Energy Loss in Heavy Ion Collisions

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Outline:

- introduction to energy loss
- p+p reference data vs pQCD
- gluon/light quark energy loss
- heavy-flavor energy loss
- direct photons

Observables: $R_{AA}$, particle ratios, two-particle correlations vs system size, energy, rapidity
High-\(p_T\) particle production in \(p+p\)

- scattering of partons followed by fragmentation \(\rightarrow\) jet
- can be calculated in perturbative QCD
- collinear factorization

\[
\frac{d\sigma^{h}_{pp}}{dyd\frac{2}{p_T}} = K \sum_{abcd} \int dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \frac{d\sigma}{dt}(ab \rightarrow cd) D_{h/c}^0 / \pi z_c
\]

- Measured in DIS
- pQCD
- e^+e^-

Parton distribution function
Matrix element
Fragmentation function
Parton energy loss in A+A ("jet quenching")

A+A collisions:
- initial state: similar to p+p
- final state: hard partons traverse medium and lose energy
  - gluon radiation
  - elastic collisions with surrounding partons
→ softening of particle spectra at high $p_T$

• energy loss different for gluon, light and heavy quarks (color factor, dead cone effect)

Goal: Use in-medium energy loss to measure medium properties
Radiative energy loss in QCD

4 jet quenching schemes:
• higher twist expansion
  Qi, Sterman, Wang, Wang, Zhang, Majumder, …
• finite temperature field theory
  Arnold, Moore, Yaffe (AMY)
• opacity expansion:
  - thin medium/single hard scattering
    Gyulassy, Levai, Vitev, Djordjevic, … (GLV)
  - thick medium/multiple soft scatterings
    Baier, Dokshitzer, Mueller, Peigne, Schiff (BDMPS)
    Armesto, Salgado, Wiedemann (ASW)

medium properties can be characterized by a single constant:

\[ \frac{d \sigma^{h_1}}{dy dp_{T_1}} \sim \int dx_a dx_b G(x_a) G(x_b) \frac{d \hat{\sigma}}{d \hat{t}_q} \hat{D}^{h_1}_q(z_1) \]

\[ \text{e.g. transport coefficient } \hat{q} = \frac{\mu^2}{\lambda} \text{ ‘average } k_T\text{-kick per mean-free-path’} \]

• static medium: \( \Delta E \propto L^2 \) due to interference effects, expanding medium: \( \Delta E \propto L \)
p+p reference data
p+p reference @ 200 GeV vs pQCD

Compilation by D. d’Enterria nucl-ex/0611012

Good agreement with theory

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Proton and pion production in p+p

\[ p+p \rightarrow \pi + X \]

Pion and proton spectra agree with NLO pQCD using the latest AKK fragmentation functions.

(Note: p is more sensitive to gluon fragmentation – KKP does not work!)

STAR, PLB 637 (2006)

A. Bazilevsky (PHENIX), QM06

\[ \pi^0 \]

9.7% scale uncertainty is not included
Strange particle production in p+p

STAR, PRC 75 (2007)

• STAR measurement of strange particles in p+p constrained AKK FF

AKK fragmentation functions agree well with both mesons and baryons at mid-rapidity.

KKP (Kniehl-Kramer-Potter): NPB 582 (200)
Hadron production in p+p at y~3

BRAHMS, hep-ex/0701041, submitted to PRL

NLO pQCD describes production of pions and kaons well at y~3, but fails to account for large proton yields and small $\bar{p}/p$ ratio even with AKK FF.

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Nuclear modification factors
Particle ratios
Direct photons:
- measured p+p reference
- $R_{AA}(\gamma) < 1$ for $p_T > 12$ GeV/c

Isospin effect seen?
Ongoing study at $\sqrt{s_{NN}} = 62$ GeV

$\pi^0$ and $\eta$:
- Run 5: extended reach in $p_T$ out to 20 GeV/c for $\pi^0$ and 15 GeV/c for $\eta$
- both have a common $R_{AA} \sim 0.2$

$R_{AA}(p_T) = \frac{d^2 N_{AA}^{dN}/dp_T d\eta}{d^2 \sigma_{NN}^{AA}/dp_T d\eta}$/ 

binary collision scaling p+p reference

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New!
Measured p+p reference at $\sqrt{s_{NN}} = 62$ GeV instead of previously used ISR data

$\rightarrow$ $R_{AA}$ at $\sqrt{s_{NN}} = 62$ GeV is now very close to $\sqrt{s_{NN}} = 200$ GeV!
Comparing $R_{AA}(\pi^0)$ to models

C. Loizides, hep-ph/0608133

$\chi^2$ minimization fit to obtain the probability of a given parameter

- values given for probability > 10%

$R_{AA}$ shows only a small sensitivity to model parameters

B. Sahlmueller (PHENIX), QM'06

$6 \leq \langle \hat{q} \rangle \leq 24 \text{ GeV}^2/\text{fm}$

$1000 \leq dN_g/\text{dy} \leq 2000$

$600 \leq dN_g/\text{dy} \leq 1600$
What do we learn from $R_{AA}$?

Energy loss distributions very different for BDMPS and GLV formalisms

BUT! $R_{AA}$ is similar

More differential probes needed!
Gluon jet contribution factor increases from $\pi$, $K$, $p$ towards $\Lambda$:

- e.g. $p_T = 8$ GeV/c: 50% for $\pi$
- 90% for $p$

If

$$\langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2$$

and

$$\frac{\Delta E_g}{\Delta E_q} \sim \frac{9}{4}$$

At high $p_T$ for same beam energy, system and centrality:

$$R_{CP}(\pi) > R_{CP}(p)$$

$$R_{CP}(K) > R_{CP}(\Lambda)$$

AKK = particle + anti-particle

Intermediate-\(p_T\) (\(p_T = 2-5\) GeV/c): baryon/meson splitting
\[ R_{CP}^{(\text{meson})} < R_{CP}^{(\text{baryon})} \]

High-\(p_T\) (\(p_T > 5\) GeV/c):
\[ R_{CP}(\pi) \approx R_{CP}(p) \]
\[ R_{CP}(K) \approx R_{CP}(\Lambda) \]

Does it mean similar energy loss of quarks and gluons?
Energy dependence: anti-particle/particle ratios

$\pi^-/\pi^+$: independent of $p_T$

$p/p$: model calculations with/without $E_{\text{loss}}$ do not describe data

$X.-N. Wang et al., PRC 70 (2004) - E_{\text{loss}}$

Baryon junction and coalescence models describe data at intermediate $p_T$

$I. Vitev et al., NPA 715 (2003) - baryon junction$

$V. Greco et al., PRC 71 (2005) - coalescence$

STAR, PRL 97, 152301 (2006)

STAR, nucl-ex/0703040
Rapidity dependence of $R_{AA}$

I. Bearden (BRAHMS), QM2006

$R_{AA}$ independent of rapidity for produced mesons
Why is $R_{AA}$ independent of rapidity?

- forward $y = a unique information about medium in the longitudinal direction in the early stage
- competing effects: shadowing, multiple scattering, energy loss (GLV), geometry
- opacity decreases $\sim$ linearly with $y$
- shadowing stronger at forward $y$
  $\rightarrow$ effects compensate each other
  $\rightarrow$ $R_{AA}$ independent of $y$

Barnafoldi, Levai, Papp, Fai, EJP C49 (2007)
$R_{AA}$ of non-photonic electrons

Models have difficulties to describe the measured $R_{AA}$:

- radiative energy loss with typical gluon densities is not enough
  
  \[ M. \text{Djordjevic et al., PLB 632 (2006) 81} \]

- models involving a very opaque medium agree better
  
  \[ N. \text{Armesto et al., PLB 637 (2006) 362} \]

- collisional energy loss/resonant elastic scattering
  
  \[ S. \text{Wicks et al., NPA 784, (2007) 426} \]
  
  \[ H. \text{v. Hees, R. Rapp, PRC 73 (2006) 034913} \]

- heavy quark fragmentation and dissociation in medium $\rightarrow$ strong suppression for $c$ and $b$
  
  \[ A. \text{Adil, I. Vitev, PLB 649, (2007) 139} \]

\[ \text{Note: } \sim \text{agreement between STAR and PHENIX} \]

\[ \text{(disagreement is common to } p+p/\text{Au+Au and cancels out in } R_{AA}) \]
Towards more differential probes …
$R_{AA}$ vs reaction plane

**Au+Au collisions at 200GeV**

- Factor 2 suppression out-of-plane than in-plane
- In plane emission shows no energy loss in peripheral bins.

3<p$_T$<5 GeV/c

PHENIX, nucl-ex/0611007, submitted to PRC
Path length dependence of energy loss

\[ L_\varepsilon = \text{matter thickness calculated in Glauber model} \]

- \( R_{AA} \) is universal function of \( L_\varepsilon \) for all centrality classes and both \( p_T \) ranges
- Little/no energy loss for \( L_\varepsilon < 2 \text{ fm} \)
- Formation time effect? Surface emission zone? \( v_2 \)?

\( \text{Au+Au } \sqrt{s_{NN}} = 200 \text{GeV} \)

\( \text{PHENIX, nucl-ex/0611007, submitted to PRC} \)

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Jet-like correlations at high-$p_T$

- Disappearance of away-side correlations observed at intermediate $p_T$ in central Au+Au collisions
- Run 4 statistics: a punch through observed at high $p_T$
  - Away-side yield is suppressed: $R_{AA} \sim I_{AA}$
  - Suppression without angular broadening or medium modification
  - $R_{AA} \sim I_{AA}$ in Cu+Cu as well
Away-side di-hadron suppression at high $p_T$

- di-hadrons have a smaller surface bias  
  $\rightarrow$ a “better” differential probe

- $\chi^2$-minimum narrower for di-hadrons  
  $\rightarrow$ stronger constraint on density

- extracted medium properties:
  \[ \varepsilon_0 = 1.68 \text{ GeV/fm} \]
  \[ q = 2.8 \pm 0.3 \text{ GeV}^2/\text{fm} \]
Di-hadron correlations: near-side peak

Near-side jet peak
Near-side ‘ridge’
Modified away-side (+ $v_2$)

The near-side jet interacts with the medium!

What is the ridge?
1) Medium heating and parton recombination
   Chiu & Hwa PRC 72, (034903) 2005
2) Radial flow + high-$p_T$ trigger particle
   Voloshin, nucl-th/0312065 NPA 749, 287 (2005)
3) Parton radiation and its coupling to the longitudinal flow
4) Momentum broadening in an anisotropic QGP
   Romatschke, PRC 75, 014901 (2007)
5) Longitudinal broadening of quenched jets in turbulent color fields
   Majumder, Mueller, Bass, hep-ph/0611135

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Near-side yields

M. Horner (STAR), QM2006

- increase of near-side yield at low $p_T^{\text{assoc}} (z_T)$ observed by STAR and PHENIX

- subtraction of $\Delta \eta$-independent ‘ridge-yield’ recovers centrality-independent jet yield

$z_T = p_{T,\text{assoc}} / p_{T,\text{trig}}$

J. Jin (PHENIX), QM2006

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Ridge properties

Ridge yield:
- increases with centrality
- ~ independent of $p_T^{\text{trigger}}$
- $p_T$-spectra are ‘bulk-like’
- particle composition in the ridge → see talk of M. Daugherity

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Energy content of the ridge

- near-side modification in published results also due to ridge
- energy content deposited in the ridge is few GeV


\[ \text{near-side } p_t \text{ magnitude sum (GeV/c)} \]

- \( 4 < p_{t,\text{trigger}} < 6 \text{ GeV/c} \)
- \( 6 < p_{t,\text{trigger}} < 10 \text{ GeV/c} \)
- \( 0.15 < p_{t,\text{assoc}} < 4 \text{ GeV/c} \)
The golden channel: $\gamma$-jet

- hard process: pQCD calculations describe well measured data
- no surface bias
- calibrated probe: $E_{T,\gamma} = \text{pre-quenched } E_{T,\text{jet}}$
- monochromatic source $\rightarrow$ differential measurement of jet-quenching

X.-N. Wang, Z. Huang, PRC 55, 3047, F. Arleo et al JEHP 0411, 009, T. Renk, PRC 71, 034906
First results on $\gamma$-hadron correlations

J. Jin, M. Nguyen, N. Grau (PHENIX), QM06
S. Chattopadhyay, F. Benedosso (STAR), QM06

- $p+p$: yields consistent with expectations from Pythia/HIJING
- Au+Au: a hint of away-side modification (?)
- ongoing studies in Cu+Cu (STAR/PHENIX)

- statistical and systematic uncertainties are large
- We have the tools, we just need more statistics 😊

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Summary

• high-statistics Run4/Run5 enable exploration of in-medium energy loss in detail:
  
  integrated \( (R_{AA}) \) \rightarrow \text{differential} \ (R_{AA} \text{ vs reaction plane, correlations})

  hadrons \rightarrow \text{identified particles} \ (\text{non-strange, strange, heavy-flavor})

  ‘the golden channel’ – γ-jet is emerging

• data trigger lots of interest in theoretical community

• upgrades to PHENIX and STAR will bring us even more exciting results

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