Heavy-ion collisions: a tool for characterizing high-density QCD at colliders

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Why heavy-ion experimental physics?

\[ \mathcal{L}_{\text{QCD}} = \bar{q}(i\gamma^\mu D_\mu - m)q - \frac{1}{4} F_{\mu\nu}^a F^{\mu\nu}_a \]
What should you expect from this short course?

- Phenomenology of heavy-ion collisions:
- Experimental signatures:
  - Bound-state dissociation
  - Jet quenching
  - Collectivity in hadronic collisions
- New experimental tools for new (and old) open questions
- Prospects for high-density QCD at colliders over the next two decades

\[ \mathcal{L}_{\text{QCD}} = \bar{q}(i\gamma^\mu D_\mu - m) q - \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu} \]
“Head-on” nucleus-nucleus collisions
→ high-temperature

L ~ 5-10 fm
T ~ 200-300 MeV

Colors are no longer “confined” to hadrons
→ partonic properties of QCD
Nuclear matter at high temperature with heavy ions

“Head-on” nucleus-nucleus collisions $\rightarrow$ high-temperature

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Colors are no longer “confined” to hadrons
$\rightarrow$ partonic properties of QCD

Phase diagram of nuclear matter at equilibrium

~155 MeV

Quark Gluon Plasma

Hadron Gas

Nuclei

H.-T. Ding et al., arXiv 1504.05274
The “standard-model” of the evolution of a heavy-ion collision


MADAI Collaboration

Nuclear matter (“cold”) at high-partonic density in Lorentz contracted nuclei at v~c composed of quarks, q̅q pairs from fluctuations, sea gluons

→ quark and gluon nuclear PDFs
→ nuclear matter at extreme gluon densities ("gluon" saturated matter)
A few hard perturbative scatterings
Large amount of "soft" scatterings (small $k_T$)
$\rightarrow$ reduce the energy of the nuclei
$\rightarrow$ leads (after $\tau_{\text{form}}$) to the formation of a medium
“QGP” phase and expansion

Quark Gluon Plasma phase

→ sensitivity to the partonic properties of the hot nuclear matter

follow by an expansion/cooling phase
Hadron formation and freeze out

Hadrons are formed when $T < T_{\text{critical}}$
Inelastic interactions stop \textit{(chemical freeze out)}
and then elastic interactions stop \textit{(kinetic freeze out)}

How are hadrons formed at the boundary of a Quark Gluon Plasma phase?
Some quantitative considerations

Run-2 conditions:
- \( E_{nucleon}^{\text{beam}} = 2510 \text{ GeV} \)
- \( \sqrt{s_{\text{NN}}} = 5020 \text{ GeV} \)
- \( m_{\text{proton}} = 0.938 \text{ GeV} \)
- \( R_{\text{Pb}} = 7 \text{ fm} \)

\[ y_{\text{beam}} = \frac{1}{2} \ln \frac{E_{\text{beam}} + p_z}{E_{\text{beam}} - p_z} = (\pm) 8.5 \]

\[ \Delta z = 2R_{\text{Pb}}/\gamma \approx 0.005 \text{ fm} \]
What is baryonic density of the medium at the LHC?
What is baryonic density of the medium at the LHC?

rapidity (y)

~ -6.5

~ +6.5

before the collision

after the collision

rapidity (y)
The challenge of experimental heavy-ion physics

What would we like to know (in brief)?
- **properties of the hot nuclear matter** at different medium temperature, baryonic densities..

BUT there are no instrumentations that allows us to measure directly $T$ or $\mu_B$ of such medium!

What can we access experimentally?
- beam energy and nucleus type
- **kinematic properties of final-state particles**

We have to find experimental ways to constrain all these properties through the kinematic properties of final state hadrons.
Phenomenology of heavy-ion collisions

How we model/classify a heavy-ion collision
Peripheral collisions (large $b$) → lower medium temperature → lower energy density

Central collisions ($b \sim 0$) → lower medium temperature → lower energy density

Can we make use of this accidental property of the collisions to classify events according e.g. to their medium temperature?
The Glauber model of heavy-ion collisions

→ heavy-ion collision as a superposition of independent nucleon-nucleon scatterings ("optical limit")

MODEL ASSUMPTIONS:
• nucleons (protons and neutrons) as point-like objects
• the initial directions of the nuclei are not modified ($k_T \sim 0$)
• protons and neutrons are indistinguishable
The Glauber model of heavy-ion collisions

→ heavy-ion collision as a superposition of independent nucleon-nucleon scatterings ("optical limit")

Impact parameter: transverse distance between the center of masses of the two nuclei

**Participants** are nucleons that are involved in a nucleon-nucleon scattering
**Spectators** are nucleons do not collide
A key application of the Glauber model

→ heavy-ion collision as a superposition of independent nucleon-nucleon scatterings (“optical limit”)

→ Glauber provides a way to describe AA collisions in terms of pp collisions

Probability of having n nucleon-nucleon collisions:

\[ P_n(n) = \binom{AB}{n} \left[ \sigma_{\text{incl}} T_{AB}(b) \right]^n \left[ 1 - \sigma_{\text{incl}} T_{AB}(b) \right]^{AB-n} \]

- Binomial coefficient = n interactions out of AB possibilities
- Probability of having n collisions among nucleons
- Probability of having AB-n non-interacting nucleon pairs

A key application of the Glauber model

→ heavy-ion collision as a superposition of independent **nucleon-nucleon scatterings** (“optical limit”)
→ Glauber provides a way to describe AA collisions in terms of pp collisions

**Probability of having n nucleon-nucleon collisions:**

\[
P_n(n) = \binom{AB}{n} [\sigma_{\text{inel}} T_{AB}(b)]^n [1 - \sigma_{\text{inel}} T_{AB}(b)]^{AB-n}
\]

\(T_{AB}(b)\) describes the “geometrical” probability of having two overlapping nucleons in A and B.

→ Estimate the number of nucleon-nucleon “hard” scatterings in a AA collision:

\[
N_{\text{coll}}(b) = AB \sigma_{\text{inel}}^{pp} T_{AB}(b)
\]

→ \(N_{\text{coll}}\) allows to compare the yields of production measured in AA collisions with pp collisions, **assuming we know b**
A key application of the Glauber model

→ heavy-ion collision as a superposition of independent nucleon-nucleon scatterings (“optical limit”)

→ Glauber provides a way to describe AA collisions in terms of pp collisions

\[
R_{AA} = \frac{1}{<N_{coll}>} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}
\]

\( R_{AA} = 1 \) under the hypothesis of simple superposition

Phenomenology of heavy-ion collisions
characterizing the global properties of the medium
How to measure the impact parameter of a collision?

The Glauber model is a “thought” experiment!

→ $b$ is not a parameter of the collision known a-priori by experimentalist
How to measure the impact parameter of a collision?

The Glauber model is a “thought” experiment!
→ *b* is not a parameter of the collision known a-priori by experimentalist

One possibility) measure the energy deposited in the ZDC by the non-interacting nucleons
→ Glauber MC simulations allows to estimate the *b* (or collision centrality) starting from spectator energy
The day-0 measurement: Charged-particle multiplicity

- Hadron production in elementary and nuclear collisions as one of the oldest puzzles in particle physics!
Charged-particle multiplicity to estimate energy density

- Hadron production in elementary and nuclear collisions as one of the oldest puzzles in particle physics!
- In heavy-ion collisions → a tool to constrain the initial energy density

Bjorken's method (valid at $\mu_b = 0$)

→ A tool to constrain the initial energy density

$$\rho_{\text{PbPb}}^{\text{energy}} (\tau = 1 \text{ fm/c}) \approx \frac{E_T}{\pi R^2 L_z} \approx 12 \text{ GeV/fm}^3$$

$$\rho_{\text{PbPb}}^{\text{energy}} (\tau = 1 \text{ fm/c}) > > \rho_{\text{energy}}^{\text{regular matter}}$$
“Signatures” for the presence of a new phase of matter

Bound states to test the presence of deconfined colors?
The spectrum of $c\bar{c}$ bound states can be well described in vacuum with a Cornell potential as:

$$H = -\frac{\vec{p}^2}{2\mu} - \frac{\alpha}{r} + kr$$

What happens to this potential when the $c\bar{c}$ state is immersed in the Quark Gluon Plasma?
The spectrum of $c\bar{c}$ bound states can be well described in vacuum with a Cornell potential as:

$$H = -\frac{\vec{p}^2}{2\mu} - \frac{\alpha}{r} + kr$$

Yukawa potential which includes a screening factor due to the presence of a high-color "density"

$$\lambda_D \sim \frac{1}{gT}$$

The bound state becomes "weaker for increasing values of temperature and coupling constant!"
The hypothesis of quarkonium sequential suppression

Different bound states have different binding energies and radii

Different dissociation temperatures in the Quark Gluon Plasma

Can the quarkonium states be used as a medium thermometer?

**J/ψ suppression at the SPS in PbPb collisions**

Anomalous suppression observed in PbPb collisions at 158 GeV if compared to expectation based on HP of superposition of pp collisions → considered the first concrete evidence for the creation of a deconfined phase of matter
**J/ψ** nuclear modification factor at RHIC (AuAu 200 GeV)

More differential study study confirmed the evidence for a strong suppression of J/ψ in Au-Au collision.

What would you expect for LHC energies?
Naively more J/ψ dissociating due to the higher temperature of the medium.
More $J/\psi$ survives even in the presence of a hotter medium???

Any competing mechanism?
J/ψ “regeneration” in the Quark Gluon Plasma

New mechanisms of hadron formation in the presence of a hot medium:
• J/ψ created in the QGP by combination of uncorrelated charm-anti-charm pairs

→ One of the highlight of the heavy-ion program at the LHC
predicted well before within the framework of Statistical Hadronization Models

Bottomonium suppression in PbPb collisions

Bottomonia less affected by recombination due to lower $b\bar{b}$ cross section!

When we “switch” off regeneration using $b$ quarks:
→ Loosely bound states (2S,3S) more suppressed than (1S) as predicted by sequential suppression

→ To this date, one of the strongest signatures for the formation of a system with deconfined colors
can we measure the stopping power of the medium with high-energy probes?
can we measure the stopping power of the medium with high-energy probes?

→ Use high-$p_T$ partons as “self-generated” probes for the medium properties

Bjorken (1982), FERMILAB-PUB-82-059-THY
The nuclear modification factor $R_{AA}$

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN/dp_T(AA)}{dN/dp_T(pp)}$$

$R_{AA} = 1$ in absence of in-medium $E_{\text{loss}}$

$R_{AA} < 1$ in presence of in-medium $E_{\text{loss}}$
→Strong suppression observed in central (head-on) collision where the hottest and largest QGP is created
Charged hadron $R_{AA}$ in “peripheral” PbPb collisions

- Suppression is reduced in peripheral collision as naively expected in presence of a colder medium
Jet-$p_T$ asymmetry to probe quenching

The two partons typically traverse a different path length inside the medium

\[ A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \]

→ increase of the number of jets with large $p_T$ asymmetry in PbPb compared to pp

→ All these measurements (both with single hadrons and jets) can be described by calculations ONLY in the presence of parton energy loss inside a colored medium!
Jet quenching measurements with heavy flavor hadrons

\[ m_c \sim 1.5 \text{ GeV} \]
\[ \Lambda_{QCD} \sim 200 \text{ MeV} \]
\[ T_{QGP} \sim 300 \text{ MeV} \]
\[ m_{u,d,s} \leq T_{QGP} \]

HQs rescatter inside the QGP
→ lose energy, probing the medium properties

Hadronizes at the boundary of the QGP phase:
→ probing the mechanisms of hadronization

“pQCD” production in vacuum \((m_{c,b} > \Lambda_{QCD})\).
Jet quenching measurements with heavy flavor hadrons

- Conserved and traceable witness of the QGP evolution (no "thermal production")
- Experimentally accessible at any $p_T$ via fully-reconstructed decays

$D^0 \rightarrow K^- \pi^+$

$\mathcal{O}(100 \mu m)$

$\pi$ interaction vertex

$K$ $D^0$ decay vertex

$\text{charmed hadron}$

$\text{QGP}$
ALICE pioneered in Run 1 the **first measurements of fully reconstructed charm meson and baryons** down to low $p_T$ with large minimum bias samples.

**Reconstruction of the secondary decay vertex**

ALICE charged particles

![Graph showing $d_{xy}$ resolution versus $p_T$](image1)

**Particle identification of final state decays**

with Time Projection Chamber $dE/dx$ and Time of Flight

![Graph showing TPC $dE/dx$ (arb. units) versus $p/z$](image2)
D and B meson reconstruction with CMS

→ test the mechanisms of heavy-quark interaction with the hot medium at higher $p_T$
→ characterize the relevance of mass in the process of enhanced gluon radiation

First B-hadron analyses in heavy-ion collisions:
→ direct access to the energy loss of b quarks

$B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$

D$^0$ measurement up to high-$p_T$

First D$^0$ jet-based trigger in heavy-ion collisions
• hardware triggers with jet-background subtraction
→ upgrade of the Level-1 trigger system
• “Online” D$^0$ tagging using software (High-Level) triggers
Evidence for in-medium energy loss of charm quarks

$D^0$ mesons

Central 0-10%
→ head-on collision!
→ larger energy density

$R_{AA} = \frac{1}{N_{coll}} \frac{dN/dp_T(AA)}{dN/dp_T(pp)}$

$R_{AA} = 1$: no modification

$R_{AA} << 1$ → charm quarks strongly interact with the hot medium, and lose a sizeable amount of energy!
Mapping the role of mass in heavy-quark $E_{\text{loss}}$

<table>
<thead>
<tr>
<th>Year</th>
<th>Reference</th>
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<td>2016</td>
<td>CMS, PRL (2016), 032301.</td>
</tr>
<tr>
<td>2020</td>
<td>CMS, PRL 125, 102001 (2020).</td>
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Mapping the role of mass in heavy-quark $E_{\text{loss}}$

Physics interpretation (perturbative QCD)

$\rightarrow$ increased gluon radiation
$\rightarrow$ modified splitting functions $P_{c \rightarrow cg}$

Suppression of small angle radiation for heavy quarks
$\rightarrow E_{\text{loss}}(c) > E_{\text{loss}}(b)$

$D^0$ mesons
$B^+$ mesons
$b \rightarrow J/\psi$

$\rightarrow$ First constraints on the different magnitude of charm and beauty $E_{\text{loss}}$
Mapping the role of mass in heavy-quark $E_{\text{loss}}$

Physics interpretation (perturbative QCD)

→ increased gluon radiation
→ modified splitting functions $P_{c\rightarrow cg}$

Suppression of small angle radiation for heavy quarks
→ $E_{\text{loss}}(c) > E_{\text{loss}}(b)$

→ Flavor-dependence of in-medium energy loss as a “clean” predictions of pQCD in the presence of a “colored” medium (although it might be not as simple as we thought …)
Summary
What have we learnt about heavy-ion physics?

The challenge

Theoretical and experimental “toolbox”
What have we learnt about the hot nuclear matter we create?

• In heavy-ion collisions, we create the conditions for forming a new phase of nuclear matter
• Several experimental evidences confirm the creation of a hot nuclear medium with deconfined color charges

• What kind of deconfined medium have we created?
• Does it behave like a weakly-interacting gas of quark and gluons?
What have we learnt about the hot nuclear matter we create?

• In heavy-ion collisions, we create the conditions for forming a new phase of nuclear matter
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• What kind of deconfined medium have we created?
• Does it behave like a weakly-interacting gas of quark and gluons?
  → More detail tomorrow 😊!

Experimental signatures (II):
  • Collectivity in hadronic collisions
  • From phenomenology to first principle QCD:
    • a new era for quenching measurements
    • High-density QCD in the 20’s, 30’s and beyond

thank you for your attention!

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BACKUP SLIDES