Jet fragmentation photons in ultrarelativistic heavy-ion collisions

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EM probes as messengers of early-time dynamics

Pre-thermal stage
Thermalized QGP

Early-time dynamics

Photon freeze-out

Photonons & other EM probes provide best access to the early-time dynamics

Shuryak (1978), McLerran & Toimela (1985), etc

Photon yield, v2, and v3 measured in RHIC and LHC!!
Recent theoretical progresses

Still small v2 in 2015 (Shen, et al., 2015.)

+ Bulk viscosity, etc. (J.-F. Paquet, et al. See his talk.)
+ NLO HTL photon rate (Ghiglieri, et al.)
+ Nonperturbative background in semi-QGP (BNL)
+ B-field (Basar, et al., Tuchin, HK, Itakura, etc.)
+ ……

**Geometrical scaling of photons in pp, dA, AA @ RHIC & LHC**

Suggests an early-time emission?

→ How is the information of Qs transferred to γ?
→ Is the large v2 again puzzling?

+ Glasma? (McLerran, Schenke; Tanji)
+ Jet fragmentation? → This talk

\[
\left(\frac{Q_s}{p_T}\right)^\lambda
\]

Klein-Boesing, McLerran (2014)
$v_2$ of jets generated by energy loss
→ Can be transferred to photon $v_2$?

$v_2$ of $\pi^0$ and $\eta$ at high $p_t$ -- Almost species independent

$R_{AA}$ of high-$p_t$ $\pi^0$

50% loss

QGP eating jets

PHENIX, 2010, 2013
Estimates by classical electrodynamics
Provides a good approximation when kinematics is properly treated.

Velocity-dependence of emission angles

Bremsstrahlung from relativistic and nonrelativistic particles

+ Relativistic particles
  Forward-dominant emission
  → Collimation btw the jet & photon momenta.

+ Non-relativistic particles
  Isotropic emission from
  → Uncollimated emission

c.f. “Dead-cone effect” in the heavy-quark jet energy loss, Dokshitzer, Kharzeev (2001)
Bremsstrahlung from a quark (antiquark) jet

Photon emission rate from quark current

\[ 2\epsilon_p \frac{d\eta_\gamma}{d^3p} = -\frac{1}{(2\pi)^3} \left. \tilde{j}^\mu(p)\tilde{j}^*_\mu(p) \right|_{p^0=|p|} \]

Quark (antiquark) current

\[ j_\mu(x) = e \left\{ \nu_{ini}^\mu \delta^{(3)}(x - \nu_{ini} t) \theta(-t) + \nu_{fin}^\mu \delta^{(3)}(x - \nu_{fin} t) \theta(t) \right\} \]

Classical trajectory after the scattering

Before the scattering \( \nu_{ini} = (0, 0, 1) \)

After the scattering \( \nu_\perp = \frac{k_t}{\epsilon_{jet}} = \frac{k_t}{\sqrt{k_t^2 + Q_{jet}^2} \cosh Y_{jet}} = \frac{\kappa}{\cosh Y_{jet}} \quad \nu_z = \tanh Y_{jet} \)

- Relativistic limit \( (k_t \gg Q_{jet}) \)
- Non-relativistic limit \( (k_t \ll Q_{jet}) \)
Degree of the collimation in the bremsstrahlung

Photon emission rate

\[ 2\epsilon_P \frac{dn_\gamma}{d^3p} = \frac{\alpha_{em}}{p^2} \left( \cdots \right) \left\{ \cosh(Y_{jet} - Y_\gamma) - \kappa \cos(\phi_{jet} - \phi_\gamma) \right\}^2 \rightarrow \frac{1}{1 - \kappa} \text{ when } Y_{jet} = Y_\gamma, \phi_{jet} = \phi_\gamma \]

\[
\frac{1}{p_t \, dp_t \, d\phi_\gamma \, dY_\gamma} \frac{dn_\gamma}{dY_\gamma}
\]

\( \kappa = 0.9 \) Collimated emission

\( \kappa = 0.7 \) Little collimation

Relativistic
What is the dominant quark-jet production process?

→ Gluon Compton scattering

1. Gluon-dominant PDF
   → Take processes involving at least one gluon.
2. Dominant diagrams from gluon exchanges

\[ \epsilon_p \frac{dN_\gamma}{d^3 p} = N_{\text{jet}} \int d^4 k_1 \int d^4 k_2 \frac{dn_{\text{jet}}}{d^4 k_1 d^4 k_2} \cdot \epsilon_p \frac{dn_\gamma}{d^3 p_\gamma} \]

Enhanced by \( 1/q \)

\( \alpha_s^2/k_t^2 \)
Transverse jet momentum distribution

Assuming the boost invariance,

\[
\epsilon_p \frac{dN_{\gamma}}{d^3 p} = N_{\text{jet}} \int dY_{\text{com}} dY \int d\phi_{\text{jet}} \int_{k_{\text{min}}}^{k_{\text{max}}} dk t dk t \frac{dn_{\text{jet}}}{k t dk t d\phi_{\text{jet}} dY} \cdot \epsilon_p \frac{dn_{\gamma}}{d^3 p}
\]

\[
Y_{\text{com}} = Y_1 + Y_2
\]

\[
Y = (Y_1 - Y_2)/2
\]

\[
\frac{dn_{\text{jet}}}{k t dk t d\phi_{\text{jet}} dY} = \frac{\alpha_s^2}{k t^2} \frac{d\sigma_{gq}}{dY} \left( \frac{1}{1 + k t/Q_{\text{sat}}} \right)^{\beta} \left( 1 + 2v_{\text{jet}}^{(2)} \cos 2\phi_{\text{jet}} + \cdots \right)
\]

+ Phenomenological parameters

\[\beta \sim 6, \ v_{\text{jet}}^{(2)} \sim v_2 \text{ of high-}p_t \pi^0\]

**Cutoffs of the transverse jet momentum**

Maximum jet momentum should be smaller than the beam energy: \[s_{gq} < s_{NN}\]

Minimum jet momentum should be larger than the photon momentum: \[\epsilon_{\text{jet}} > \epsilon_{p_{\gamma}}\]

If this condition allows for less 1 GeV, the momentum is cutoff sharply at 1 GeV.
Expectations for photon yield and v2

\[ \frac{dn_{\text{jet}}}{k_t dk_t d\phi_{\text{jet}} dY} \bigg|_{\phi,Y=0} \]

- Uncollimated emission
  - Large contribution
- Collimated emission
  - Small contribution

\[ k_t \text{ distribution} \]

-- Power law with the exponent \( \sim 8 \)
Results: RHIC energy

\[ \epsilon_p \frac{dN_\gamma}{d^3p} = \frac{1}{2\pi p_t} \frac{dN_\gamma}{dp_t dY_\gamma} \left( 1 + 2\nu_\gamma^{(2)} \cos 2\phi_p + \cdots \right) \]

Photon yield
from the jet fragmentation

Ratio of the anisotropies: \( \frac{\nu_\gamma^{(2)}}{\nu_{\text{jet}}^{(2)}} \) (\%)
-- Momentum anisotropy transferred from jets to photons.

\[ \left. \frac{1}{2\pi p_t} \frac{dN_\gamma}{dp_t dY_\gamma} \right|_{\gamma_{\text{jet}}=0} \]

\( Q_{\text{jet}} = 1 \text{ GeV} \quad Q_s = 1 \text{ GeV} \)
\( Q_{\text{jet}} = 0.5 \text{ GeV} \)
\( Q_{\text{jet}} = 0.1 \text{ GeV} \)
Converting the jet $v_2$ to the photon $v_2$

High $p_t$ pion $v_2$

PHENIX, 2010, 2013

$P_t$ averaged jet $v_2$
- 0-10%: 0.066
- 10-20%: 0.097
- 20-30%: 0.12
- 30-40%: 0.148
- 40-50%: 0.136
- 50-60%: 0.173

Fragmentation photon $v_2$

50-60% Centrality
Summary

We investigated the jet fragmentation photons by the simplest and clearest setup, which captures the importance of kinematics and jet mass.

Conclusion for the first estimate:

Large v2 ⇔ Small yield

Small v2 ⇔ Large yield

What about the medium-induced photon radiation?

c.f., Turbide, et al.

Need to pursue mechanisms of the geometrical scaling of photons.
Recent photon measurements  See next talks.
How precisely do we know photon sources?

\[ N_{\text{dir}} = N_{\text{prompt}} + N_{\text{jet}} + N_{\text{QGP}} + N_{\text{Had}} + \cdots \]

- Hard
- Semi-hard
- High T
- Soft
- Low T

1D expansion \( \rightarrow \) 3D expansion
(Transverse-flow development)

\[ \nu_{\text{dir}}^{(2)} = N_{\text{prompt}}\nu_{\text{prompt}}^{(2)} + N_{\text{jet}}\nu_{\text{jet}}^{(2)} + N_{\text{QGP}}\nu_{\text{QGP}}^{(2)} + N_{\text{Had}}\nu_{\text{Had}}^{(2)} + \cdots \]

- Small
- ???
- Small
- Large

Ellipsis includes other sources such as Glasma, strong B-fields, etc.

Early theoretical observations:
+ Small v2 in QGP phase
+ Large v2 in hadron phase
\( \rightarrow \) On average, small v2 of direct photons

Kolkata-Ohio, (2006)
Consistent results from McGill-BNL, (2011)
\[
\frac{dn_{\text{jet}}}{k_t dk_t d\phi_{\text{jet}} dY} = \frac{\alpha_s^2}{k_t^2} \frac{d\sigma_{qq}}{dY} \left( \frac{1}{1 + k_t/Q_{\text{sat}}} \right)^\beta \left\{ 1 + 2v_{\text{jet}}^{(2)} \cos 2\phi_{\text{jet}} + \cdots \right\}
\]

\[
\epsilon_p \frac{dN_\gamma}{d^3 p} = \frac{1}{2\pi p_t} \frac{dN_\gamma}{dp_t dY_\gamma} \left\{ 1 + 2v_\gamma^{(2)} \cos 2\phi_p + \cdots \right\}
\]

\[
\frac{v_\gamma^{(2)}}{v_{\text{jet}}^{(2)}} = \frac{\int \cos(2\phi)f_0(k_t, Y) \cdot \epsilon_p \frac{dn_\gamma}{d^3 p}}{\int f_0(k_t, Y) \cdot \epsilon_p \frac{dn_\gamma}{d^3 p}}
\]
Rapidity distribution of jets emitting photons in mid-rapidity

\[ Y_{\text{jet}} \sim 0 \]
- Collimated emission

\[ Y_{\text{jet}} \neq 0 \]
- Uncollimated emission
Bremsstrahlung from a quark (antiquark) jet

Photon emission rate from quark current

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Quark (antiquark) current

\[ j^\mu(x) = e \left\{ \nu^\mu_{\text{ini}} \delta^{(3)}(x - v_{\text{ini}} t) \theta(-t) + \nu^\mu_{\text{fin}} \delta^{(3)}(x - v_{\text{fin}} t) \theta(t) \right\} \]

\[ v_{\text{ini}} = (0, 0, 1) \]

Classical trajectory after the scattering

\[ \epsilon^2_{\text{jet}} - k^2_{\text{jet}} = Q^2_{\text{jet}} \]

\[ \nu_\perp = \frac{k_t}{\epsilon_{\text{jet}}} = \frac{k_t}{\sqrt{k_t^2 + Q^2_{\text{jet}}} \cosh Y_{\text{jet}}} \]

\[ \kappa \rightarrow 1 \quad \text{Relativistic limit} \quad (k_t \gg Q_{\text{jet}}) \]

\[ \rightarrow 0 \quad \text{Non-relativistic limit} \quad (k_t \ll Q_{\text{jet}}) \]

Photon emission rate

\[ 2 \epsilon p \frac{dn_\gamma}{d^3 p} \propto \frac{\alpha_{\text{em}}}{p^2_\perp} \left\{ \cosh(Y_{\text{jet}} - Y_\gamma) - \kappa \cos(\phi_{\text{jet}} - \phi_\gamma) \right\}^2 \]

Specific processes discussed in the next slide.
What is the dominant quark-jet production process? → Gluon Compton scattering

1. Gluon-dominant PDF
   → Take processes involving at least one gluon.

2. Dominant diagrams from gluon exchanges

   ![Diagrams showing gluon exchanges](image)

   **Leading-order results**

   \[
   \frac{d\sigma_{qq}}{d\hat{t}} = \frac{\pi \alpha_s^2}{\hat{s}^2} \left[ -\frac{4}{9} \left( \hat{s} + \hat{u} \right) + \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} \right]
   \]

   \[
   \frac{d\sigma_{gg}}{d\hat{t}} = \frac{\pi \alpha_s^2}{\hat{s}^2} \left[ \frac{1}{6} \left( \hat{t} + \hat{u} \right) - \frac{3}{8} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2} \right]
   \]

   Enhanced by 1/q²

   Suppressed by COM energy

   \[
   \hat{s} = (2k_t \cosh Y)^2
   \]

   \[
   \hat{t} = -\hat{s} (1 - \tanh Y)/2
   \]

   \[
   \hat{u} = -\hat{s} (1 + \tanh Y)/2
   \]