Results from heavy ion collisions

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Standard model of heavy ion physics
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Initial State

QGP

Freeze-out

Phase Transition/Cross Over

Chemical Freeze-Out (inel. collisions cease)

Thermal Freeze-Out (el. collisions cease)

Collision

pre-equilibrium

QGP

Hadron Gas

\( T_c \)

\( T_{ch} \)

\( T_{fo} \)

\( \tau_0 \)

\( t \)
Standard model of heavy ion physics

Initial State

QGP

 Freeze-out

Hydrodynamical flow

Jet quenching


https://physics.aps.org/articles/v7/97
Relativistic Heavy Ion Collider

- PHOBOS
- BRAHMS
- PHENIX
- STAR
- Upton, NY
- 1.2km diameter
- p+p, d+Au, Cu+Cu, Au+Au, U+U
- $\sqrt{s_{NN}} = 9 - 200$ GeV

Large Hadron Collider

- ALICE
- ATLAS
- LHCb
- LHCf
- Geneva, Switzerland
- 8.6km diameter
- p+p, p+Pb, Pb+Pb
- $\sqrt{s_{NN}} = 2.76$ GeV, 5.5 TeV
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Forming the QGP
How can we estimate the energy density?

- Transverse energy ($E_T$)
  - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- $\tau =$ formation time
- Energy density $\varepsilon$

$$\varepsilon = \frac{1}{V} \frac{dE_T}{dy} = \frac{J}{A_T \tau c} \frac{dE_T}{d\eta}$$

- QGP formation for $\varepsilon > 0.5$ GeV/fm$^3$
Energy dependence from $dE_T/dy$

$\rightarrow$ Higher than extrapolations of RHIC data

$\epsilon \approx 1 \text{ fm/c}$

$QGP$ formation

$\epsilon = \frac{1}{A c \tau_0} \frac{dE_T}{dy}$

ALICE Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

Standard estimate $\tau_0 \approx 1 \text{ fm/c}$
Where are we on the phase diagram?
- Ratios of particles expected from a model
Chemistry - equilibrium

- Ratios of particles expected from a model

**ALICE Preliminary**
Pb-Pb $s_{NN} = 2.76$ TeV, 0-10%

**Model**
- THERMUS 2.3:
  - $155 \pm 2$ MeV
  - $\chi^2$/NDF: 24.5/9
- GSI-Heidelberg:
  - $156 \pm 2$ MeV
  - $\chi^2$/NDF: 18.4/9
- SHARE 3:
  - $156 \pm 3$ MeV
  - $\chi^2$/NDF: 15.1/9

**arXiv:1701.07065**
QCD Phase Diagram

arXiv:1701.07065

Au+Au Collisions

Quark-Gluon Plasma

Hadron Gas

Grand Canonical Ensemble (Yield Fit)
Thermal photons

Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
Inverse slope: $T = 221 \pm 19$ (stat) $\pm 19$ (syst) MeV

Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
Inverse slope: $T = 304 \pm 51$ MeV

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A quarkonium-thermometer

Clear hierarchy in $R_{AA}$ of different quarkonium states

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A quarkonium-thermometer

CMS-PAS HIN-11-011
arXiv:1708.04962 [nucl-ex]

CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV

Note: $6.5 < p_T < 30$ GeV for $J/\psi$ and $\psi(2s)$

Clear hierarchy in $R_{AA}$ of different quarkonium states

Expected in terms of binding energy

CMS-PAS HIN-12-014, HIN-12-007

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The trajectory of the system is shown in the graph. The graph plots $T_{ch}$ (MeV) against $\mu_B$ (MeV) for Au+Au Collisions. The data points are labeled as follows:

- 00-05% (circles)
- 30-40% (squares)
- 60-80% (triangles)

The graph also includes fits from Cleymans et al. and Andronic et al., as well as the Grand Canonical Ensemble (Yield Fit).

The graph is referenced with arXiv:1701.07065.
Hydrodynamical flow
Hydrodynamical flow

- **Radial Flow**
  - Affects shape of low $p_T$ particle spectra

- **Elliptic Flow**
  - Sensitive to initial geometry
  - Requires early thermalization of the medium

- **Directed Flow**
  - Produced in the pre-equilibrium phase of the collision
  - Decreases with increasing $\sqrt{s_{NN}}$
Hadron spectra

- Radial flow boosts hadrons
  - low $p_T$: mass dependent slope
  - high $p_T$: common hardening of $p_T$ spectra

\[ T_{\text{eff}} \approx T_f + \frac{1}{2} m \beta_T^2 \quad p_T \ll m \]

\[ T_{\text{eff}} \approx T_f \sqrt{\frac{1 - \beta_T}{1 + \beta_T}} \quad p_T \gg m \]
Radial Flow and Baryon/Meson Ratio

- Radial flow pushes protons to intermediate $p_T$ and depletes low $p_T$
  - Stronger radial flow in central Pb–Pb collisions
- Similar effects observed in high-multiplicity pp and p–Pb collisions
Charmed baryons

- First midrapidity measurement of $\Lambda_c$ in pp and p–Pb collisions
  - Charmed baryon/meson ratio not reproduced by event generators
- First measurement of $\Xi_c$ in pp collisions
- Constraints of charm hadronization
- Benchmark for measurements in heavy ion collisions
Anisotropic flow

- Initial overlap asymmetric $\rightarrow$ pressure gradients
- Momentum anisotropy $\rightarrow$ Fourier decomposition:

$$\frac{d^2 N}{dp_T \, d\phi} \approx 1 + 2 v_1 \cos(d \phi) + 2 v_2 \cos(2d \phi) + 2 v_3 \cos(3d \phi) + 2 v_4 \cos(4d \phi) + 2 v_5 \cos(5d \phi) + \ldots$$

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Anisotropic flow - $v_2$

- $v_2$ sensitive to:
  - initial conditions: geometry
  - final state: particle interactions (medium properties, e.g. shear viscosity)
- Data in agreement with hydrodynamic models at low $p_T$
Anisotropic flow - $v_4$

- $v_4$ more sensitive to interactions and less to initial state
  - hydrodynamic models work at low $p_T$ ($p_T<1$ GeV/c)
  - only describes trend at intermediate $p_T$ ($1<p_T<2$ GeV/c)
D meson $v_2$

- Even heavy quarks flow!

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$v_2$ in p–Pb

- mass ordering like in Pb–Pb
Energy loss in the medium
Nuclear modification factor

- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions

- If high-$p_T$ probes (jets) are suppressed, this is evidence of jet quenching

\[ R_{AA} = \frac{d^2N_{AA}/dp_Td\eta}{T_{AA}d^2\sigma_{pp}/dp_Td\eta} \]

[Diagram showing $R_{AA}$ vs. transverse momentum with regions labeled 'Enhancement' and 'Suppression']
Nuclear modification factor

- Charged hadrons (colored probes)
  - Suppressed in Pb—Pb
  - Not suppressed in p—Pb at midrapidity
  - Some cold nuclear matter effects at forward rapidities
- Electroweak probes not suppressed
Nuclear modification factor

- Charged hadrons (colored probes)
  - Suppressed in Pb—Pb
  - Not suppressed in p—Pb at midrapidity
  - Some cold nuclear matter effects at forward rapidities
- Electroweak probes not suppressed
- Qualitatively in agreement with models

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• **Electromagnetic probes** – consistent with no modification – medium is transparent to them

• **Strong probes** – significant suppression – medium is opaque to them - even heavy quarks!
Jet $R_{AA}$ also demonstrates suppression

Less suppression of heavy quark jets
Conclusions

- Mapping out the phase diagram
- Evidence for hydrodynamical flow
  - Some indications of similar phenomena in small systems
- Evidence for jet quenching
  - No evidence of similar phenomena in small systems
- Need for systematic extraction of QGP properties
Next step: global fits of models to wide array of heavy ion collision data

Global Bayesian Analysis; S. Bass, Quark Matter 2017
MADAI collaboration

- **diagonals**: probability distribution of each parameter, integrating out all others
- **off-diagonals**: pairwise distributions showing dependence between parameters

Parton distributions in projectiles (density, correlations, fluctuations)

Equilibration dynamics

Shear viscosity

Bulk viscosity

\[ T_{sw} \leq T_c \]

Backup
Finite Temperature QCD on the Lattice ($\mu_B=0$)

- Slow convergence to non-interacting Steffan-Boltzmann limit
- What carries energy - complex bound states of q+g? “strongly-coupled” plasma?

Energy density

Cross-over, not sharp phase transition (like ionization of atomic plasma)
Charged particle $R_{AA}$

$R_{AA} = \frac{d^2N_{AA}/dp_Td\eta}{T_{AA}d^2\sigma_{pp}/dp_Td\eta}$

- $R_{AA} > 1$: enhancement
- $R_{AA} < 1$: suppression
- Strong modification of the spectrum shape in most central collisions
- Strong centrality dependence
- $R_{AA}$ at 5.02 TeV similar to 2.76 TeV
Light-by-light scattering
First evidence of light-by-light scattering

\[
\text{ATLAS} \quad \gamma\gamma \rightarrow \gamma\gamma \text{ MC} \quad \gamma\gamma \rightarrow e^+e^- \text{ MC} \quad \text{CEP} \gamma\gamma \text{ MC}
\]

Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV

Signal selection
no Aco requirement

\[
\text{ATLAS} \quad \gamma\gamma \rightarrow \gamma\gamma \text{ MC} \quad \gamma\gamma \rightarrow e^+e^- \text{ MC} \quad \text{CEP} \gamma\gamma \text{ MC}
\]

Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV

Signal selection
with Aco < 0.01

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