Heavy ion physics

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A heavy ion collision

- ~ 1600 primary charged hadrons per unit rapidity
- p+p at comparable $\sqrt{s}$: $dN_{ch}/d\eta \sim 4 - 5$
Heavy ion collisions: bird’s eye view

▶ heavy ion collisions create **strongly** interacting system of **high density**

▶ Bjorken’s energy density estimate:

\[
\epsilon_0 \simeq \frac{1}{\pi R^2 \tau_0} \left. \frac{dE_\perp}{d\eta} \right|_{\eta=0} \simeq 25 \text{ GeV}/\text{fm}^3
\]


▶ there has to be **re-scattering** in the final state

▶ scattering drives a system towards thermal equilibrium

▶ How and to what extent does the final state in heavy ion collisions equilibrate?

▶ What are “material properties” of hot and dense QCD matter?
Three main discoveries in heavy ion physics

1. hydrodynamic behaviour

2. jet quenching

3. similarity between p+p and A+A
Discovery # 1: Hydrodynamic behaviour

Soft particles in A+A collisions behave like an almost perfect fluid.

soft = low transverse momentum

- anisotropy due to different pressure gradients
- collective flow

event displays from G. Roland, CMS
Collective flow

Collective flow

\[ v_2 = \langle \cos(2\phi) \rangle \]

- at large coupling hydrodynamics correct description
- mass ordering due to common velocity
Shear viscosity and black holes

- efficiency of $v_2$ generation sensitive to shear viscosity $\eta$
- heavy ion collisions least dissipative system known

![Graph showing $v_2$ vs. $p_T$ for different values of $\eta/s$.]


- conjectured lower bound form obtained with AdS/CFT techniques

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

saturated by field theories with gravity duals

Higher harmonics

no odd harmonics

fluctuations generate odd harmonics

Higher harmonics

- **no odd harmonics**
- **fluctuations generate odd harmonics**

Higher harmonics

no odd harmonics

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Higher harmonics

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fluctuations generate odd harmonics

- very central collisions
- $v_2$ small
Discovery # 2: Jet quenching

Jet quenching: Hard jets are suppressed and their structure modified. hard = high transverse momentum

- proton-proton collisions: 2 jets with balancing transverse momentum
- in heavy ion collisions: significant softening of jets
→ thermalisation of a far-from-equilibrium system
→ jet quenching informs us about equilibration in QCD
What happens to jets in medium?

**Scenario I:** hard partons don’t resolve quasi-particles
- interactions between jet & medium at **large coupling**
- AdS/CFT techniques

**Scenario II:** hard partons do resolve quasi-particles
- jet – medium **interactions** at **weak(ish) coupling**
- perturbative techniques
- thermalisation through elastic re-scattering (slow)
- parton energy loss through **QCD bremsstrahlung**
- destructive interference in multiple scattering **LPM effect**

**relevant scale:** momentum transfer $q$ between hard parton and medium
Jets and thermalisation

In both scenarios jet quenching related to thermalisation:

- early stages of HIC and jets are far-from-equilibrium systems
- jet quenching can be seen as “jet thermalisation”
- effective kinetic theory describing thermalisation

Arnold, Moore, Yaffe, JHEP 0301 (2003) 030

\[ -\frac{df_p}{d\tau} = C_{1\leftrightarrow2}[f_p] + C_{2\leftrightarrow2}[f_p] + C_{\text{exp}}[f_p] \]

- \( C_{1\leftrightarrow2} \): splitting/merging rate in presence of multiple scattering including LPM effect
- \( C_{2\leftrightarrow2} \): elastic scattering rate
- both processes also responsible for parton energy loss
Jet quenching: setting the stage

Jets in p+p

- jets in proton-proton collisions fairly well understood in pQCD
  - jet production
  - jet sub-structure
  - jet reconstruction using dedicated algorithms

most commonly used at LHC: anti-$k_{\perp}$
Jet quenching: setting the stage

Jets in p+p
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Jets in A+A
- jet production in heavy ion collisions understood
  only nuclear modification in pdf’s
- cross-check: vector boson production
- observed: strong modifications of jets
- due to re-scattering in final state
What happens to jets in medium?

- time it takes to radiate a gluon: $t_{\text{form}} \approx \omega / k_{\perp}^2$
- time needed for jet evolution $\sim$ medium size
- jet evolution & re-scattering happen simultaneously
- multi-scale problem
- cannot be solved exactly

analytic results for special cases
What is known analytically

- single gluon emission off a hard parton in eikonal limit
  - Zakharov, JETP Lett. 65 (1997) 615

- non-Abelian LPM effect plays important role

- 2-gluon emission
  - Arnold, Chang, Iqbal, JHEP 1610 (2016) 124
  - Casalderrey-Solana, Pablos, Tywoniuk, JHEP 1611 (2016) 174

- radiation off colour dipole

- non-eikonal kinematics
  - Apolinário, Armesto, Milhano, Salgado, JHEP 1502 (2015) 119
A Monte Carlo model for jet quenching: JEWEL

Zapp, Krauss, Wiedemann, JHEP 1303 (2013) 080

- jet production in initial N+N collisions: ME+PS
A Monte Carlo model for jet quenching: JEWEL

- jet production in initial N+N collisions: ME+PS
- re-scattering: ME+PS
  - generates elastic & inelastic processes
  - with leading log correct relative rates
  - general kinematics
A Monte Carlo model for jet quenching: JEWEL

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- emission with shortest formation time is realised
  - all emissions (vacuum & medium induced) treated equally
  - hard structures remain unperturbed
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- emission with shortest formation time is realised
  - all emissions (vacuum & medium induced) treated equally
  - hard structures remain unperturbed
- LPM interference
  - also governed by formation times
  - without kinematic restrictions
Jet shape and jet sub-structure observables

- observables built from jet constituents
  particles, partons, calorimeter cells, ... 

- characterise distribution of momentum & find structures inside jet

- various grooming techniques studied in p+p to separate hard structure from soft contaminations
  filtering, trimming, pruning, ... 

- shapes/sub-structure of quenched jets sensitive to medium’s reaction to energy & momentum deposited by jets
Intra-jet energy distribution: Jet profile

- suppression of activity at intermediate $r$
- increase near the edge of the jet

Theory results

**Pb-Pb @ 2.76TeV (0-10%)**

- **anti-** $k_T$ $R=0.3$
- $p_{T,jet}^{jet}>100$ GeV/c, $p_{T,track}^{track}>1$ GeV/c
- $0.3<|\eta^{jet}|<2$
- CMS 0-10%

**Inclusive, PbPb (2.76 TeV)**

- $p_{T,jet}^{jet}>100$ GeV/c, $R=0.3$
- $q=0.17$ GeV^2/fm$^2$, $\omega_{cut}=1.0$ GeV/c
- $p_T^{jet,byy}>1.0$ GeV/c

- **CMS (0-10 %)**
- Shower+Hydro
- CMS

**JEWEL+PYTHIA (0 − 10%), Pb+Pb $\sqrt{s} = 2.76$ TeV**

- w/o Recolls
- w/ Recolls 4MomSub
- CMS
- $\Delta k_T R=0.3$, $|p_{T,jet}| < 2$
- $p_T > 100$ GeV

**Park, Jeon, Gale, arXiv:1807.06550**

**Park, Jeon, Gale, arXiv:1807.06550**

**Kumarwalkam Elayavalli, Zapp, JHEP 1707 (2017) 141**

**Chien, Vitev, JHEP 1605 (2016) 023**

**Korinna Zapp (LIP & CERN)**

Heavy ion physics
Discovery # 3: similarity between p+p and A+A

- (partial) equilibration of final state in A+A
- expectation: p+p qualitatively different from A+A
  p+p collisions too dilute to develop collectivity
- observed:

Soft particle production in high-multiplicity p+p and p+A closely resembles A+A, but so far no jet quenching is observed.
Possible explanations

Final state interactions

azimuthal anisotropies due to response to initial geometry

- hydrodynamics
- kinetic theory

Initial state correlations

initial state correlations imprinted on final state

- color-glass condensate
  - effective field theory of saturated gluons generated by color sources in nuclei

Alternative explanations

models inspired by p+p physics

- string shoving
  - Bierlich, Gustafson, Lönnblad, arXiv:1612.05132
  - at hadronisation densely packed strings repel each other
The escape mechanism

- kinetic theory set-up:
  - initially isotropic particle distribution
  - with spatial anisotropy
  - number of scatterings $O(1)$
  - scattering isotropises particles
  - anisotropic scattering probability
  - generates $v_n$'s closely resembling hydrodynamic $v_n$'s

- also observed in transport code AMPT

- have to reassess hydrodynamic interpretation of A+A data
Conclusions

1. Soft particles in A+A collisions behave like an almost perfect fluid.
   - very well described by hydrodynamics with $\eta/s \gtrsim 1/4\pi$
   - indications of at least partial equilibration

2. Jet quenching: Hard jets are suppressed and their structure modified.
   - jet quenching closely related to thermalisation
   - chance to resolve quasi-particles in background medium
   - jet shape/sub-structure may be sensitive to medium response
     - chance to observe thermalisation of deposited energy
   - no consensus about relevant processes

3. Soft particle production in high-multiplicity p+p (and p+A) closely resembles A+A, but so far no jet quenching is observed.
   - largely unresolved
   - possible explanations: final state interactions, initial state correlations, hadronisation effects
   - questions our understanding of soft particle production in p+p and/or collectivity in A+A