Heavy Ions: theory overview
Outline

• Part I:
  • Heavy-Ion collisions:
    • What? Why?
  • Quark-Gluon Plasma:
    • What? Why?
    • Hydrodynamics & Flow
    • Initial state
  • Small Systems
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Part I:
- Heavy-Ion collisions:
  - What? Why?
- Quark-Gluon Plasma:
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  - Initial state
- Small Systems

Part II:
- Probes of QGP short wave-length behaviour:
  - High-momentum particles
  - Jets & Jet substructure
    See Gian Michele’s lectures for quarkonia and heavy-quarks
- Quark-Gluon Plasma properties:
  - Transport coefficients
  - Timescale evolution
Outline

Today's lecture:

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  - Initial state
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Heavy Ions: theory overview

Part I
Introduction
SM & QCD

- Standard Model (SM);
  - Strong and Electro-weak interactions
- Color sector of SM:
  - Described by Quantum Chromodynamics (QCD)
Quantum Chromodynamics (QCD)

- Lagrangian structure fixed by requiring SU(3) gauge invariance:
  
  - All (anti-)quark flavours exist in 3 (anti-)colours: R(ed), G(reen), B(lue)

\[ \psi_a = \begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{bmatrix} \]
Quantum Chromodynamics (QCD)

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\psi_a = \begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{bmatrix} \quad \mathcal{L}_{\text{QCD}} = \sum_{\text{flavours}} (\mathcal{L}_q + \mathcal{L}_g) \quad \mathcal{L}_q = \bar{\psi}_a (i \gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t_{ab}^C A_\mu^C - m) \psi_b
\]

Quark propagator + interaction term
Quantum Chromodynamics (QCD)

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\]

Quark propagator + interaction term

\[
\mathcal{L}_g = -\frac{1}{4} F^{\mu \nu}_A F^{A \mu \nu}
\]

Gluon propagator + gluon self-interaction terms

\[
F^{A \mu \nu} = \partial_\mu A^A_\nu - \partial_\nu A^A_\mu - g s f_{ABC} A^B_\mu A^C_\nu
\]

\[
[t^A, t^B] = i f_{ABC} t^C
\]
Quantum Chromodynamics

- Coupling is scale dependent (renormalisation)
- Self-interacting gauge fields lead to asymptotic freedom
- Quarks and gluons as degrees of freedom only at short distances (high momentum scales)

See: Gregory Soyez's lectures

\[ \alpha_s(Q) = \frac{\alpha_s(m_Z)}{\sqrt{Q}} \]

\[ \alpha_s(m_Z) = 0.1175 \pm 0.0003 \ (\text{TEEC Global}) \]

\[ \alpha_s(m_Z) = 0.1179 \pm 0.0009 \ (\text{PDG 2022}) \]
From dilute QCD to dense QCD

- QCD is not limited to a collection of small particles…
- QCD matter has a rich and vast phase diagram
From dilute QCD to dense QCD

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- QCD matter has a rich and vast phase diagram

QCD theory (1973)
SU(3) Color symmetry; confinement; asymptotic freedom, …

QGP initial idea (1975)
“Weakly coupling quark soup”
State of matter where quarks and gluons are asymptotically free
From dilute QCD to dense QCD

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State of matter where quarks and gluons are asymptotically free

QGP at present
“Strongly coupled fluid”

Fundamental question: How collectivity emerge from elementary particles interaction?
QCD Phase transition

- If quarks and gluons effectively become free → new d.o.f

- Stefan-Boltzmann (SB) ideal quark-gluon gas:

  \[ \epsilon(T) = n_{d.o.f} \frac{\pi^2}{30} T^4 \quad n_{d.o.f} = N_B + \frac{7}{8} N_F \]

\[ N_B = 2 \times 8, \quad N_F = 2 \times 2 \times 3 \times 3 \]

- particle/antiparticle
- spin
- color
- spin
- color
- flavor: u/d/s
QCD Phase transition

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- Lattice QCD results (first principles calculations)
- QGP far from SB limit due to non-perturbative effects
QCD Phase transition

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Discovering QCD phase diagram

- How to unveil the unknown corners of the QCD phase diagram?
  - Through heavy-ion collisions:

![Diagram](image)
Discovering QCD phase diagram

- How to unveil the unknown corners of the QCD phase diagram?
- Through heavy-ion collisions:

Heavy-ion address this question in the regime of highest temperature and densities accessed in laboratories.
QGP @ Colliders

- Macroscopic quantities estimated from the number of particles produced at mid-rapidity:

\[
\frac{dN_{ch}}{d\eta} \bigg|_{\eta=0} \propto (\sqrt{s_{NN}})^{0.3}
\]

\[\tau_0 \sim 1 \text{fm}/c\]

- Energy density computed with Bjorken estimate:

\[
\varepsilon = \frac{dE_T}{d\eta} \frac{1}{\tau_0 \pi r^2} \quad r \sim A^{1/3}
\]

[A. Dainese et al. (1605.01389)]
**QGP @ Colliders**

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<table>
<thead>
<tr>
<th>Quantity</th>
<th>SPS</th>
<th>RHIC</th>
<th>LHC</th>
<th>FCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sqrt{s_{\text{NN}}} ) [TeV]</td>
<td>0.017</td>
<td>2</td>
<td>5.5</td>
<td>39</td>
</tr>
<tr>
<td>Homogeneity volume [fm(^3)]</td>
<td>1200</td>
<td>2300</td>
<td>6200</td>
<td>11000</td>
</tr>
<tr>
<td>( \epsilon(\tau = 1,\text{fm/c}) ) [GeV/fm(^3)]</td>
<td>3-4</td>
<td>4-7</td>
<td>16-17</td>
<td>35-40</td>
</tr>
<tr>
<td>Decoupling time [fm/c]</td>
<td>4</td>
<td>7</td>
<td>11</td>
<td>13</td>
</tr>
</tbody>
</table>

Denser medium ⇒ longer expansion and larger volume
Higher initial energy ⇒ larger temperature and smaller thermalisation time
Proton-proton vs heavy-ions

- Proton-proton vs heavy-ion collisions:

Proton-proton collisions
Low multiplicity event
Proton-proton vs heavy-ion collisions:

- Proton-proton collisions
- Low multiplicity event

- Lead-Lead collisions
- High multiplicity event (result of QGP formation)
Quark-Gluon Plasma (QGP)

- We can create it in the lab. But how to study it?
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Caveat: need to rely on self-generated probes
Quark-Gluon Plasma (QGP)

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Soft probes
non-pQCD

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Quark-Gluon Plasma (QGP)

- We can create it in the lab. But how to study it?

Caveat: need to rely on self-generated probes
Setting the collision system...
Collision Geometry

- Colliding Nuclei ~ collection of nucleons
- Collision system ~ nucleons that participate in the collision
Collision Geometry

- Colliding Nuclei ~ collection of nucleons
- Collision system ~ nucleons that participate in the collision
  
- To define collision geometry:
  - Impact parameter (b): the transverse distance between the center of masses of the two nuclei
  - It will control the extent of the medium that is created
Centrality Classes

- Using a geometrical model (Glauber), one can relate impact parameter to average
- Number of participants in the collision
Centrality Classes

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  - Number of participants in the collision
  - Number of produced particles

![Peripheral Collision](image1.png)

![Central Collision](image2.png)
Centrality Classes

- Using a geometrical model (Glauber), one can relate impact parameter to average
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- Number of produced particles
- Centrality class defined as percentile ranges of minimum-bias cross section

![Peripheral Collision](image1)
![Central Collision](image2)
Centrality Classes

- Using a geometrical model (Glauber), one can relate impact parameter to average
- Number of participants in the collision
- Number of produced particles
- Centrality class defined as percentile ranges of minimum-bias cross section

See Gian Michele’s lectures
Macroscopic view:

Soft Probes
Collection of final-state particles that are the result of the QGP evolution

Soft probes
non-pQCD

Sensitive to global properties of the QGP
From central to peripheral

- Try different centralities and check response of the system to initial spatial anisotropy:

Superposition of multiple pp collisions

Reaction plane: z-x plane
From central to peripheral

- Try different centralities and check response of the system to initial spatial anisotropy:

Superposition of multiple pp collisions

Collective bulk behaviour

Pressure driven expansion:

Reaction plane: z-x plane
From central to peripheral

- Try different centralities and check response of the system to initial spatial anisotropy:

**Superposition of multiple pp collisions**

**Collective bulk behaviour**

$t = 0.0 \text{ fm/c}$
From central to peripheral

- Try different centralities and check response of the system to initial spatial anisotropy:

Superposition of multiple pp collisions  Collective bulk behaviour

$t = 0.0 \text{ fm/c}$
From central to peripheral

- Try different centralities and check response of the system to initial spatial anisotropy:

![Image of superposition of multiple pp collisions and collective bulk behaviour](image.png)

*Reaction plane: z-x plane*
From central to peripheral

- Try different centralities and check response of the system to initial spatial anisotropy:
Spatial anisotropies

- Quantification through Fourier transformation of the particles angular distribution:

\[
\frac{dN}{d\phi} = \frac{N}{2\pi} \left( 1 + 2 \sum_{n=1}^{\infty} \nu_n \cos(n(\phi - \Psi_n)) \right)
\]
Spatial anisotropies

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Reaction plane angle
(where the nth harmonic component has its maximum multiplicity)

Fourier parameterisations:
Spatial anisotropies

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**Reaction plane angle**
(where the nth harmonic component has its maximum multiplicity)

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dN = N_2 \pi \left( 1 + \sum_{n=1}^{\infty} \nu_n \cos \left( n(\phi - \Psi_n) \right) \right)
\]

From charged multiplicity, extract elliptic (v2), triangular (v3),... flow coefficients

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\nu_2 = \langle \cos 2(\phi - \Psi_2) \rangle
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...
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Hydrodynamics

- Why hydrodynamics?
- Complicated to withdraw information from QCD Lagrangian...

\[ \mathcal{L}_{QCD} = \sum_{\text{flavours}} (\mathcal{L}_q + \mathcal{L}_g) \]

\[ \mathcal{L}_g = -\frac{1}{4} F_{\mu\nu} F^{A\mu\nu} \]

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Hydrodynamics

- Why hydrodynamics?
  - Complicated to withdraw information from QCD Lagrangian…
  - Lattice QCD:
    - Discretise space-time and evaluate numerically the Lagrangian
    - Use Monte Carlo sampling to obtain the relative likelihood of all possible configurations
    - Excellent tool to calculate static properties but it is computational demanding for high-energy processes

\[
\mathcal{L}_{QCD} = \sum_{\text{flavours}} (\mathcal{L}_q + \mathcal{L}_g)
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\[
\mathcal{L}_g = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu}^{A}
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Hydrodynamics

- Why hydrodynamics?
  - Effective theory that describes extremely well QGP phenomena
  - Input includes the Equation-of-State (EoS)

**Energy-momentum tensor (ideal hydro):**

\[ T^{\mu\nu} = \epsilon u^\mu u^\nu + p (g^{\mu\nu} + u^\mu u^\nu) \]

**EoS (ideal hydro):**

\[ p = p(\epsilon) \]

**Hydrodynamic evolution equations**

- Energy-momentum conservation:
  \[ \partial_\mu T^{\mu\nu} = 0 \]

- Current conservation:
  \[ \partial_\mu N^\mu = 0 \]

\[ \downarrow \]

L. Apolinário
Hydrodynamics

- Why hydrodynamics?
  - Effective theory that describes extremely well QGP phenomena
  - Input includes the Equation-of-State (EoS)
    - Provided by, e.g: Lattice QCD

Energy-momentum tensor:

\[ T^{\mu\nu} = \epsilon u^\mu u^\nu + (p + \pi_{\text{bulk}})(g^{\mu\nu} + u^\mu u^\nu) + \pi^{\mu\nu} \]

EoS:

\[ p = p(\epsilon, n) \]

Energy-momentum conservation:

\[ \partial_\mu T^{\mu\nu} = 0 \]

Current conservation:

\[ \partial_\mu N^\mu = 0 \]

(More involving) 3+1 Hydrodynamic evolution equations

Deviations from ideal hydro (viscous hydro) include additional coefficients:

Shear viscosity \( \eta \), bulk viscosity \( \zeta \), ...
Specific Shear Viscosity $\eta/s$

The shear viscosity ($\eta$) of a system measures its resistance to flow.
Specific Shear Viscosity $\eta/s$

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- The “specific shear viscosity ($\eta/s$) measures the effects of shear viscosity in a relativistic fluid

  - Dimensionless parameter that quantifies the amount of entropy produced within the fluid as a sound wave propagates through it.
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- Dimensionless parameter that quantifies the amount of entropy produced within the fluid as a sound wave propagates through it.

$$\eta/s + \text{EoS} + \text{temperature dependence}$$

⇒ Hydrodynamic calculation data comparison
(With hadronic re-scattering after QGP)
QGP Fluidity

- QGP is an (almost) ideal fluid:
QGP Fluidity

- QGP is an (almost) ideal fluid:

![Graph showing flow extracted from simulations and hydrodynamic calculations](image)

![Graph showing elliptic flow as a function of centrality of collisions](image)
QGP Fluidity

- QGP is an (almost) ideal fluid:

Highly sensible to $\eta/s$

![Graph comparing shear viscosity to entropy ratio of QGP with various ordinary matter.](image)

Peripheral

**Fig. 2.** Comparison of the shear viscosity to entropy ratio of QGP with various ordinary matter.
QGP Fluidity

- QGP is an (almost) ideal strongly-coupled fluid:

![Graph showing the temperature dependence of the QGP fluidity](image.png)

String Theory Bound (KSS)
pQCD (AMY) [dashed for scale dependence]
QGP Fluidity

- QGP is an (almost) ideal strongly-coupled fluid:

\[
\alpha_s = \frac{g_s^2}{4\pi} \ll 1
\]

Weak coupling

\[
\alpha_s \approx 1
\]

Strong coupling

**Figure 1.4**: (Left) The ratio of shear viscosity to entropy density, \(\frac{\eta}{s}\), normalized by the conjectured KSS bound as a function of the reduced temperature, \(\frac{T}{T_c}\), for water, Nitrogen, and Helium. The cusp for Helium as shown corresponds to the case at the critical pressure.

(Right) Calculation of hot QCD matter (quark-gluon plasma) for a weakly coupled system. Dashed lines show the scale dependence of the perturbative calculation.
Initial State

From nuclei to QGP
Initial state

- Will the final result depend on the initial conditions?

What were the QGP initial conditions?
Initial state

- Will the final result depend on the initial conditions?

What were the QGP initial conditions?

Are the fluctuations of the initial energy density distribution able to survive the hydrodynamic evolution?
Initial state

- Will the final result depend on the initial conditions?
Initial state

- Will the final result depend on the initial conditions?

\[
\begin{align*}
\text{Ideal hydrodynamics} & \quad \text{Viscous hydrodynamics} \\
t = 0.5 \text{ fm/c}
\end{align*}
\]
Initial state

- Will the final result depend on the initial conditions?
Initial state

- Will the final result depend on the initial conditions?
Nuclear Parton Distribution functions

- In collinear factorisation:

$$\sigma_O(s, Q^2) = \sum_{n=0}^{\infty} \alpha_S^2(\mu_R^2) \cdot \sum_{i,j} \int dx_1 dx_2 f_{i/h_1}(x_i, \mu_F^2) f_{j/h_2}(x_j, \mu_F^2) \times \hat{\sigma}_{i,j\rightarrow O+X}(Q(x_i, x_j, s), \mu_R^2, \mu_F^2) ,$$

- Nuclear PDF (nPDF):

$$f_{i,(A,Z)}(x, \mu_F) = \frac{Z}{A} f_{i,p(A,Z)}(x, \mu_F) + \frac{A - Z}{A} f_{i,n(A,Z)}(x, \mu_F)$$

Average proton and neutrons PDFs

Modifications less important for higher energies, but it will affect softer processes

⇒ Extraction of QGP properties highly dependent on initial conditions
Nuclear Parton Distribution functions

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Nuclear Parton Distribution functions

- Able to probe nucleus through DIS:
- Kinematic coverage still limited…
Nuclear Parton Distribution functions

- Able to probe nucleus through DIS:
  - Kinematic coverage still limited…
  - Low-x region dominated by uncertainties…

Effect of including additional data (D-mesons and dijets) on gluon PDF:

\[ \text{[Apolinário et al (2203.16352)]} \]
Nuclear Parton Distribution functions

- Able to probe nucleus through DIS:
- Kinematic coverage still limited…
- Low-x region dominated by uncertainties…
- Onset of saturation:

\[ \pi R_A^2 \sim \frac{Axg(x, Q_s^2)}{Q_s^2} \Rightarrow Q_s^2 \sim A^{1/3}(\sqrt{s_{NN}})^{0.3}e^{0.3y} \]

HINTS OF BREAKING OF LINEAR EVOLUTION AT HERA
but not yet conclusive evidence..

Number of gluons

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Small systems

Conditions for QGP formation?
From AA to pA

- Going to a “simpler” system to understand the initial conditions:

  AA collisions
  (Large systems)
  pA collisions
  (Small systems)

  Learn about incoming nuclei (Pb/Au)

  Learn about created medium (QGP)
From AA to pA

- Going to a “simpler” system to understand the initial conditions:

AA collisions (Large systems)

Learn about created medium (QGP)

pA collisions (Small systems)

Learn about incoming nuclei (Pb/Au)
From AA to pA

- Going to a “simpler” system to understand the initial conditions:

Collectivity signs? → QGP?

(Compatible with hydrodynamics expectations)
From AA to pA

- Going to a “simpler” system to understand the initial conditions:

\[ R_{AA} = \frac{Y_{AA}^X}{\langle T_{AA} \rangle \cdot \sigma_{pp}^X} \]

Normalised ratio of yields between AA and pp

Hard sector

No jet quenching → no QGP

\[ R_{AA} = 0: \text{No Energy loss} \]

\[ R_{AA} < 1: \text{Energy loss} \]
From AA to pA

- Going to a “simpler” system to understand the initial conditions:

  Soft probes Collectivity signs? → QGP?

  Hard sector No jet quenching → no QGP

(Compatible with hydrodynamics expectations)
QGP onset conditions

- Extrapolation from dense to light needs further understanding…

![Graph showing QCD kinetic theory and phases](image)
QGP onset conditions

- Extrapolation from dense to light needs further understanding…

![Graph showing QGP kinetic theory](https://via.placeholder.com/150)

Kurkela [1601.03283]

- QGP Thermalisation
- Hydrodynamic
- Energy loss
**QGP onset conditions**

- Extrapolation from dense to light needs further understanding…

![Diagram of QCD kinetic theory with annotations](image)

- **QGP Thermalisation**
- **Hydrodynamic**
- **Energy loss**

Kurkela [1601.03283]
QGP onset conditions

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Effective kinetic theory can bridge the dynamics from out-of-equilibrium initial conditions to hydrodynamic description

Weak coupling ↔ Strong coupling
QGP onset conditions

- Extrapolation from dense to light needs further understanding…

Effective kinetic theory can bridge the dynamics from out-of-equilibrium initial conditions to hydrodynamic description

**Weak coupling ↔ Strong coupling**

Description based on quasiparticle distribution functions $f_p$

Evolution follow Boltzmann equation with elastic and radiative collision rates:

$$-\frac{\partial f_p}{\partial \tau} = C^{1\leftrightarrow2}[f_p] + C^{2\leftrightarrow2}[f_p]$$
Effective Kinetic Theory

- Pre-equilibrium studies using effective kinetic theory:

How does the thermalisation time arise?

\[-\frac{\partial f_p}{\partial \tau} = C^{1\leftrightarrow 2}[f_p] + C^{2\leftrightarrow 2}[f_p]\]

![Diagram of particle escape, fluid expansion, and strong fields](image)

![Graph showing total pressure anisotropy](image)

- Coupling constant: \(\lambda\)
**Effective Kinetic Theory**

- Pre-equilibrium studies using effective kinetic theory:

How does the thermalisation time arise?

\[-\frac{\partial f_p}{\partial \tau} = C^{1\leftrightarrow2}[f_p] + C^{2\leftrightarrow2}[f_p]\]

[Kurkela et al (1811.03068)]
Future Experiments

Electron Ion Collider (EIC)
Nucleon/Nuclei Structure affect the initial state (important for small systems)
> 2025

RHIC/LHC Upgrades
+ 
OO run (LHC)
2018-2025

Beam Energy Scan (RHIC)/ FAIR
- High baryon densities, hadron gas phase
2018-2020, > 2024
Future Experiments

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LHeC
Take-home messages

- Heavy-Ion collisions are a rich laboratory to study QCD
  - QGP Phase transition at high temperature/density
  - Application of first principle QCD (pQCD, Lattice QCD) and effective models (Hydrodynamics,…)

- Soft probes (non-pQCD sector) are a powerful tool to identify QGP macroscopic properties
  - Quark-Gluon Plasma is a strongly coupled fluid:
    - Present in proton-nucleus (small systems)?
    - Conditions to form a QGP? Saturation effects?
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Thank you!
Acknowledgments
Backup Slides
Collision Geometry

- Colliding Nuclei ~ collection of nucleons
- Collision system ~ nucleons that participate in the collision
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- To define collision geometry:
  - Impact parameter: the transverse distance between the center of masses of the two nuclei
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  - To define collision geometry:
    - Impact parameter: the transverse distance between the center of masses of the two nuclei
    - Location and motion of the nucleons in the nuclei

Monte Carlo Simulation for RHIC AuAu 200 GeV

[Spectators]
[Participants]

[Image: Borsányi et al (1007.2580)]
Collision Geometry

- Colliding Nuclei ~ collection of nucleons
- Collision system ~ nucleons that participate in the collision
  - To define collision geometry:
    - Impact parameter: the transverse distance between the center of masses of the two nuclei
    - Location and motion of the nucleons in the nuclei
- $N_{\text{Spec}} + N_{\text{Part}} = A_L + A_R$
  - $N_{\text{spec}}$ will continue travelling along beam pipe (but cannot be measurable experimentally)
  - $N_{\text{part}}$ will collide with at least other nucleon (what we want to know)
Glauber Model

- Geometric model to calculate:
  - $N_{\text{part}}$: number of participants
  - $N_{\text{coll}}$: number of total collisions

Monte Carlo Simulation for RHIC AuAu 200 GeV

Nuclear thickness function:

$$T_{A/B}(b) = \int \rho_{A/B}(b, z_{A/B}) \, dz_{A/B}$$

Probability of finding a nucleon at a point $(b, z)$ per unit volume

Thickenss function from overlap region:

$$T_{AB}(b) = \int T_A(s) \, T_B(s - b) \, d^2s$$

$$\int T_{AB}(b) \, db = A \cdot B$$
Glauber Model

- Geometric model to calculate \(N_{\text{part}}\) and \(N_{\text{coll}}\)

\[
N_{\text{coll}}(b) = \sigma^{NN}_{\text{inel}} T_{AB}(b)
\]

\[
N_{\text{part}}(b) = \int T_A(s) \left(1 - \exp \left[ -\sigma^{NN}_{\text{inel}} T_B(b - s) \right] \right) ds
\]

+ \[
\int T_B(b - s) \left(1 - \exp \left[ -\sigma^{NN}_{\text{inel}} T_A(b) \right] \right) ds
\]

Geometry (Optical Glauber model) allows to calculate average \(N_{\text{part}}\) and \(N_{\text{coll}}\)
Glauber Model

- Geometric model to calculate $N_{\text{part}}$ and $N_{\text{coll}}$

$$N_{\text{coll}}(\mathbf{b}) = \sigma_{\text{inel}}^{NN} T_{AB}(\mathbf{b})$$

$$N_{\text{part}}(\mathbf{b}) = \int T_A(s) \left( 1 - \exp \left[ -\sigma_{\text{inel}}^{NN} T_B(\mathbf{b} - \mathbf{s}) \right] \right) ds$$

+ \int T_B(\mathbf{b} - \mathbf{s}) \left( 1 - \exp \left[ -\sigma_{\text{inel}}^{NN} T_A(\mathbf{b}) \right] \right) ds

Geometry (Optical Glauber model) allows to calculate average $N_{\text{part}}$ and $N_{\text{coll}}$

**How about fluctuations?**

Individual nucleons are stochastically distributed event-by-event in nuclei following Wood-Saxon distribution

$$\rho(r) = \rho_0 \frac{1 + w(r/R)^2}{1 + \exp\left( \frac{r-R}{a} \right)}$$
Glauber Model

- Geometric model to calculate $N_{\text{part}}$ and $N_{\text{coll}}$

\[
N_{\text{coll}}(b) = \sigma^{NN}_{\text{inel}} T_{AB}(b)
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Geometry (Glauber model) relates multiplicity to $N_{\text{part}}$ and impact parameter ($b$)
Glauber Model

- Geometric model to calculate $N_{\text{part}}$ and $N_{\text{coll}}$

$$N_{\text{coll}}(b) = \sigma^{NN}_{\text{inel}} T_{AB}(b)$$

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Geometry (Glauber model) relates multiplicity to $N_{\text{part}}$ and impact parameter ($b$)

Can now define centrality classes

- [0-5]% Central collisions
- [50-70]% Peripheral collisions
Centrality Classes

- Centrality class defined as percentile ranges of minimum-bias cross section:

\[
|\eta|<1
\]
Big-Bang vs “Little-Bang”

- Harmonics also applied to CMB analysis

Cosmic Microwave Background

CMB anisotropies reveal information about recombination epoch (when photons decoupled)
Big-Bang vs “Little-Bang”

- Harmonics also applied to CMB analysis

In heavy-ion collisions, they yield the anisotropic coefficients
Big-Bang vs “Little-Bang”
Big-Bang vs “Little-Bang”

Similarities:
- Pressure, entropy, energy density
- Quark/Gluon vs Hadrons
- Temperature when hadrons are formed

Strong Force
- Nearly perfect fluid
Big-Bang vs “Little-Bang”

Similarities:
- Pressure, entropy, energy density
- Quark/Gluon vs Hadrons
- Temperature when hadrons are formed

Strong Force:
- Nearly perfect fluid

System Size: Entire Universe
- Equilibrated system
- 1 data point

System Size: Finite volume effects
- Out-of-equilibrium (viscosity,...)
- Several events with different shapes
From dense to light systems

- Extrapolation from dense to light needs further understanding…
- Future oxygen runs can help us to determine the smallest amount of energy loss, provided that we control the initial state

Future OO run similar to PbPb peripheral (better suited to system-size dependence)
Future pO run crucial do reduce nPDF uncertainties

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Cold or Hot nuclear matter effects?

Nucleon structure at high energy: or ?
Effective Kinetic Theory

- Pre-equilibrium studies using effective kinetic theory also on jets (next lecture)

\[- \frac{\partial f_p}{\partial \tau} = C^{1\leftrightarrow2}[f_p] + C^{2\leftrightarrow0}[f_p] + C^{\text{exp}}[f_p] \]

How does the thermalisation time arise?

Longitudinal expansion

[Boguslavski et al (2303.12595)]

Glasma

Kinetic theory

Hydrodynamics

\[ \dot{q} \text{ (GeV$^2$/fm)} \]

\[ \tau \text{ (fm/c)} \]

\[ E_{\text{jet}} = 100 \text{ GeV} \]

\[ E_{\text{jet}} = 20 \text{ GeV} \]
QGP onset?

- Hydrodynamic applies when system is in local equilibrium

Need to collider smaller/different systems to identify QGP onset conditions
From dense to light systems

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![Graph showing E-loss models and other models compared to data.](image)