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Testing Radiative Energy Loss at RHIC and the LHC

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These are preliminary lecture notes, intended only for distribution to participants
Testing radiative energy loss
at RHIC and the LHC

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1. Motivation (I): (Baier et al '00; Kovner et al '03; Gyulassy et al '03)

Medium-induced gluon radiation dominates over elastic scattering at high parton $E_\perp$ at $y=0$:

- Degrades the energy of the leading hadron: jet quenching.
- Broadens the associated parton shower.
- Increases the associated hadron multiplicity.

The BDMPS(-GLV-ZW-WZ) formalism describes this in pQCD: interference of production and re-scatterings of the radiated gluon leading to

\[ \Delta E \simeq \int d\omega \omega \frac{dI}{d\omega} \propto \alpha_s C_R \omega_c = \alpha_s C_R \hat{q} L^2 / 2 \]

\[ n(z) \sigma(r) \propto \hat{q}(z) r^2 \]

→ Interference and mass effects: \[ \exp \left( -\Delta z \frac{k^2 + x^2 m^2}{2\omega} \right), \quad x = \frac{\omega}{E} \ll 1 \]

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1. Motivation (II):

It has become the ‘canonical’ explanation for the suppression of leading particle spectra at large $p_T$ and $y=0$:

- Magnitude of the suppression: $n(z)\sigma(r)$.
- Dependence of the suppression with centrality and azimuth: $L^2$.
- Disappearance of back-to-back correlations: NP $\sigma(r)$, tangential emission?

To further test it and constrain parameters:

- High $p_T$ particle correlations, jet shapes and multiplicities.

Genuine prediction of this approach:

$\Delta E (q) > \Delta E (Q)$

color charge

mass effect

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1. Motivation (III):

- Massive partons radiate less in the vacuum: **dead cone effect**, postulated for the medium (Dokshitzer-Kharzeev '01).
- Technically: rescattering+dead cone (Djordjevic et al '03; Zhang et al '03; Armesto et al '03).

  - **Heavy-to-light ratios** $R_{D,B/h} = R_{AA}^{D,B}/R_{AA}^{h}$: sensitive to (Armesto et al '05)
    - **Color-charge dependence** (g to light hadrons important, increases $R_{D,B/h}$).
    - **Mass dependence** (Q radiate less, increases $R_{D,B/h}$).
    - Detailed behavior of the partonic $p_T$ spectrum (softer for Q, increases $R_{D,B/h}$) and fragmentation functions (harder for Q, decreases $R_{D,B/h}$).
2. Model (I):

Standard LO pQCD (PYTHIA):

\[
\frac{dN_{\text{medium}}^{AB\rightarrow h}}{dp_T \, dy}_{y=0} = \sum_{i,j} \left. \int dx_i \, dx_j \, d(\Delta E/E) \, dz_k \, f_{i/A}(x_i) \, f_{j/B}(x_j) \right|_{y=0} \left( P(\Delta E/E, R, \omega_c, m/E) \, D_{k\rightarrow h}(z_k) \right)
\]

**Quenching weights**

(www.pd.infn.it/~dainesea/qwmassive.html):
- probability for medium energy loss,
- they contain a no-loss contribution.

- CTEQ4L pdf's, EKS98.
- All channels into account.
- Ff into D (B) and semileptonic e-decays.
- RHIC: tune to STAR D-meson data.
- LHC: tune to NLO pQCD calculation.

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2. Model (II):

(Dainese et al '04, '05; Eskola et al '04)

Detailed modeling of geometry.

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\[ \alpha_s = \frac{1}{3}-1/2 \]
3. Results for RHIC:

\[ R_{D/h} = \frac{R_{AA}^D}{R_{AA}^h} \quad (\text{Dokshitzer-Kharzeev '01}). \]

- \( q/g \) difference affects all \( p_T \).
- Mass effects sizeable for \( p_T < 12 \text{ GeV} \).
- Look at \( 7 < p_T < 12 \text{ GeV} \).

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4. Results for the LHC:
Transport coefficient (density) scaled by multiplicity: factor 2.5 to 7 larger at the LHC than at RHIC (Armesto et al '04, Eskola et al '04).

- Small difference between massless c and b.
- $10 < p_T < 20$ GeV: charm sensitive to color (g at low x), bottom to mass.

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5. Single electrons at RHIC (I):

- RHIC data in AuAu: non-photonic electron spectra (measured - cocktail - conversion: PHENIX '06; STAR '05), weak correlation in $p_T$ with parent D, and other contributions (B’s) (Djordjevic et al '05; '06; Armesto et al ‘05).

- Heavy flavor: FONLL (Cacciari et al '98; '01; '05) partonic spectra supplemented with radiative eloss via quenching weights plus FONLL fragmentation:
  * Uncertainties (mass and scale variation).

- DY: PYTHIA tuned to NLO (Gavin et al '95), it may become important for $p_T > 10$ GeV.

- A 10% contribution from DY may influence $R_{AuAu}^{e}$ as much as 0.1.
5. Single electrons at RHIC (II):

- pp data underestimated by FONLL (Cacciari et al '05).
- Suppression in AuAu compatible with c only.
- Variations in q^2 uncertainties.
- $v_2$ compatible with data (PHENIX '05).

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5. Single electrons at RHIC (III):

If $R_{\text{AuAu}}^{e} < 0.4$ in the range $5 < p_T < 10$ GeV:

- Strong interaction of Q with the medium; hadronization inside, elastic scattering? (Djordjevic et al '06, Hees et al 05, Teaney et al '05).
- Larger transport coefficient? (but upper bound to come, hopefully, from correlations (PHENIX '05; STAR '06)).

- How well do we control the production of heavy flavors at RHIC?

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Note: elastic scattering

- Historically considered << than radiative eloss (Bjorken '82; Gyulassy-Braaten-Thoma '91).

- Mustafa '05; Djordjevic et al '06; Alam et al '06: new interest due to single electron data, idea extended from heavy to light flavors.

- Peigne et al '05: elastic eloss strongly reduced due to finite L.

- Djordjevic '06: effect of finite interaction time (L) negligible.

- Wang '06: elastic and inelastic elosses in the same multiple scattering formalism. For light flavors:

$$\frac{\Delta E_{\text{rad}}}{\Delta E_{\text{el}}} \sim 3.14 \alpha_s LT \ln(EL/11) \sim 22$$

for $E=10$ GeV, $T=0.2$ GeV, $L=6$ fm, $\alpha_s=0.3$
6. **Conclusions:**

- Heavy flavors constitute an experimentally accessible testing ground for our understanding of radiative energy loss.

- Both at RHIC and at the LHC heavy-to-light ratios offer solid possibilities to check the formalism like those presented here.

- Single electrons in AuAu at RHIC may demand other effects like elastic scattering, hadronization in medium, strong interactions,…

  **BUT**

  **Experimental data are not inconsistent with radiative eloss.**

- **Clarification of this issue will demand** (at RHIC and at the LHC):
  * pp/dAu reference to be controlled.
  * If possible, data for mesons, not only for electrons.

- **Further work needed:** energy constraints, consideration of virtualities,…, crucial for associated particle production.
Backup I: quenching weights

probability of no-energy loss

\[ P_0 \]

\[ R \equiv \omega_c L \]

Mass effect smaller for smaller \( R = q_{hat} L^{3/2} \), so smaller for smaller lengths.

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Backup II: fixed vs. variable L

To try to understand a disagreement with Djordjevic et al ‘05

- $m_c = 1.5$ GeV, $m_b = 4.75$ GeV; no fragmentation.
- $\hat{q} = 1.2$ GeV$^2$/fm with fixed $L = 6$ fm reproduce $R_{AA}(0-10\%) \sim 0.2$ for pions.
- A large fixed length produces a larger effect of the mass on the $e$loss: mass effect small for small $L$.

FONLL at 200 AGeV, $\mu = m_T$, CTEQ6M

- $\hat{q} = 4$ GeV$^2$/fm, variable length
- $\hat{q} = 14$ GeV$^2$/fm, variable length

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Backup III: bottom in FONLL

Cacciari et al 03; 04

Reasonable description of b production.

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Backup IV: further contraints on qhat

Tangential emission (Dainese '05); associated spectra not yet understood.

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