Heavy Ion Physics
(QCD \rightarrow QGP)

QCD at high temperature and density

Bias: Selected topics: jets, heavy flavor, small systems
High Energy Heavy Ion Experiments

ALICE

ATLAS

CMS

LHCb

PHENIX

STAR

Energy range: ~10 GeV to ~10 TeV (center of mass energy / nucleon pair)
Collision systems: p+p, p+A, A+A (A = Au, Al, Pb)
Temperature conditions

- Hard scattering
- QCD medium: elastic and inelastic collisions (+radiation)
- Hadronisation
- Decoupling Freeze-outs (chemical + kinetic)
Hard scattering in medium

~ Vacuum jet

~ Medium jet

• Initial conditions (+geometry)

• Initial hard and soft scatterings (qq, qg, gg) depending on: x (momentum fraction) gluon density (not well known)

• Energy dissipation by gluon radiation or parton scattering

• Modification of fragmentation ?

Energy dissipation: Where does the energy go?
—> It changes momentum of particles ?
—> It changes the particle angular distribution ?
—> It changes particle species ?

Questions:
What is the medium ?
How is the medium influenced by the jet ?
How is the jet influenced by the medium ?
Vary system size of collision

(medium size)

- p+p
- p+A peripheral (40-50% centrality)
- p+A central (0-5% centrality)

Measure particle multiplicity (activity) at LHC energies (e.g. in TPC |eta| < 0.5)

- 2 - 100 (n_charge)
- 2 - 100 (N_part)
- 20 - 2000 (N_central)

-> measurements: AA/pp
General Particle Production

Time and mass dependence

- Hard scattering (jet), high $p_T$ = early parton-parton scattering with large $Q^2$
- Heavy flavor = early production short formation time

- Low $p_T$ = medium = late fragmentation and further interactions
- Low mass = medium (late) multiple interactions
  -> thermalized medium

~1% of yield

~99% of yield
Outline

Energy dissipation in medium

Jet shape

Baryon/meson production

Correlations (jet + medium)

Strangeness production

Small collision systems
Relative momentum distribution (AA/pp)

charged hadrons

Interaction with medium $\rightarrow$ energy dissipation $\rightarrow$ energy loss of initial parton $\rightarrow$ suppression of high momentum hadrons ($p \sim 10$ GeV/c)

System size or path length dependent energy loss:
larger medium size $\rightarrow$ larger energy loss $\rightarrow$ smaller $R_{AA}$

Gluon density RHIC $\frac{dN_{glue}}{dy} \simeq 1000$

\[ R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll} \rangle dN^{pp}/dp_T} \]
Heavy flavor - mass dependent energy loss

Heavier b-quark smaller RAA -> lose less energy than c-quark in partonic medium.

C-quark energy loss is similar to light quark (u,d) energy loss.

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Jet Shapes
Jet shape (radius)

\[ R_{D}(p_T, r) = \frac{D(p_T, r)_{\text{Pb+Pb}}}{D(p_T, r)_{\text{pp}}} \]

- High momentum particles stay closer to jet axis
- Low momentum particles are enhanced at larger radius
  \[ \rightarrow \text{Energy loss} \rightarrow \text{transferred to low momentum particles with large radial distance} \]
- Question: Is this a contribution from gluon rather than quark interaction?

\[ r = \sqrt{\Delta \phi^2 + \Delta \eta^2} \]
Baryon Production
Baryon production ($\Lambda^+/D^0$) (early)

- Enhanced charm baryon/meson at LHC energies (Pb+Pb)
- Enhancement is increasing with larger system size at RHIC energies (Au+Au)
- Significant enhancement observed with respect to PYTHIA for small and large collision systems

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Light flavor baryon/meson production (late)

- ALICE Preliminary
  - pp, \( \sqrt{s} = 7 \text{ TeV} \)
  - p-Pb, \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

ALICE

- \( p+p (\times 6) \)
- \( 2K^0 \)
- \( \Lambda+\bar{\Lambda} \)
- \( 2\phi (\times 2) \)

Event charged particle multiplicity \( \langle dN_{\text{ch}}/d\eta \rangle |\eta| < 0.5 \)

- Centrality = medium size
- \( \Lambda^+/D^0 \) ratio comparable to \( \Lambda/\pi \) light flavour.
- However proton/pion is rather flat
- Low multiplicity pp is in agreement with PYTHIA
Jet (parton) + Medium

→ particle correlations
c-quark - fragmentation ($D^0$-h)

Reminder: triggered correlation -> same-side sees a little bit of the medium

away-side correlation
More medium on the away-side

same-side correlation
Still medium on the same-side

\[ \Delta \eta = \eta_{D^0} - \eta_h \]
\[ \Delta \phi = \phi_{D^0} - \phi_h \]

\[ \Delta \phi \] - h-h correlation

\[ \Delta \phi \] - h-h correlation

STAR collaboration PhysRevLett.91.072304
Correlation components ($D^0$-h)

**trigger $D^0$**: $p_T = 2-10$ GeV/c

**associate $h^\pm$**: $p_T > 0.15$ GeV/c

**Au+Au 200 GeV**

Jet (+medium) near-side 2D gauss

Jet (+medium) away-side 2D gauss

Medium cos2 $\Delta\phi$

Medium offset

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c-quark - fragmentation ($D^0$-$h$)

Reminder: triggered correlation -> near side experiences a little bit of the medium

$D^0$: $p_T^{D^0} = 2$-10 GeV/c $h$: $p_T^h > 0.15$ GeV/c

Au+Au 200 GeV

- Broadening of near-side hadron distribution with increasing centrality (medium size)
- Associated hadron yield (~pions) is increasing
- PYTHIA in agreement with small medium (peripheral)
- Large medium (central) $\rightarrow$ More hadrons and spread out further.

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c-quark - fragmentation \((D^0-h,h-h)\)

Reminder: triggered correlation -> near side experiences a little bit of the medium

\[
D^0: \ p_T^{D^0} = 2-10 \text{ GeV/c} \quad h: \ p_T^h > 0.15 \text{ GeV/c}
\]

**Near Side \(\Delta \phi\)-width**

- di-Hadron, Mean Trigger \(p_T = 5.7 \text{ GeV/c}\)
- di-Hadron, Mean Trigger \(p_T = 2.56 \text{ GeV/c}\)
- Pythia \(D^0\)-Hadron, Mean \(D^0 p_T = 3 \text{ GeV/c}\)
- \(D^0\)-Hadron AuAu 200 GeV, Mean \(D^0 p_T = 3 \text{ GeV/c}\)

**Near Side hadron yield**

- di-Hadron, Mean Trigger \(p_T = 5.7 \text{ GeV/c}\)
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\[\sigma_{NS, \Delta \phi}\]

\[
\begin{array}{c}
\text{pythia} \\
\text{50-80\%} \\
\text{20-50\%} \\
\text{0-20\%}
\end{array}
\]

- Same for \(D^0\) and hadron triggered distribution
  
  \(-\rightarrow\) similar energy loss for heavy and light quarks? Theory is needed!
Heavy flavor (D⁰) tagged jets

Study the modification of jet fragmentation and modification of jet radial profile

Radial distribution of D⁰ in jets -> angular distribution of D⁰ w.r.t jet axis

Low-p_T D⁰: 4 < p_T^{D⁰} < 20 GeV/c

Low-p_T D⁰: increasing trend with r
→ could indicate D⁰ further away from jet-axis in Pb-Pb compared to pp.

High-p_T D⁰: p_T^{D⁰} > 20 GeV/c

High-p_T D⁰: ratio consistent with unity → D⁰ distribution not changed by medium
Medium : small -> large (size)

- Smooth transition of small to large medium with multiplicity (event activity) of hadrons in collision
- In pp, pA and AA collisions
Multiple interactions in pp $\rightarrow$ medium

$\rightarrow$ multiple parton interactions
$\rightarrow$ gluon radiation

$\rightarrow$ higher event multiplicity
Strangeness/pion production (pp, pA, AA)

- Strangeness enhancement in AA with respect to pp scales with strange quark content
  -> coming from multiple parton interactions (not hadronic)

- Smooth transition from pp, pA to AA

- In small systems: (small QGP ?)
  -> modified hadron production in small systems?
  -> modified fragmentation function?

- Described with PYTHIA (string frag) in low multiplicity pp collisions

\[
\text{Event charged particle multiplicity } \langle dN_{\text{ch}} / d\eta \rangle_{|\eta|<0.5}
\]

\[
Pb-Pb \ 70-80\% = p-Pb \ 0-5\% = 45
\]

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Omega/pion vs event activity

EPOS: Multiple pomeron exchange via Gribov-Regge theory
Hard interactions based on pQCD

Core-Corona approach
with multiple parton scattering

EPOS 3.210  ALICE (black)

Corona (blue)
= ”partons” with no interactions
—> string decay
—> VACUUM
(consistent with PYTHIA)

Core (green)
= ”partons” with multiple interactions
—> conservation laws (hydro)
—> statistical decay
—> MEDIUM

- Enhanced strangeness production in core medium
- Strangeness enhancement from partonic medium
—> partonic medium (QGP?) in small systems (pp and pA)
Baryon production ($\Lambda^+/D^0$) p+p and p-Pb

PYTHIA, DIPSY, HERWIG are not describing the data in min bias pp and pPb events (not lowest multiplicity events !)

NEW: PYTHIA including color reconnection (CR) for multiple strings in medium (junctions for string-string reconnection) $\rightarrow$ closer to data in low $p_T$ region
Correlations in small systems

LHCb Pb+p \( \sqrt{s_{NN}} = 5 \text{ TeV} \)
1.0 < \( p_T \) < 2.0 GeV/c
Event class 0-3%

• Correlations similar to AA collisions
• Broadening on the away-side

Pb+p 5 TeV 0-3%

Jet broadening in small (p+A)

- Larger broadening on the away-side in high multiplicity events
  —> more collisions —> larger broadening
  —> scattering in partonic medium
  —> broadening is system size dependent
Summary

- Energy dissipation is medium size and mass dependent
- Jet modification due to medium interactions
- Enhanced baryon production in larger systems
- Enhanced strangeness production
- Partonic medium in small collision systems
- (Theory needed)
- Important to understand gluon density, distributions and gluon interactions $\rightarrow$ EIC

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Thanks!