Jet Quenching in Evolving QGP Medium

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McGill-AMY Team & Collaborators

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- **G. Qin**
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- **J. Ruppert**
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- U. Heinz
- D. Srivastava
- S. Bass
- C. Nonaka
- M. Mustafa
- E. Frodermann
- R. Fries

... and many thanks to A. Majumder, L. Yaffee, P. Arnold, and others...
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Cast of many and the list of Acronyms

(Arbitrary ordering)

- **GW** (Gyulassy and Wang)
- **BDMPS-Z** (Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov)
- **(WHD)GLV** (Gyulassy, Lévai, Vitev, Djordjevic, Adil, Wicks, Horowitz, ...)
- **AWS** (Armesto, Wiedemann, Salgado, Dainese, Loizides, Paić, Eskola, Honkanen, Renk, Ruppert, ...)
- **HT** (Higher-Twist, Wang, Guo, Zhang, Zhang, Majumder, Fries, Muller, ...)
- **McGill-AMY** (Qin, Turbide, Ruppert, Schenke, Gale, Moore, Jeon, ...)
- Sarcevic, Huang, Jalilian-Marian, ...
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- GW (Gyulassy and Wang)
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- HT (Higher-Twist, Wang, Guo, Zhang, Zhang, Majumder, Fries, Muller, ...)
- McGill-AMY (Qin, Turbide, Ruppert, Schenke, Gale, Moore, Jeon, ...)
- Sarcevic, Huang, Jalilian-Marian, ...
What is Jet Quenching?
Away side jet disappears! – Proof of principle

Near-side jet
Away-side jet
Hard scattering

Now we need more informative observables to study detailed properties of the medium.

STAR PRL91, 072304 (2003)
Away side jet disappears! – Proof of principle

Near-side jet
Away-side jet
Hard scattering

Now we need more informative observables to study detailed properties of the medium.
Back in 1990...

Miklos Gyulassy and Michael Plümer

*Jet quenching in lepton nucleus scattering*

in Nuclear Physics B Volume 346, 1 (1990).

**Key Idea:** Compare high $p_T$ spectrum in sth-$N$ and sth-$A$ by plotting the ratio.

How jets are disappearing in hot/dense medium can tell us about the medium
Back in 1990...

Xin-Nian Wang and Miklos Gyulassy,
*Jets in relativistic heavy ion collisions*
in BNL RHIC Workshop
1990:0079-102
(QCD199:R2:1990)

![Dijet reduction factor graph](image)

**Fig. 7** Dijet reduction factor for central $U + U$ collisions at $\sqrt{s} = 200$ GeV/n as a function of the dijet energy $E = P_{T1} + P_{T2}$, for different values of $\kappa_Q/\kappa_H$ assuming $\kappa_H = 1$ GeV/fm.

transverse coordinate, $\phi$ the azimuthal angle of the jet and $\tau_f(r, \phi)$ the escape time. Assuming only Bjorken[31] scaling longitudinal expansion and a Bag model equation of state[31], one can find the time dependence of $dE(\tau)/dx$ and get the reduction rate of jet production at fixed $P_T$ by averaging over the initial coordinates $(r, \phi)[22]$, 

$$R_{AA}(E) = \frac{\sigma_{jet}(E)_{\text{quenching}}}{\sigma_{jet}(E)_{\text{no-quenching}}}.$$  

(11)

In the plasma phase, the temperature decreases as $T(\tau)/T_c = (\tau_Q/\tau)^{1/3}$. According to Eq. 9, $dE/dx \approx \kappa_Q(\tau_Q/\tau)^{2/3}$, denoting the energy loss in the plasma phase by
$R_{AA}$ ($\pi^0$) for central Pb+Pb collisions at $\sqrt{s_{NN}} = 17$ GeV and central Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV.

$R_{AA}$ ($\pi^0$) for central and peripheral Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

Presented by S. Mioduszewski at QM 2002
In 2008

PHENIX, PRL 101, 232301, 2008

\[
\frac{dN_{AA}/dp_T}{N_{coll}dN_{pp}/dp_T} \approx \text{Const.}
\]

for \( p_T \geq 4 \text{ GeV} \)
Jet Quenching
– Schematic Ideas
Hadronic Jet production

Jets in QGP
If $Q \gg \Lambda_{\text{QCD}}$, $\alpha_s(Q) \ll 1$:
Jet production is perturbative.

Bethke, hep-ex/0606035
If $Q \gg \Lambda_{QCD}$, $\alpha_s(Q) \ll 1$: Jet production is perturbative.

→ Calculation is possible.
If $Q \gg \Lambda_{\text{QCD}}$, $\alpha_s(Q) \ll 1$: Jet production is perturbative.

- Calculation is possible.
- We understand this process in hadron-hadron collisions.
Hadronic Jet production

Hadron-Hadron Jet production scheme:

\[
\frac{d\sigma}{dt} = \int_{abcd} f_{a/A}(x_a, Q_f) f_{b/B}(x_b, Q_f) \times \frac{d\sigma_{ab\rightarrow cd}}{dt} D(z_c, Q)
\]
What we want to study:

- How does QGP modify jet property?
What we want to study:
- How does QGP modify jet property?

Complications:
- How well do we know the initial condition?
  - Nuclear initial condition?
- What happens to a jet between the production and the formation of (hydrodynamic) QGP?

(Not a part of this talk. See B. Schenke, Fri.5A)
Schematically, 

\[
\frac{d\sigma_{AB}}{dt} = \int_{\text{geometry}} \int_{abcd} \times f_{a/A}(x_a, Q_f) f_{b/B}(x_b, Q_f) 
\times \frac{d\sigma_{ab\rightarrow cd}}{dt} 
\times \mathcal{P}(x_c \rightarrow x'_c|T, u^\mu) 
\times D(z'_c, Q) 
\]

\[
\mathcal{P}(x_c \rightarrow x'_c|T, u^\mu): \text{ Medium modification of high energy parton property}
\]
https://wiki.bnl.gov/TECHQM/

Results for finite length medium calculations of $P(x_c \rightarrow x'_c|T)$ (the “brick”)
- WHDG (Wicks-Horowitz-Djordjevic-Gyulassy)
- GLV-WMC (Wick’s Monte-Carlo)
- McGill-AMY
- Higher-Twist
- YaJEM
- ASW
- APC
Why it is not-trivial

- Hot and dense system
  ➔ Even perturbative expansion requires resummation
- Finite size system
- System is evolving
Why it is not-trivial

- Hot and dense system
  $\implies$ Even perturbative expansion requires resummation
- Finite size system
- System is evolving

I will mainly discuss **radiational (inelastic)** energy loss.
General calculational scheme

First calculate the *local* radiation rate $\frac{dN_g}{d\omega dt}$

The magenta box:

- QGP medium characterized by $T, g_s$ – AMY, DGLV
- Static medium characterized by $\mu, l_{mfp}$ – BDMPS-Z, GLV, AWS, ...
- General nuclear medium with short color correlation – HT
First calculate the *local* radiation rate $\frac{dN}{d\omega dt}$

The cyan box:

- Infinite sum vs opacity expansion
- Momentum space vs Coordinate space
Then string them up $\equiv$ Solve the Fokker-Planck equation

$$\frac{dP(p)}{dt} = \int_k \frac{dN}{dkdt} P(p + k) - P(p) \int_k \frac{dN}{d\omega dt}$$
Then string them up $\equiv$ Solve the Fokker-Planck equation

$$\frac{dP(p)}{dt} = \int_k \frac{dN}{dkdt} P(p + k) - P(p) \int_k \frac{dN}{d\omega dt}$$

The underlying medium evolves: The quantities $T(t, \mathbf{x}), u_\mu(t, \mathbf{x})$ or $\mu(t, \mathbf{x}), l_{\text{mfp}}(t, \mathbf{x})$ must be obtained from hydro calc’s (for instance)
Radiational Energy Loss – Why coherence matters
Coherent scattering can be important

Following BDMPS

\[ \theta \sim k_\perp / k \]

\[ p \gg \mu \]

\[ l_{\text{mfp}} \]

\[ k \gg \mu \]

\[ p - k \gg \mu \]

\[ t_1 \quad t_2 \quad t_3 \quad \ldots \quad t_N \]

\[ s_1 \quad s_2 \quad s_M \]
Coherent scattering can be important

Following BDMPS

Point here: Radiated gluon also undergoes multiple scatterings.
Coherent scattering can be important

Following BDMPS

\[
\theta \sim \frac{k_\perp}{k}
\]

Point here: Radiated gluon also undergoes multiple scatterings.

What we need to calculate \( R_{AA} \):

\[
\omega \frac{dN_g}{d\omega dz}
\]

Medium dependence comes through a scattering length scale

\[
l \approx t
\]

\[
\omega \frac{dN_g}{d\omega dz} \approx \frac{1}{l} \omega \frac{dN_g}{d\omega} \bigg|_{BH}
\]
Coherent scattering can be important

Following BDMPS

- If all scatterings are incoherent ($l_{mfp} > l_{coh}$),

$$l = l_{mfp} = 1 / \rho \sigma$$
Coherent scattering can be important

Following BDMPS

- If all scatterings are incoherent ($l_{\text{mfp}} > l_{\text{coh}}$),
  \[ l = l_{\text{mfp}} = 1/\rho\sigma \]

- If $l_{\text{coh}} \geq l_{\text{mfp}} \implies \text{LPM effect:}$
  All scatterings within $l_{\text{coh}}$ effectively count as a single scattering.
Coherent scattering can be important

Following BDMPS

- If all scatterings are incoherent \( (l_{\text{mfp}} > l_{\text{coh}}) \),
  \[
  l = l_{\text{mfp}} = \frac{1}{\rho \sigma}
  \]

- If \( l_{\text{coh}} \geq l_{\text{mfp}} \implies \text{LPM effect:} \)
  All scatterings within \( l_{\text{coh}} \) effectively count as a single scattering.

- How to estimate \( l_{\text{coh}} \):

\[
\langle \theta^2 \rangle \approx N_{\text{coh}} (\bar{\theta}_g^2 + \bar{\theta}_q^2) \approx l_{\text{coh}} l_{\text{mfp}} (\mu_g^2 \omega_{\text{LPM}}^2 + \mu_q^2 E_q^2)
\]

Hence (with \( E_{\text{LPM}} = \mu_l^2 l_{\text{mfp}} \))

\[
l_{\text{coh}} = l_{\text{mfp}} \sqrt{\frac{\omega_{\text{LPM}}}{E_{\text{LPM}}}} \frac{\sqrt{E_q^2}}{E_{\text{LPM}}} \approx l_{\text{mfp}} \sqrt{\frac{\omega_{\text{LPM}}}{E_{\text{LPM}}}} \quad \text{for} \quad E_q \gg \omega_{\text{LPM}}\]
Coherent scattering can be important

Following BDMPS

- If all scatterings are incoherent \((l_{\text{mfp}} > l_{\text{coh}})\),
  \[ l = l_{\text{mfp}} = \frac{1}{\rho \sigma} \]

- If \(l_{\text{coh}} \geq l_{\text{mfp}} \implies\) LPM effect:
  All scatterings within \(l_{\text{coh}}\) effectively count as a single scattering.

- How to estimate \(l_{\text{coh}}\):
  \(l_{\text{coh}}\): Length needed to accumulate \(O(1)\) phase change in \(e^{ik\Delta x}\)
  \[ 1 \sim k_g^\mu \Delta x_\mu^q \sim t_{\text{coh}} \omega_g (1 - \hat{k}_g \cdot \Delta \hat{x}_q / t_{\text{coh}}) \sim l_{\text{coh}} \omega_g \langle \theta^2 \rangle \]
Coherent scattering can be important

Following BDMPS

- If all scatterings are incoherent \((l_{\text{mfp}} > l_{\text{coh}})\),
  \[
  l = l_{\text{mfp}} = \frac{1}{\rho \sigma}
  \]

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  All scatterings within \(l_{\text{coh}}\) effectively count as a single scattering.

- How to estimate \(l_{\text{coh}}\):
  \(l_{\text{coh}}\): Length needed to accumulate \(O(1)\) phase change in \(e^{ik\Delta x}\)
  \[
  1 \sim k_\mu \, \Delta x^q_\mu \sim t_{\text{coh}} \omega g (1 - \hat{k}_g \cdot \Delta \hat{x}_q / t_{\text{coh}}) \sim l_{\text{coh}} \omega g \langle \theta^2 \rangle
  \]
  Both \(g\) and \(q\) undergo random walk:
  \[
  \langle \theta^2 \rangle \approx N_{\text{coh}} (\bar{\theta}_g^2 + \bar{\theta}_q^2) \approx \frac{l_{\text{coh}}}{l_{\text{mfp}}} \left( \frac{\mu^2}{\omega_g^2 + \frac{E_q^2}{E_q^2}} \right)
  \]
Coherent scattering can be important

Following BDMPS

- If all scatterings are incoherent \((l_{\text{mfp}} > l_{\text{coh}})\),
  \[
  l = l_{\text{mfp}} = 1/\rho\sigma
  \]

- If \(l_{\text{coh}} \geq l_{\text{mfp}} \implies \text{LPM effect:}\)
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    \]
  - Both \(g\) and \(q\) undergo random walk:
    \[
    \langle \theta^2 \rangle \approx N_{\text{coh}} (\bar{\theta}_g^2 + \bar{\theta}_q^2) \approx \frac{l_{\text{coh}}}{l_{\text{mfp}}} \left( \frac{\mu^2}{\omega_g^2} + \frac{\mu^2}{E_q^2} \right)
    \]

  Hence (with \(E_{\text{LPM}} = \mu^2 l_{\text{mfp}}\))

  \[
  l_{\text{coh}} = l_{\text{mfp}} \sqrt{\frac{\omega_g}{E_{\text{LPM}}}} \sqrt{\frac{E_q^2}{E_q^2 + \omega_g^2}} \approx l_{\text{mfp}} \sqrt{\frac{\omega_g}{E_{\text{LPM}}}} \quad \text{for } E_q \gg \omega_g > E_{\text{LPM}}
  \]
What we learned

\[ l_{\text{coh}} \approx l_{\text{mfp}} \sqrt{\frac{\omega g}{E_{\text{LPM}}}} = \sqrt{\frac{\omega g}{\hat{q}}} \]

where \( \hat{q} = \mu^2 / l_{\text{mfp}} \)

If your chosen process is

- **Soft** gluon emission, \( \omega < \mu^2 l_{\text{mfp}} \),
  \implies Coherence matters not. BH should suffice. No need to resum.

- **Hard** gluon emission, \( E \gg \omega > \mu^2 l_{\text{mfp}} \),
  \implies Coherence matters. Resummation needed.

- **Both**
  \implies Need the cross-section that is correct in both limits.

**Key quantity:** \( E_{\text{LPM}} = \mu^2 l_{\text{mfp}} \sim T \) in pert. thermal QCD
Radiational E-loss – Theory
Remember this slide?

\[
\frac{d\sigma_{AB}}{dt} = \int_{\text{geometry}} \int_{abcd} \times f_{a/A}(x_a, Q_f) f_{b/B}(x_b, Q_f) \times \frac{d\sigma_{ab\rightarrow cd}}{dt} \times P(x_c \rightarrow x'_c|T, u^\mu) \times D(z'_c, Q)
\]

This is what we need.

\[
\int_{\text{geom}} P(x_c \rightarrow x'_c|T, u^\mu)D(z'_c, Q): \text{Medium modified frag. function}
\]
Main task: To sum over all such diagrams and then square. This gets you the rate.
Main task: To sum over all such diagrams and then square. This gets you the rate.

Different approaches: What do \( t_i, s_j \) represent?
Main task: To sum over all such diagrams and then square. This gets you the rate.

Different approaches: What do $t_i$, $s_j$ represent?

Different approaches: How and what to sum?
Main task: To sum over all such diagrams and then square. This gets you the rate.

Different approaches: What do $t_i, s_j$ represent?

Different approaches: How and what to sum?

Different approaches: How to deal with the evolving medium?
Main task: To sum over all such diagrams and then square. This gets you the rate.

I will use McGill-AMY as an example (since I am familiar with it the most)
Medium is weakly coupled QGP with thermal quarks and gluons

Requires $g \ll 1$, $p > T$, $k > T$
Medium is weakly coupled QGP with thermal quarks and gluons

Requires $g \ll 1$, $p > T$, $k > T$

Sum all interactions with the medium
Medium is weakly coupled QGP with thermal quarks and gluons

- Requires \( g \ll 1, \ p > T, \ k > T \)
- Sum all interactions with the medium
- Leading order: 3 different kinds of collinear pinching poles
SD-Eq:

\[ = + + + \]

Figures from G. Qin
Rate $\propto \sum$ rungs cuts pinching

$\mu \approx gT$

$\frac{dN_g(p, k)}{dkdt} = \frac{C_s g_s^2}{16\pi p^7} \left( \frac{1}{1 \pm e^{-k/T}} \right) \left( \frac{1}{1 \pm e^{-(p-k)/T}} \right) \times \left\{ \begin{array}{ll} \frac{1+(1-x)^2}{x^3(1-x)^2} & q \rightarrow qg \\ \frac{x^2+(1-x)^2}{x^2(1-x)^2} & g \rightarrow q\bar{q} \\ \frac{1+x^4+(1-x)^4}{x^3(1-x)^3} & g \rightarrow gg \end{array} \right\} \times \int \frac{d^2h}{(2\pi)^2} 2h \cdot \text{Re} F(h, p, k)$

: Hard Thermal Loop

Rate for $p > T, k > T$ (valid for $p \gg T$ and $k \gg T$ as well)
Evolution - Medium enters through $T(t, x)$ and $u^\mu(t, x)$

\[
\frac{d\mathcal{P}_q(p)}{dt} = \int_k \mathcal{P}_q(p+k) \frac{dN_{qg}(p+k, k)}{dkdt} - \mathcal{P}_q(p) \int_k \frac{dN_{qg}(p, k)}{dkdt} \\
+ \int_k 2\mathcal{P}_g(p+k) \frac{dN_{q\bar{q}}(p+k, k)}{dkdt},
\]

\[
\frac{d\mathcal{P}_g(p)}{dt} = \int_k \mathcal{P}_q(p+k) \frac{dN_{qg}(p+k, p)}{dkdt} + \int_k \mathcal{P}_g(p+k) \frac{dN_{gg}(p+k, k)}{dkdt} \\
- \mathcal{P}_g(p) \int_k \left( \frac{dN_{q\bar{q}}(p, k)}{dkdt} + \frac{dN_{gg}(p, k)}{dkdt} \Theta(k-p/2) \right) 
\]
Modified fragmentation function with jet initial condition $s, n, p_i$

$$\tilde{D}_{\pi^0,c}(z, Q; s, n) = \int dp_f \frac{Z'}{Z} \left( P_{qq/c}(p_f; p_i) D_{\pi^0/q}(z', Q) + P_{g/c}(p_f; p_i) D_{\pi^0/g}(z', Q) \right),$$

$$\tilde{D}(z, Q) = \int d^2 s \frac{T_A(s) T_B(s+b)}{T_{AB}(b)} \tilde{D}_{\pi^0,c}(z, Q; s, n)$$
Collision geometry including path length fluctuations are all included.

- Both BH and LPM limits included
- Unique features of McGill-AMY
  - Includes all leading order splittings
  - Includes thermal absorption
  - All produced quarks and gluons fragment
  - Medium evolution \((T(t, x), u_{\mu}(t, x))\) fully taken into account including the effect of flow vector
  - Easy to add other process such as elastic coll. (done), \(\gamma\) production (done) within leading order QCD/QED.
(3+1)-D relativistic hydrodynamics (Nonaka & Bass)

- Based on conservation laws: \( \partial_\mu T^{\mu\nu} = 0, \partial_\mu j^\mu = 0 \).
- For ideal fluid, \( T^{\mu\nu} = (\epsilon + p) U^\mu U^\nu - pg^{\mu\nu}, j^\mu = n_B U^\mu \).
- EOS: Bag model + Hadron with extended volume
- Initial conditions: \( \epsilon(x, y, \eta) = \epsilon_{\text{max}} W(x, y; b) H(\eta), \)
  \( n_B(x, y, \eta) = n_{B\text{max}} W(x, y; b) H(\eta) \)

- Particle spectra: Cooper-Frye Formula

\[
E \frac{dN_i}{d^3p} = \int_\Sigma p \cdot d\sigma \frac{g_i}{(2\pi)^3} \exp \left[ \frac{1}{T_f} \left( \frac{p \cdot U - \mu_i}{T_f} \right) \right] \pm 1
\]

Nonaka and Bass, Phys.Rev.C75:014902,2007
$R_{AA}$ at RHIC – $\pi^0$ - Full (Qin)

3+1D hydro
- Includes radiational and collisional energy loss: rad+coll, rad, coll
- Strong coupling $\alpha_s$: 0.33 (rad) and 0.27 (rad+coll)

Guangyou Qin, J. Ruppert, C. Gale, S. Jeon, G.D. Moore, M.G. Mustafa
Phys.Rev.Lett.100: 072301, 2008
Comparing with other E-loss schemes

What do $t_i$ and $s_j$ represent?
- (Infinitely) Heavy scattering centers – BDMPS-Z, GLV, AWS, ...
- Dynamic scatterers – DGLV
- General nuclear medium with short color correlation – HT

How and what to sum?
- Sum over diagrams with all possible soft interactions – BDMPS
- Use path integral representation of hard parton propagation – AWS, Zakharov
- Reaction operator method: All orders formalism – WHDGLV (up to the 9-th order in the opacity)
Comparing with other E-loss schemes

- How to deal with the evolving medium? (BDMPS, WHDGLV, AWS)

  - Calculate

    \[
    \frac{dN_g(t_f)}{d\omega} = \int_{t_0}^{t_f} dt \frac{dN_g}{d\omega dt}
    \]

  - Then use the Poisson ansatz

    \[
    \mathcal{P}(\epsilon, t_f | \mu, \hat{q}) = e^{-\int_{t_0}^{t_f} dt \int d\omega \frac{dN_g}{d\omega dt}} \sum_{n=0}^{\infty} \frac{1}{n!} \left[ \prod_{i=1}^{n} \int_{t_0}^{t_f} dt \int d\omega_i \frac{dN_g}{d\omega_i dt} \right] \delta \left( \epsilon - \sum_{i=1}^{n} \omega_i \right)
    \]
Comparing with other E-loss schemes

How to deal with the evolving medium? (HT)

Modified DGLAP equation (includes medium induced radiation)
stands in for time evolution.

\[
\frac{\partial \tilde{D}_{q\rightarrow h}(z_h, \mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s}{2\pi} \int_{z_h}^{1} \frac{dz}{z} \left[ \tilde{\gamma}_{q\rightarrow qg}(z, x, x_L, \mu^2) \tilde{D}_{q\rightarrow h}(z_h/z, \mu^2) + \tilde{\gamma}_{q\rightarrow gq}(z, x, x_L, \mu^2) \tilde{D}_{g\rightarrow h}(z_h/z, \mu^2) \right]
\]

Medium dependence in

\[
\hat{q} = \frac{2\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dt \left\langle F^{\mu \alpha}(t) v_{\alpha} F_{\mu}^\beta(0) v_{\beta} \right\rangle
\]
Comparing with other E-loss schemes

- How to deal with the evolving medium?
  - Medium enters mainly through $\hat{q}$
  - Needs additional model to related $\hat{q}$ to the medium properties $T$ and $u^{\mu}$.

- Collision geometry including path length fluctuations taken into account
A. Majumder’s table from Hard Probe 08
(disclaimer: many of the formalisms have moved beyond these standards)

| Phenomena          | Transverse broadening | Thermal push | Elastic loss Feedback | Flavor changes | Vacuum interference |
|--------------------|-----------------------|--------------|-----------------------|----------------|---------------------|
| Model              |                       |              |                       |                |                     |
| HT                 | ✓                     | ✗            | ?                     | ?              | ✓                   |
| AMY                | ✓                     | ✓            | ✓                     | ✓              | ✗                   |
| ASW                | ✓                     | ✗            | ✗                     | ✗              | ✓                   |
| GLV                | ✓                     | ?            | ?                     | ✗              | ✓                   |
| Expt.              | ![](graph1.png)        | ![](graph2.png) | ![](graph3.png)       | ?              |                     |

Jeon (McGill)
A. Majumder’s table from Hard Probe 08

(disclaimer: many of the formalisms have moved beyond these standards)

| Phenomena | Transverse broadening | Thermal push | Elastic loss Feedback | Flavor changes. | Vacuum interference |
|-----------|------------------------|--------------|-----------------------|----------------|---------------------|
| Model     |                        |              |                       |                |                     |
| HT        | ✓                      | ×            | ✓                     | ?              | ✓                   |
| AMY       | ✓                      | ✓            | ✓                     | ✓              | ×                   |
| ASW       | ✓                      | ×            | ×                     | ×              | ✓                   |
| GLV       | ✓                      | ?            | ?                     |                 | ×                   |

Expt.

Jeon (McGill)

Jets in QGP

QM2009 27 / 40
Model comparison study

Bass, Gale, Majumder, Nonaka, Qin, Renk, Jorg Ruppert, arXiv:0808.0908 [nucl-th]

All models constrained to have

- Same nuclear profile
- Same structure func.
- Same fragmentation func.
- Same 3D hydro medium
Similar results from GLV and WHDG

I. Vitev, QM2005

Wicks, Horowitz, Djordjevic, Gyulassy, Nucl.Phys.A783: 493-496, 2007 (Hard Probes 2006)
What we learned so far

- All schemes can characterize the medium using $\hat{q} = \left\langle q_{\perp}^2 \right\rangle / l_{\text{mfp}}$
- But this ranges from $19 \text{ GeV}^2 / \text{fm}$ to $1.5 \text{ GeV}^2 / \text{fm}$ $\Longrightarrow$ Too model-dependent.
- All models can reproduce $R_{AA}$ with reasonable/realistic assumptions.
What we learned so far

- All schemes can characterize the medium using \( \hat{q} = \left\langle q_\perp^2 \right\rangle / l_{\text{mfp}} \)

- But this ranges from 19 GeV\(^2\)/fm to 1.5 GeV\(^2\)/fm \( \Rightarrow \) Too model-dependent.

- All models can reproduce \( R_{AA} \) with reasonable/realistic assumptions.

- \( R_{AA} \) is not very sensitive
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  T. Renk, Phys.Rev.C77: 017901, 2008.
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- Need more corroborating and/or differential/discriminating observables
For instance,

**High $p_T$ photon calculation within McGill-AMY**

![Graph](image)

**Guang-You Qin, Hard Probe 2008**
For instance,

High $p_T$ photon calculation within GLV with first order in opacity
– Cold nuclear matter effect dominates

Ivan Vitev, Ben-Wei Zhang Phys.Lett.B669: 337-344, 2008
Comprehensive Phenomenology

All formalism must address all phenomenon within the range of applicability

- Two particle correlation
- High $p_T$ photon spectrum
- $I_{AA}$
- $\gamma$ triggered FF
- $R_{AA}(\phi)$
- $p_T$ broadening
- Mach cone
- Jet shape
- AdS/CFT, AdS/QCD?

**Talks**

- G. Qin (McGill-AMY): Photon production and tagging, Thurs.3A
- X.-N. Wang: $\gamma$-Jet correlation (HT), Thur.3A
- M. Djordjevic: Dynamic effects in E-loss (WHD-LGV), Tues.1A
- I. Vitev: Jet shapes (GLV), Tues.2A
- M. Mia: $\eta/s$ and $\hat{q}$ in AdS/QCD, Tues.2C
- B. Betz: Flow-Jet interaction, Fri.6A
Some samples...

PHENIX Prelim., $p_{T,h} = 3-5$ GeV, $|y_h, y_γ| < 0.35$

Qin, $I_{AA}$

Xin-Nian, $γ$ triggered FF

M. Djordjevic, Effect of dynamic medium

Vitev, Jet shape
Event generators are in development!

- YaJEM – T. Renk, Tues. Plenary
  (Yet another Jet Energy loss Model)

- JEWEL – Zapp, Ingelman, Rothsman, Stachel, Wiedemann – K.C. Zapp, Tues. 1A
  (Jet Evolution With Energy Loss)

- Q-PYTHIA – Armesto, Salgado, Cunqueiro, Corcella – C. Salgado, Tues. 2A

- PQM – Dainese, Loizides, Paić
  (Parton Quenching Model)

- PYQUEN/HYDJET – Lokhtin, Petrushanko, Snigirev, Teplov, Mailinina, Arsene, Tywoniuk

- MARTINI – McGill-AMY
  (Modular Algorithm for Relativistic Treatment of Heavy Ion Interactions)
B. Schenke, C. Gale, S. Jeon, $10^9$ events
B. Schenke, C. Gale, S. Jeon, $10^9$ events
Conclusions

- TECHQM collaboration is set up to compare different jet quenching scenarios and deposit standardized test results.
- Model comparison has been carried out under controlled environment with many groups participating.
  - Familiar conclusion: $19 \text{ GeV}^2/\text{fm} < \hat{q} < 2 \text{ GeV}^2/\text{fm}$
  - A consistent way needs to be found to relate $\hat{q}$ to the local medium properties. Otherwise, it must be treated as a model dependent parameter.
- Only way to discriminate models: Calculate other observables without turning any more knobs $\implies \gamma$ spectrum and tagging. Di-hadron fragmentation function, Medium response, $R_{AA}(\phi)$, ... $\implies$ Many reports in this conference.
Conclusions

- Standardize or not Standardize?
  - Jet quenching uses hard probes to study the properties of the bulk matter.
  - But jet quenching models need a model of underlying bulk evolution, for instance, hydro
  - To study details (Read: Correlations), it is vital that both the bulk evolution models and the hard-probe models evolve together.
  - TECHQM has also set up standardized tests for (viscous) hydro codes and proposed to standardize the output format

- Recent development: Jet quenching MC models

- Theory effort is strong as ever. Ideas are plenty. Coherent picture will emerge!
To do

- What happens between the production of the jet and the formation of QGP?
  - Strong color field?
  - Pre-hydro flow?
  - Time evolution vs scale evolution?
  - Strong initial correlations – ridge?
  - Where does viscosity fit in all this?
  - LHC: More of the same or radical new territory?