alpha_s}{2\pi}\right)$	$-\ln\frac{u}{t}C_A\left(\frac{\alpha_s}{2\pi}\right)$
$D^{(1)}$	$C_F\left(\frac{\alpha_s}{2\pi}\right)$	$C_A\left(\frac{\alpha_s}{2\pi}\right)$

$$\mathcal{F}_{\rm NP}(Q^2,b_*) = g_1 b^2 + g_2\ln\frac{Q}{Q_0}\ln\frac{b}{b_*}$$

Z+jet(along with definition on vector and axial-vector gauge couplings):

$$\sigma_0^{Z+\rm jet} \sim \frac{\alpha_s(g_V^2+g_A^2)\pi}{s^2}$$

$$g_V = \frac{g_W}{2\cos\theta_W}(\tau_3^q - 2Q_q\sin^2\theta_W),\quad g_A = \frac{g_W}{2\cos\theta_W}\tau_3^q$$

H+jet (with effective coupling in large top mass limit):

$$\sigma_0^{H+\rm jet} \sim \frac{\alpha_s^3\sqrt{2}G_F\pi}{s^2}$$

$$\begin{aligned} H_{ab\to BJ} &= H^{(0)}_{ab\to BJ} + H^{(1)}_{ab\to BJ} + \cdots \\ &= H^{(0)}_{ab\to BJ}\left(1 + \frac{\alpha_s}{2\pi}[\cdots] + \cdots\right) \end{aligned}$$

Formalism - Z+jet hard factor

$$H^{(0)}_{q\bar{q}\to Zg} = \frac{8}{3} C_F \left[\frac{t^2 + u^2 + 2m_Z^2 s}{tu} \right], \qquad H^{(0)}_{qg\to Zq} = C_F \left[\frac{s^2 + t^2 + 2m_Z^2 u}{-st} \right]$$

$$\begin{aligned}
H^{(1)}_{q\bar{q}\to Zg} = H^{(0)}_{q\bar{q}\to Zg} \frac{\alpha_s}{2\pi} \Bigg\{ \Bigg[& -2\beta_0 \ln\left(\frac{R^2 P_{J\perp}^2}{\mu_{\rm res}^2}\right) + \frac{1}{2}\ln^2\left(\frac{R^2 P_{J\perp}^2}{\mu_{\rm res}^2}\right) + \mathrm{Li}_2\left(\frac{m_Z^2}{m_Z^2 - t}\right) + \mathrm{Li}_2\left(\frac{m_Z^2}{m_Z^2 - u}\right) \\
& - \ln\left(\frac{\mu_{\rm res}^2}{m_Z^2}\right) \ln\left(\frac{s m_Z^2}{tu}\right) - \frac{1}{2}\ln^2\left(\frac{\mu_{\rm res}^2}{m_Z^2}\right) + \frac{1}{2}\ln^2\left(\frac{s}{m_Z^2}\right) - \frac{1}{2}\ln^2\left(\frac{tu}{m_Z^4}\right) + \ln\left(\frac{-t}{m_Z^2}\right)\ln\left(\frac{-u}{m_Z^2}\right) \\
& + \frac{1}{2}\ln^2\left(\frac{m_Z^2 - t}{m_Z^2}\right) + \frac{1}{2}\ln^2\left(\frac{m_Z^2 - u}{m_Z^2}\right) - \frac{1}{2}\ln^2\left(\frac{1}{R^2}\right) - \frac{2\pi^2}{3} + \frac{67}{9} - \frac{23 N_f}{54} \Bigg] C_A + 6\beta_0 \ln \frac{\mu_{\rm ren}^2}{\mu_{\rm res}^2} \\
& + \left[2\ln\left(\frac{s}{m_Z^2}\right) \ln\left(\frac{\mu_{\rm res}^2}{m_Z^2}\right) - \ln^2\left(\frac{\mu_{\rm res}^2}{m_Z^2}\right) - 3\ln\left(\frac{\mu_{\rm res}^2}{m_Z^2}\right) - \ln^2\left(\frac{s}{m_Z^2}\right) + \pi^2 - 8 \right] C_F \Bigg\} + \delta H^{(1)}_{q\bar{q}\to Zg}
\end{aligned}$$

$$\begin{aligned}
H^{(1)}_{qg\to Zq} = H^{(0)}_{qg\to Zq} \frac{\alpha_s}{2\pi} \Bigg\{ \Bigg[& -\mathrm{Li}_2\left(\frac{m_Z^2}{s}\right) + \mathrm{Li}_2\left(\frac{m_Z^2}{m_Z^2 - t}\right) - \ln\left(\frac{\mu_{\rm res}^2}{m_Z^2}\right) \ln\left(\frac{u m_Z^2}{st}\right) - \frac{1}{2}\ln^2\left(\frac{\mu_{\rm res}^2}{m_Z^2}\right) \\
& - \frac{1}{2}\ln^2\left(\frac{-st}{m_Z^4}\right) + \ln\left(\frac{s}{m_Z^2}\right)\ln\left(\frac{s - m_Z^2}{m_Z^2}\right) - \frac{1}{2}\ln^2\left(\frac{s}{m_Z^2}\right) + \frac{1}{2}\ln^2\left(\frac{m_Z^2 - t}{m_Z^2}\right) + \frac{1}{2}\ln^2\left(\frac{-u}{m_Z^2}\right) \\
& + \frac{\pi^2}{2} \Bigg] C_A + 6\beta_0 \ln \frac{\mu_{\rm ren}^2}{\mu_{\rm res}^2} + \left[-\frac{3}{2}\ln\left(\frac{R^2 P_{J\perp}^2}{\mu_{\rm res}^2}\right) + \frac{1}{2}\ln^2\left(\frac{R^2 P_{J\perp}^2}{\mu_{\rm res}^2}\right) + 2\ln\left(\frac{-u}{m_Z^2}\right)\ln\left(\frac{\mu_{\rm res}^2}{m_Z^2}\right) \right. \\
& \left. - \ln^2\left(\frac{\mu_{\rm res}^2}{m_Z^2}\right) - 3\ln\left(\frac{\mu_{\rm res}^2}{m_Z^2}\right) - \ln^2\left(\frac{-u}{m_Z^2}\right) - \frac{1}{2}\ln^2\left(\frac{1}{R^2}\right) - \frac{2\pi^2}{3} - \frac{3}{2} \right] C_F \Bigg\} + \delta H^{(1)}_{qg\to Zq}
\end{aligned}$$

1810.03804

Formalism - H+jet hard factor

$$H^{(0)}_{gg\to Hg} = C_A\left[\frac{s^4+t^4+u^4+m_H^8}{stu}\right], \qquad H^{(0)}_{qg\to Hq} = C_F\left[\frac{s^2+t^2}{-u}\right]$$

$$\begin{aligned}
H^{(1)}_{gg\to Hg} = H^{(0)}_{gg\to Hg}\frac{\alpha_s}{2\pi}\Bigg[&-2\beta_0\ln\left(\frac{R^2P_{J\perp}^2}{\mu_{\rm res}^2}\right)+\ln^2\left(\frac{\mu_{\rm res}^2}{P_{J\perp}^2}\right)+\ln\left(\frac{1}{R^2}\right)\ln\left(\frac{\mu_{\rm res}^2}{P_{J\perp}^2}\right)+6\beta_0\ln\frac{\mu_{\rm ren}^2}{\mu_{\rm res}^2}-2\ln\left(\frac{P_{J\perp}^2}{\mu_{\rm res}^2}\right)\ln\left(\frac{s}{\mu_{\rm res}^2}\right)\\
&-2\ln\left(\frac{s}{-t}\right)\ln\left(\frac{s}{-u}\right)+\ln^2\left(\frac{m_H^2-t}{m_H^2}\right)-\ln^2\left(\frac{m_H^2-t}{-t}\right)+\ln^2\left(\frac{m_H^2-u}{m_H^2}\right)-\ln^2\left(\frac{m_H^2-u}{-u}\right)\\
&+2\mathrm{Li}_2\left(1-\frac{m_H^2}{s}\right)+2\mathrm{Li}_2\left(\frac{t}{m_H^2}\right)+2\mathrm{Li}_2\left(\frac{u}{m_H^2}\right)+\frac{67}{9}+\frac{\pi^2}{2}-\frac{23N_f}{54}\Bigg]C_A+\delta H^{(1)}_{gg\to Hg}
\end{aligned}$$

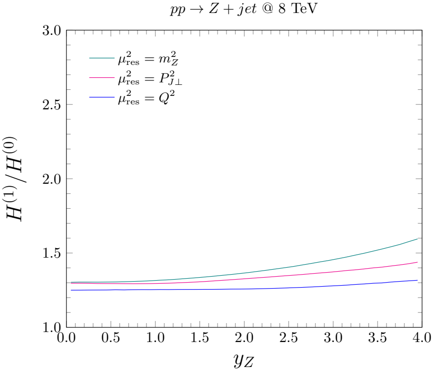
$$\begin{aligned}
H^{(1)}_{qg\to Hq} = H^{(0)}_{qg\to Hq}\frac{\alpha_s}{2\pi}\Bigg\{\Bigg[&\frac{1}{2}\ln^2\left(\frac{\mu_{\rm res}^2}{P_{J\perp}^2}\right)+\ln\left(\frac{P_{J\perp}^2}{\mu_{\rm res}^2}\right)\ln\left(\frac{u}{t}\right)+\ln\left(\frac{P_{J\perp}^2}{\mu_{\rm res}^2}\right)\ln\left(\frac{s}{\mu_{\rm res}^2}\right)-2\ln\left(\frac{-t}{\mu_{\rm res}^2}\right)\ln\left(\frac{-u}{\mu_{\rm res}^2}\right)\\
&-4\beta_0\ln\left(\frac{-u}{\mu_{\rm res}^2}\right)+6\beta_0\ln\frac{\mu_{\rm ren}^2}{\mu_{\rm res}^2}+2\mathrm{Li}_2\left(\frac{u}{m_H^2}\right)-\ln^2\left(\frac{m_H^2-u}{-u}\right)+\ln^2\left(\frac{m_H^2-u}{m_H^2}\right)+\frac{7+4\pi^2}{3}\Bigg]C_A\\
&+20\beta_0+\Bigg[\frac{1}{2}\ln^2\left(\frac{\mu_{\rm res}^2}{P_{J\perp}^2}\right)+\frac{3}{2}\ln\left(\frac{\mu_{\rm res}^2}{R^2P_{J\perp}^2}\right)+\ln\left(\frac{1}{R^2}\right)\ln\left(\frac{\mu_{\rm res}^2}{P_{J\perp}^2}\right)-\ln\left(\frac{P_{J\perp}^2}{\mu_{\rm res}^2}\right)\ln\left(\frac{u}{t}\right)\\
&-\ln\left(\frac{P_{J\perp}^2}{\mu_{\rm res}^2}\right)\ln\left(\frac{s}{\mu_{\rm res}^2}\right)+3\ln\left(\frac{-u}{\mu_{\rm res}^2}\right)+2\mathrm{Li}_2\left(1-\frac{m_H^2}{s}\right)+2\mathrm{Li}_2\left(\frac{t}{m_H^2}\right)-\ln^2\left(\frac{m_H^2-t}{-t}\right)\\
&+\ln^2\left(\frac{m_H^2-t}{m_H^2}\right)-\frac{3}{2}-\frac{5\pi^2}{6}\Bigg]C_F\Bigg\}+\delta H^{(1)}_{qg\to Hq}
\end{aligned}$$

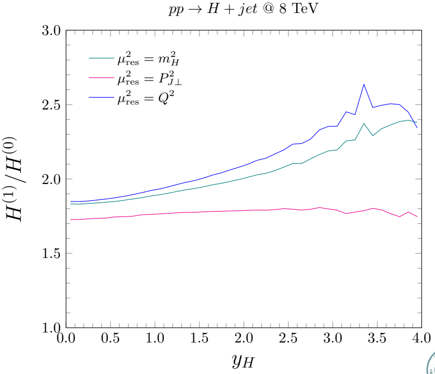
PRL **114** 202001, PLB **769** 57

Formalism - scale dependence

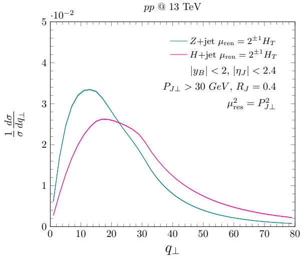
$$\mathrm{PDF}(\mu_{\mathrm{fac}}) \quad \xrightarrow[\int_{\mu_{\mathrm{fac}}}^{\mu_{\mathrm{res}}} \frac{d\mu^2}{\mu^2} \qquad H(\mu_{\mathrm{res}},\mu_{\mathrm{ren}})]{\text{Soft} \qquad \mu_{\mathrm{res}} \qquad \text{Hard}} \quad \sigma_0(\alpha_s(\mu_{\mathrm{ren}}))$$

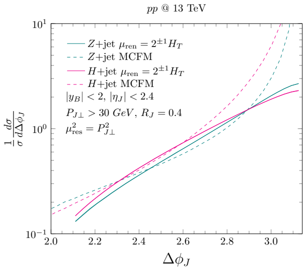
$$\mu_{\mathrm{fac}} = b_0/b_*, \quad \mu_{\mathrm{res}}^2 = p_{J\perp}^2, \quad \mu_{\mathrm{ren}} = H_T$$

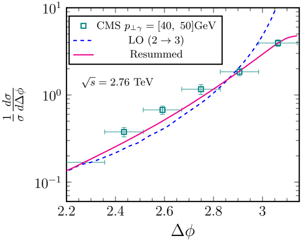


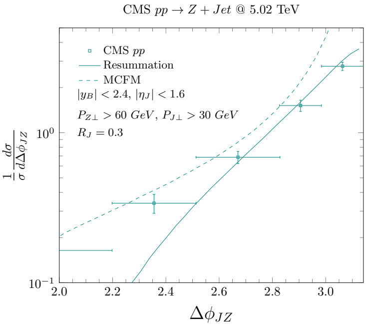


pp AND SMEARING



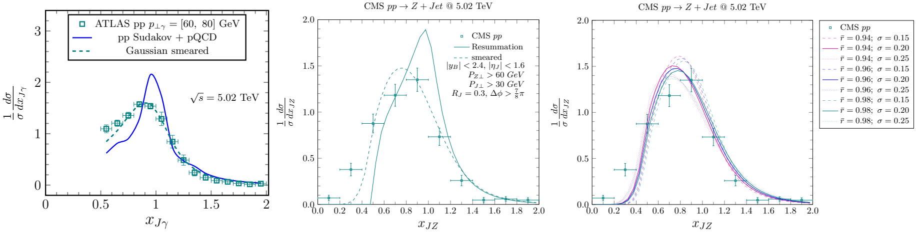






- Comparison between Higgs and Z showed that heavier particles have a higher tendency to give off soft radiations.
- this pushes the applicable region of the perturbative calculation further down to smaller $\Delta\phi$ region, while extending the applicability of resummation near π.
- as a result, the phase space near $\Delta\phi$ is dominated by 2-to-2 processes with soft radiations.

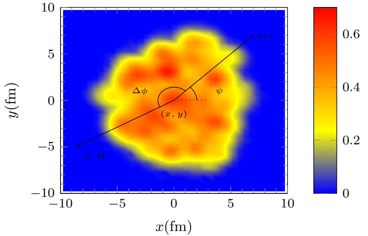
pp AND SMEARING

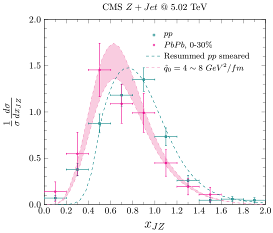


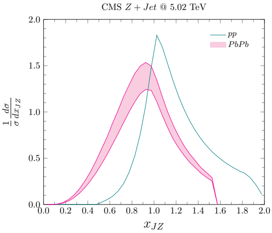
$$\frac{d\sigma_{\text{smeared}}}{dP_{J\perp}} = \int_{\bar{r}-5\sigma}^{\bar{r}+5\sigma} \frac{dr}{\sqrt{2\pi}\sigma} e^{-\frac{(\bar{r}-r)^2}{2\sigma^2}} \frac{1}{r} \frac{d\sigma}{dP'_{J\perp}}\bigg|_{P'_{J\perp}=P_{J\perp}/r}$$

- We note that the small x_J shoulder comes mainly from hard splittings. However, since the region $7/8\pi \leq \Delta\phi \leq \pi$ is mostly dominated by 2-to-2 processes, resummation results alone can give a good description of the experimental data.
- A simple Gaussian smearing is performed to mimic the effects of detector resolution and response.

AA AND JET QUENCHING







$$\epsilon D(\epsilon) = \sqrt{\frac{\alpha^2\omega_c}{2\epsilon}} \exp\left[-\frac{\pi\alpha^2\omega_c}{2\epsilon}\right], \quad \omega_c(x, y, \psi) = \hat{q}\frac{L^2}{2} = \hat{q}_0 \int \frac{T^3(x, y, \tau)}{T_0^3}\tau \, d\tau$$

$$\frac{d\sigma}{dP_{J\perp}} = \int \frac{dx dy d\psi}{T_{AB}} \int d\epsilon \, \epsilon D(\epsilon, \omega_c(x, y, \psi; \hat{q}_0)) \left.\frac{d\sigma}{dP'_{J\perp}}\right|_{P_{J\perp} = P'_{J\perp} - \epsilon}$$

- We then simulate a viscous hydro profile and extracted a radiation frequency profile assuming a simple temperature relation to the transport coefficient.
- the energy loss probability as a function of the radiation frequency given by the BDMPS formalism is used in our framework. Then an integral over the collision geometry is performed to give the quenched x_J distribution, which is similar to those given by Monte-Carlo parton showers.
- Finally, the unsmeared result is provided to give a hint of what the distribution would look like when experimental results are unfolded.

Summary and Outlook

- Previous dijet, gamma-jet results have shown that precision measurements and calculations are needed to further narrow down the uncertainties when extracting the transport coefficient.
- Heavy boson tagged jets could become a new standard in quantitative extraction of the $\hat{q}$ variable.
- results shown that as the produced particle gets heavier, the $\Delta\phi$ distribution near π will be dominated by 2-to-2 processes with soft radiations.
- Advantage of choosing events from phase-space that is dominated by 2-to-2 neutral tagged jets, is that we can discriminate the species of the jet by the energy loss factor.
- the *pp* baseline was established by fixing the smearing parameter, then $\hat{q}_0$ is extracted by simulating the jets in the hydro profile.

- include the effects of nPDF
- comparison between different energy loss models (GLV, HT, etc.)
- look at hadronic observables(gamma-hadron, Z-hadron)