High-$p_T$ asymmetries as a probe of initial stages in heavy-ion collisions

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High-$p_T$ Workshop
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Motivation
$R_{AA}$

CMS Collaboration, JHEP 04 039 (2017)

CMS-PAS-HIN-18-004

R$_{AA}$

$27.4\text{ pb}^{-1}$ (5.02 TeV pp) + 404 $\mu$b$^{-1}$ (5.02 TeV PbPb)

CMS

Preliminary

Normalization uncertainty

$|\eta| < 1$

CMS 5.44 TeV XeXe

LBT

Djordjevic

CUJET3.1/CIBJET

Andrés et al.

SCET$_G$

CMS 5.44 TeV XeXe

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Andrés et al.

SCET$_G$

CMS-PAS-HIN-18-004

$0$-$10\%$

Total data uncertainty

CMS Collaboration, JHEP 04 039 (2017)

Austin Baty, QM2018
High-$p_T$ $v_2$

**High-$p_T v_2$**

\[ \frac{dE}{dL} \sim LT^3 \]

\[ \frac{dE}{dL} \sim T^2 \]

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B. Betz and M. Gyulassy, JHEP 08, 090 (2014)
The scalar product

\[ \frac{R_{AA}(p_T, \phi)}{R_{AA}(p_T)} = 1 + 2 \sum_{n=1}^{\infty} v_n^{\text{hard}}(p_T) \cos \left[ n\phi - n\psi_n^{\text{hard}}(p_T) \right] \]

Average over all the events

\[ v_n^{\exp}(p_T) = \frac{\langle v_n^{\text{soft}} v_n^{\text{hard}}(p_T) \cos \left[ n \left( \psi_n^{\text{soft}} - \psi_n^{\text{hard}}(p_T) \right) \right] \rangle}{\sqrt{\langle (v_n^{\text{soft}})^2 \rangle}} \]

PbPb 2.76 TeV


Energy loss \( \frac{dE}{dL} \sim LT^3 \)

Hydro: v-USPhydro

\[ \tau_0 = 0.6 \text{ fm} \]
High-$p_T v_2$

$\tau_0 = 0.197$ fm

$\hat{q}(\tau) = \hat{q}(\tau_0), \tau < \tau_0$

$T_{dec} = 100$ MeV

$\hat{q}(\tau_0) = 0.197$ fm

v$_2$ 2.76 TeV 20-30% CMS

Failure?
High $p_T$-$v_2$

**CIBJET**
VISHNU viscous hydrodynamics

**JETSCAPE**
arXiv: 1902.05934
Formalism
**Formalism**

- **Single-inclusive cross section:**

\[
\frac{d\sigma^{AA\rightarrow h+X}}{dp_Tdy} = \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} \frac{dz}{z} \sum_{i,j,k} x_1 f_i/A(x_1, Q^2) x_2 f_j/A(x_2, Q^2) \frac{d\hat{s}^{ij\rightarrow k}}{d\hat{t}} D_{k\rightarrow h}(z, \mu_F^2)
\]

- **CTEQ6.6 + EPS09**

- **Fragmentation functions:**

\[
D_{k\rightarrow h}^{(med)}(z, \mu_F^2) = \int_0^1 d\epsilon P_E(\epsilon) \frac{1}{1-\epsilon} D_{k\rightarrow h}^{(vac)} \left( \frac{z}{1-\epsilon}, \mu_F^2 \right)
\]

**ENERGY LOSS: ASW Quenching Weights (QWs)**

Probability distribution of a fractional **energy loss**, \( \epsilon = \Delta E/E \), of the hard parton in the medium

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Quenching Weights

- Computed in the Multiple Soft Scattering approximation

\[ \sigma(r)n(\xi) \approx \frac{1}{2} \hat{q}(\xi)r^2 \quad \text{Perturbative tails neglected} \]

- Relation between \( \hat{q} \) and the hydrodynamic properties of the medium

\[ \hat{q}(\xi) = K \cdot 2\epsilon^{3/4}(\xi) \]

- Fitting parameter  
- EKRT hydro
**EKRT hydrodynamics**

- EKRT event by event hydrodynamics

Initial conditions: minijets + saturation model

\[ \tau_f = 0.197 \text{ fm} \]

\[ \eta/s = \text{param1} \]

\[ T_{\text{ch}} = 175 \text{ MeV} \]

\[ T_{\text{dec}} = 100 \text{ MeV} \]

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Open questions

• When do we **STOP** the energy loss?

\[ T_q = T_{ch} = 175 \text{ MeV} \]

\[ T_q = T_{kin} = 100 \text{ MeV} \]

• When do we **START** the energy loss?

- Case i) \( \tau_q = 0 \) \( (\hat{q}(\xi) = \hat{q}(\tau_f) \text{ for } \xi < \tau_f = 0.197 \text{ fm}) \)

- Case ii) \( \tau_q = 0.197 \text{ fm} \)

- Case iii) \( \tau_q = 0.572 \text{ fm} \) [Energy loss delayed \( \sim 0.6 \text{ fm} \)]
Dependence on FFs
High-$p_T v_2$ underestimated

High-$p_T v_2$ almost insensitive to the FFs

$T_q = T_{ch} = 175$ MeV

Case ii) $\tau_q = 0.197$ fm
Dependence on $T_q$
High-p_T $v_2$ still not well described. Better with **NO** energy loss in the hadronic phase

DSS07

Case ii) $\tau_q = 0.197$ fm
Dependence on $\tau_q$
High-$p_T$ harmonics are very sensitive to initial stages!

\[ T_q = T_{ch} = 175 \text{ MeV} \]
Conclusions

- The high-\(p_T\) \(v_2\) puzzle is not as simple as one could think

- We have analyzed the sensitivity of the high-\(p_T\) \(v_2\) to:
  - FFs
  - \(T_{\text{dec}}\)
  - \(\tau_q\)
- The high-\(p_T\) azimuthal asymmetries are very sensitive to the early times

- The high-\(p_T\) \(v_2\) data indicate the need of switching off the energy loss for the first \(\sim 0.6 \text{ fm}\)
We can fit the high-$p_T$ harmonics, but can we really understand why?
Backup slides
Quenching Weights

\[ P(\Delta E) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[ \prod_{i=1}^{n} d\omega_i \frac{dI^{(med)}(\omega_i)}{d\omega} \right] \delta \left( \Delta E - \sum_{i=1}^{n} \omega_i \right) \exp \left[ - \int_{0}^{\infty} d\omega \frac{dI^{(med)}}{d\omega} \right] \]

\[ \omega \frac{dI^{(med)}}{d\omega} = \frac{\alpha_s C_R}{(2\pi)^2 \omega^2} 2 Re \int_{\xi_0}^{\infty} d\bar{y}_l \int_{y_l}^{\infty} d\bar{y}_l \int_{0}^{\chi_{\omega}} d\k \ e^{-i\k \cdot \u} e^{-\frac{1}{2} \int_{y_l}^{\infty} d\xi n(\xi)\sigma(\u) \frac{\partial}{\partial y} \frac{\partial}{\partial u}} \]

\[ \times \int_{y=0}^{\bar{y}_l} Dr \exp \left[ i \int_{y_l}^{\bar{y}_l} d\xi \frac{\omega}{2} \left( \dot{r}^2 - \frac{n(\xi)\sigma(\r)}{i\omega} \right) \right] \]
Quenching Weights

- Based on two assumptions:
  - Fragmentation functions are **NOT** medium-modified
  - Gluon emissions are independent

**Total coherence case:**
- Jets lose energy as a single parton
- FFs vacuum-like

*Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk, PLB 725 357 (2013)*

- Gluon emissions are independent

*Good approximation for soft radiation*

*J. P. Blaizot, F. Dominguez, E. Iancu and Y. Mehtar-Tani, JHEP 1301 143 (2013)*
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Figure 3. Transport coefficient as a function of energy density for different media: cold, massless hot pion gas (dotted) and (ideal) QGP (solid curve)