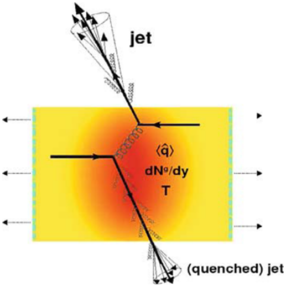
Lecture 22
Jets as a probe of QGP (part II)

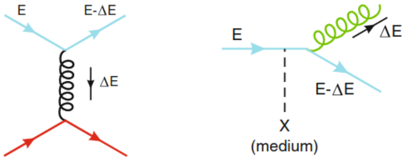


In this lecture, we discuss energy lost by jets and what this teaches us about the QGP.

Mechanisms of In-Medium Energy Loss

The main two mechanisms of in-medium energy loss by a color charge are the following:

- Collisional energy loss through **elastic** scatterings with the medium constituents
  This dominates at low particle momentum (more later)
- Radiative energy loss through **inelastic** scatterings within the medium
  This dominates at higher momenta.



Left: Collisional energy loss. Right: Radiative energy loss

Estimate for collisional energy loss

Details and references in d'Enteria and Betz

$\Delta E_{coll}^{1\,scat} = \frac{1}{\sigma T} \int_{t_{min}}^{t_{max}} t \frac{d\sigma}{dt} dt$ where t is the squared transferred momentum,
$t_{min} = m_D^2(T) \sim 4\pi\alpha_s T^2(1 + N_f/6)$ and $t_{max} = s \sim ET$

For parton-parton elastic collisions: $\frac{d\sigma}{dt} \sim C_i \frac{4\pi\alpha_s^2(t)}{t^2}$ with
$\alpha_s(t) = \frac{12\pi}{(33-2n_f)\ln\left(t/\Lambda_{QCD}^2\right)}$
and $C_i = 9/4, 1, 4/9$ respectively for gg,gq, qq scatterings.

> This leads to the energy loss per unit length
> - Light quark, gluon: $-\frac{dE_{coll}}{dl}|_{q,g} = \frac{1}{4} C_R \alpha_s(ET) m_D^2 \ln \frac{ET}{M^2}$
> - Heavy quark: $-\frac{dE_{coll}}{dl}|_{Q} = -\frac{dE_{coll}}{dl}|_{q} - \frac{2}{9} C_R \pi T^2 \alpha_s(M^2) \alpha_s(ET) \ln \frac{ET}{M^2}$
>
> where C_R=4/3 for quark and 3 for gluon.

Note that $\Delta E_{coll}^{tot} \equiv N \Delta E_{coll}^{1\,scat}$ where N is the number of scatterering centers and $-\frac{dE_{coll}}{dl} = E_{coll}^{tot}/L$ where L is the medium thickness, so ΔE_{coll}^{tot} is linear in L and depends only logarithmically on the initial parton energy.

Estimate for radiative energy loss

Details and references in d'Enteria and Betz

$\Delta E_{rad}^{1\,scat} = \int^E \omega \frac{dI_{rad}}{d\omega} d\omega$ where ω is the radiated gluon energy.

There are two regimes:

- If L« λ (Bethe-Heitler or BH regime): $\omega \frac{dI_{rad}}{d\omega} \sim \alpha_s C_R \hat{q} L^2/\omega$
- If L» λ (Landau-Pomeranchuk-Migdal or LPM regime):

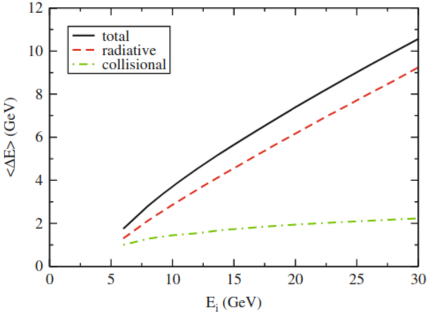
$$\omega \frac{dI_{rad}}{d\omega} \sim \begin{cases} \alpha_s C_R \sqrt{\hat{q} L^2/\omega} & \text{if } \omega < \omega_c \\ \alpha_s C_R \hat{q} L^2/\omega & \text{if } \omega > \omega_c \end{cases}$$

where $\hat{q} = m_D^2/\lambda = m_D^2 \rho\sigma$ is a transport coefficient that measuring the typical squared momentum transferred per mean free path and $\omega_c = (1/2)\hat{q}L^2$ is used to differentiate soft and hard gluon emission.

From which:

- $\Delta E_{rad}^{BH} \sim \alpha_s C_R \hat{q} L^2 \ln\big(E/(m_D^2 L)\big)$
- $$\Delta E_{rad}^{LPM} \sim \begin{cases} \alpha_s C_R \hat{q} L^2 & \text{if } \omega < \omega_c \\ \alpha_s C_R \hat{q} L^2 \ln\big(E/(\hat{q} L^2)\big) & \text{if } \omega > \omega_c \end{cases}$$

Comparison between energy loss mechanisms



G.-Y.Qin et al. Phys. rev. Lett. 100(2008) 072301: Au+Au collision at $\sqrt{s_{NN}}$=200 GeV, b= 2.4fm, α_s=0.27, parton starting from the center of the medium

Radiative energy loss dominates for large parton energy

The mechanisms described above are simplified, assuming in particular static uniform QGP. They have been incorporated in more sophisticated models accouting for finite dimensions, expansion, dependence on position, fluctuations, etc. Some known models are called BDMPS-LCPI/ASW, DGLV, HT, AMY

Monte Carlo models have also been developped.

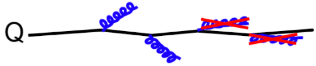
Hierarchy Expected for Different Types of Partons

$$\Delta E_{\text{Gluon}} > \Delta E_{\text{Quark},m=0} > \Delta E_{\text{Quark},m\neq 0}$$

larger color factor
for gluons:

$$C_F = \begin{cases} 3 & \text{for gluon jets} \\ 4/3 & \text{for quark jets} \end{cases}$$

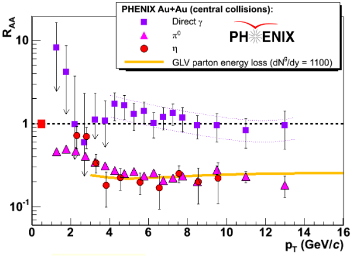
Dead cone effect:
Heavy quarks (c, b)
radiate fewer gluons



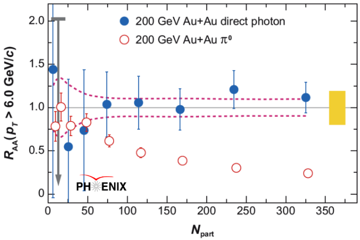
Dead cone effect = for heavy quark, the emission of gluons at small angle is suppressed:

$$\omega \frac{dI_{rad,Q}}{d\omega} \sim \omega \frac{dI_{rad,q}}{d\omega} \frac{1}{[1+(M/E)^2/\theta^2]^2}$$

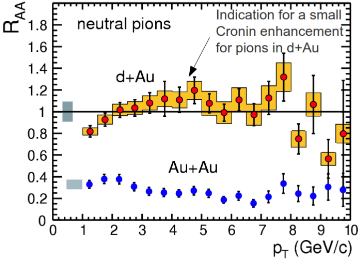
The Discovery of Jet Quenching at RHIC



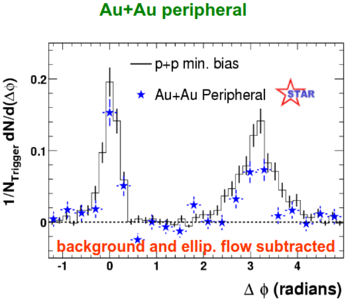
- Hadrons are VERY suppressed, direct photons not
- Evidence for parton energy loss

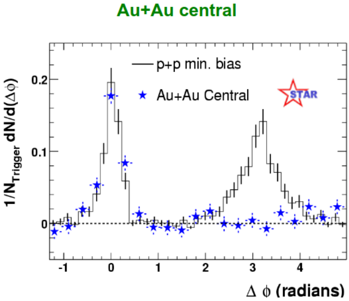


- Direct photons follow T_{AB} scaling as expected for a hard probe not affected by the medium, hadrons not



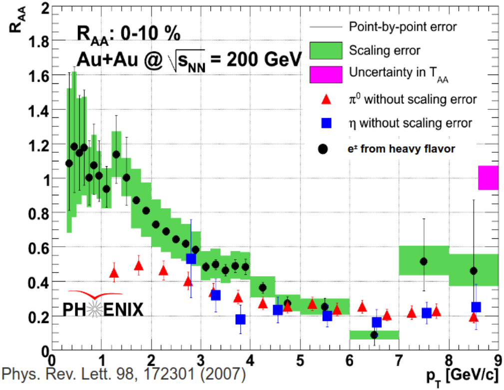
• No pion suppression in min. bias d+Au collisions ⇒ pion suppression is a final state effect caused by the created medium





Trigger particle: $p_\perp > 4$ GeV, associated particle: $p_\perp > 2$ GeV

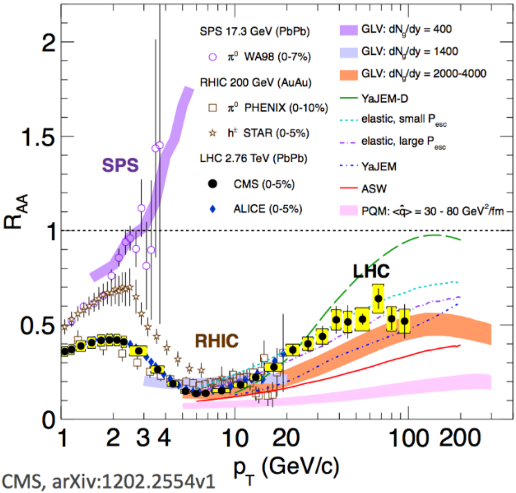
• No jet correlation around 180^o in central Au+Au: consistent with jet quenching picture



Phys. Rev. Lett. 98, 172301 (2007)

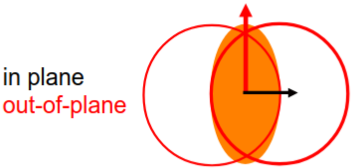
- $e^{\pm}$ from c and b decays as strongly suppressed as pions: no evidence for hierarchy

Dependence of energy loss on $p_\perp$



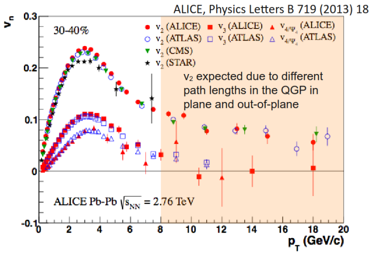
- Rise of R_{AA} with $p_\perp$ for the first time established
- This may help to discriminate between models.

$v_2 > 0$ at large $p_\perp$: signal of parton energy loss

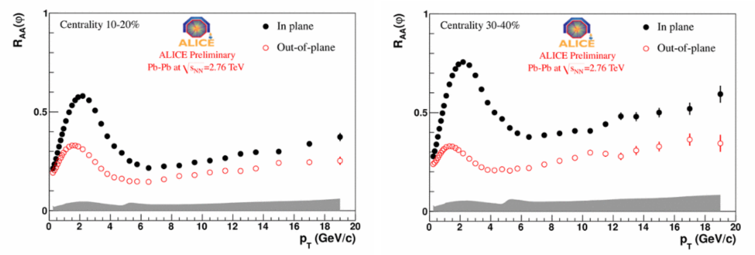


- The smaller path length in-plane compared to out-of-plane implies a non-zero $v_2(p_\perp)$ for large $p_\perp$ (NOT a hydro effect) and different $R_{AA}(p_\perp)$in-plane compared to out-of-plane .

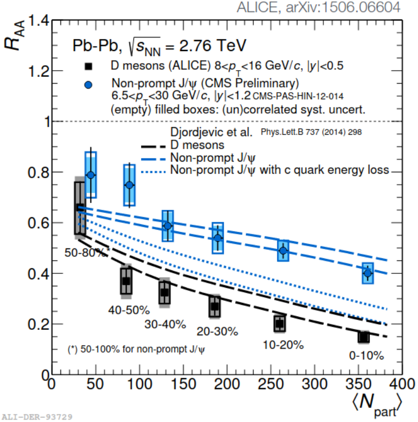
- This is indeed seen



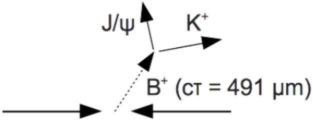
- $R_{AA}(p_\perp)$ is more suppressed out-of-plane than in-plane as expected



Evidence for energy loss hierarchy between c and b quarks

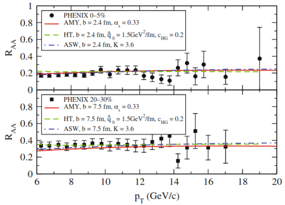


b quark energy loss via non-prompt J/ψ:



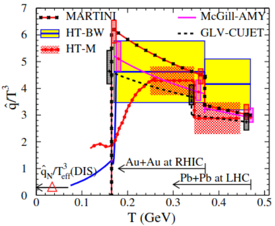
What do we learn?

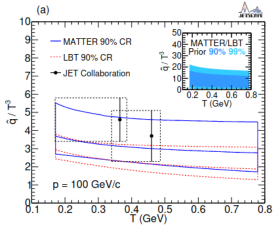
- All jet quenching observables in AuAu collisions at 200 GeV can only be reproduced with medium parameters consistent with a QGP at tem- peratures above the QCD phase transition



- Precisely:
  We saw that radiative energy loss dominates and that $\Delta E_{rad} \sim C_R \alpha_s \hat{q} L^2$: a large energy loss implies a large $\hat{q} = m_D^2 \rho \sigma$
  Assuming a gluon medium and using
  $\sigma = K\sigma_{gg}^{pert} = K9\pi\alpha_s^2/(2m_D^2)$ with $\alpha_s = 0.5$, $\rho = n_g \sim (16/9)T^3$
  $\Rightarrow \hat{q}(GeV^2/fm) = 36K\,T(GeV)^3$
  So a large $\hat{q}$ implies large T (above crossover i.e. QGP) and large K (not simple perturbative cross section, which hints at sQGP).

More precise calculations support this





Left: Results from 5 models (JET Collaboration) arXiv:1312.5003. Right: Bayesian analysis for RHIC and LHC data

(JETSCAPE Collaboration arXiv2102.11337

Jet quenching allows to establish the creation of (s)QGP at RHIC and LHC, in a way totally independent of hydro and soft particle production

Homework

On slide 9, $R_{AA}(p_\perp)$ is constant and ~ 0.25 for $p_\perp > 4$ GeV. A simple way to explain this is to assume that $p_\perp$ is reduced due to the jet quenching and the fractional energy loss $\epsilon_{loss} \equiv \Delta p_\perp / p_\perp$ is constant. At $\sqrt{s_{NN}} = 200$ GeV, the transverse momentum spectrum for p+p and Au+Au is $dN/dp_\perp \propto 1/p_\perp^{n-1}$ with n=8. Then it can be shown that the $\epsilon_{loss} \sim 1 - R_{AA}^{1/(n-2)}$ (PHENIX PRC 76 (2007) 034904).

Compute ϵ_{loss}.

Other references on this topic

- D. d'Enterria and B. Betz "High-p_T Hadron Suppression and Jet Quenching" in "The Physics of the Quark-Gluon Plasma", ed. S.Sarkar, H.Satz, B.Sinha, Springer 2010
- S.Cao and X.-N. Wang " Jet quenching and medium response in high-energy heavy-ion collisions: a review" arXiv:2002.04028
- L.Cunqueiro and A,M,Sickles "Studying the QGP with Jets at the LHC and RHIC" arXiv:2110.14490