Heavy Ions 3/3

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Evidence of the creation of a strongly-interacting medium in central heavy ion collisions comes from the observed strong suppression of particle production, explained by the energy loss of colored partons in the colored QGP.

- Radiative energy loss dominates at high $p_T$ for light flavours, gluons and charm
- $c$ and $b$ also affected by dead cone effect and collisional energy loss

A quantitative characterization of the properties of the medium (e.g. transport coefficient, …) requires models.
How does the presence of a colored QGP affect hadron formation?
Quarkonium as a thermometer for QGP

Charmonium suppression ($J/\psi, \psi', \ldots$) was suggested as “smoking gun” signature for the QGP back in the 1980’s [Matsui, Satz, PLB178 (1986) 416-422]

In vacuum (T=0), $q\bar{q}$ is bound by the Cornell potential.

$$V(r) = -\frac{\alpha}{r} + kr$$

In the dense and hot QGP (T>0), the binding potential is modified by color-charge (Debye) screening effects

$$V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$

The effective coupling between $q$ and $\bar{q}$ at large distances gets reduced $\rightarrow q\bar{q}$ melting
Quarkonium as a thermometer for QGP

c\bar{c} (J/\Psi, \Psi',..) and b\bar{b} (\Upsilon', \Upsilon'', \Upsilon''') states are a laboratory for QCD:

- Small decay width (~keV), significant BR into dileptons
- Intrinsic separation of energy scales: m_Q >> \Lambda_{QCD} and m_Q >> B_E
- A variety of states characterized by different binding energies

→ Goal: understand mechanisms of **dissociation and regeneration** in QGP
J/ψ (c¯c) suppression

- observed at the SPS (√s_{NN} = 17 GeV)
- later measured at RHIC (√s_{NN}=200 GeV)
  up to very high multiplicities

For similar multiplicities the suppression at SPS is similar to that at RHIC despite the energy difference (not shown)

At the LHC, J/ψ is less suppressed than at RHIC
→ larger charm cross section
→ regeneration
**c¯c cross section vs energy**

The cross section for producing a c¯c pair increases with $\sqrt{s}$

In a central event
- At SPS $\sim 0.1$ c¯c
- At RHIC $\sim 10$ c¯c
- At LHC $\sim 100$ c¯c

c from one c¯c pair may combine with ¯c from another c¯c pair at hadronization to form a J/ψ → regeneration!

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Phys. Rev. D 105, L011103 (2022)
J/\psi\ regeneration

\[ R_{AA} \text{ midrapidity} > R_{AA} \text{ forward rapidity} \]

- **Regeneration of charmonium** and charmed hadrons take place in QGP or at the phase boundary.

- \( R_{AA} \) depends on the local charm quark density in the medium

→ **Signature of de-confinement.**

![Graph showing \( R_{AA} \) vs. \( p_T \) for ALICE data.](image)

Sequential melting of $b\bar{b}$ states

Measurements reveal a sequential suppression of high mass $b\bar{b}$ states (bottomonium).

- The centrality dependence is consistent with progressive suppression in a hotter medium.
Sequential melting of $b\bar{b}$ states

Measurements reveal a sequential suppression of high mass $b\bar{b}$ states (bottomonium).
- The centrality dependence is consistent with progressive suppression in a hotter medium.
- Increased suppression with increased collision energy → no recombination at hadronisation
The study of quarkonium ($c\bar{c}$, $b\bar{b}$) states provides information on the mechanisms of **dissociation and regeneration** of strongly-bound state in a medium ($T>0$).

- The high density of color charges in the QGP leads to melting of quarkonia
- The large abundance of charm quarks at LHC results in regeneration of the amount of $J/\psi$
- States with smaller binding energies are more suppressed
How does the QGP affect production of hadrons?
The bulk of particles is **soft** and composed by **light flavour** hadrons that are produced when the **QGP transitions** into a hot (T< 155 MeV) and dense gas of hadrons and resonances.

A **collective motion** is observed: the **dynamic and thermodynamic properties of the QGP** are studied by measuring $p_T$ and azimuthal distributions of particles produced in the bulk.
The hadron-gas phase and freeze-outs

After hadronisation, the system is a hot (T< 155 MeV) and dense gas of hadrons and resonances.

Chemical freeze-out
- Inelastic collisions stop
- Relative particle abundances are fixed

Kinetic freeze-out
- (pseudo)elastic collisions stop
- Momentum distributions are fixed

→ Fit abundance of identified hadrons: probe chemical equilibrium at chemical freeze-out
→ Fit shape of $p_T$ spectra: probe final hadron kinematics at kinetic freeze-out
Identified particle production

$\pi K p$ are the most abundant hadronic species produced in the collision

$\rightarrow$ Integrate $d^2N/(dydp_T)$ spectra over $p_T$ to extract yields, $dN/dy$. 

80% $\pi$, 12% $K$, 5% $p$, 3% everything else.
Particle abundances are obtained from the partition function of a Grand Canonical (GC) ensemble where chemical potential for quantum numbers are constrained with conservation laws.

\[ n_i = \frac{N_i}{V} = \frac{T}{V} \frac{\partial \ln Z_i}{\partial \mu_i} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_i)/T] + 1} \]

where chemical potential for quantum numbers are constrained with conservation laws.

\[ \mu_i = \mu_B B_i + \mu_S S_i + \mu_I I_{3,i} + \mu_C C_i \]

- Predict yields (see right figure) at a given temperature
- Fit measured particle yields (or ratios) to extract $\mu_B$, $T_{\text{ch}}$, $V$. 

Statistical hadronisation model in a nutshell

It models an ideal relativistic gas of hadrons and resonances in chemical equilibrium (as the result of the hadronization of a QGP in thermodynamical equilibrium.)
Production of (most) light-flavour hadrons (and anti-nuclei) is described \((\chi^2/\text{ndf} \sim 2)\) by thermal models with a single chemical freeze-out temperature, \(T_{\text{ch}} \approx 156 \text{ MeV}\).

→ Approaches the critical temperature roof from lattice QCD: limiting temperature for hadrons!

→ the success of the model in fitting yields over 10 orders of magnitude supports the picture of a system in local thermodynamical equilibrium.
Hydrodynamics at play: radial flow (1/2)

A **collective motion** is superimposed to the thermal motion of particles → the system as a **medium**

**Radial flow**
radial expansion of a medium in the vacuum under a common velocity field → Affects the low $p_T$ distribution of hadrons and their ratios depending on their mass

$$m_T = \sqrt{(m^2 + p_T^2)}$$

purely thermal source

$$\frac{dN}{m_T dm_T} \propto e^{-m_T/T}$$

light

1/$m_T$ dN/dm_T

heavy

$T, \beta$

explosive source

1/$m_T$ dN/dm_T

light

heavy

R. Snellings
Hydrodynamics at play: radial flow (2/2)

At low $p_T$, the radial flow “pushes” particles to higher momenta
→ spectra get “harder” for more central collisions
→ mass dependence

A simplified hydrodynamical model, the Boltzmann-Gibbs blast-wave model is used to quantify radial flow and the kinetic freeze-out temperature.

More central (higher multiplicity) events have lower $T_{\text{kin}}$ and higher flow velocity

$T_{\text{kin}} \sim 100$-140 MeV
Initial geometrical anisotropy ("almond" shape) in non-central HI collisions → eccentricity

**Pressure gradients** develop → more and faster particles along the reaction plane than out-of-plane

Scatterings among produced particles convert **anisotropy** in coordinate space into an observable momentum anisotropy → **anisotropic flow** → quantified by a Fourier expansion in azimuthal angle $\varphi$

$$E \frac{d^3N}{dp^3} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} (1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)])$$

$v_n = \text{harmonics}$
The strong centrality dependence of $v_2$ reflects the degree of “anisotropy” in initial geometry.

Fluctuations of the initial state energy-density lead to different shapes of the overlap region → non-zero higher-order flow coefficients (“harmonics”)
Collectivity can also be studied by looking at correlations of two particles vs $\Delta \eta$ (difference in rapidity) and $\Delta \varphi$ (difference in azimuthal angle).

**Two-particle correlations in Pb-Pb collisions**

Peak at $\Delta \eta \sim 0$: short-range correlations $\rightarrow$ jets

Broad "ridge" in a wide $\Delta \eta$ range: long-range correlations emerging from early times (causality) $\rightarrow$ anisotropic flow

In azimuth: structure determined by the medium response to the initial transverse geometry

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Collectivity can also be studied by looking at correlations of two particles vs $\Delta \eta$ (difference in rapidity) and $\Delta \varphi$ (difference in azimuthal angle).

→ Decomposition in Fourier series of the azimuthal distribution at large $\eta$.
Hydrodynamical modeling

Ideal hydrodynamics
- applies to a system in local equilibrium (e.g. thermodynamical)
- requires energy and charge conservation
- system is described by energy density $\varepsilon$, pressure $P$, velocity $u^\nu$, and charge $n$ and by 5 equation of motion, closed by one equation-of-state (EOS) $\varepsilon = \varepsilon(P)$
- The response of the system to external solicitation is controlled by the EOS

\[ \nabla_\mu T^{\mu\nu} = 0 \quad \nabla_\mu J_\mu = 0 \]

Viscous hydrodynamics
- Includes corrections for dissipative effects: bulk $\zeta$ and shear viscosity $\eta$, charge diffusion, $\kappa$

\[ T^{\mu\nu} = \varepsilon u^\mu u^\nu - (P - \zeta \dot{\Theta}) \Delta^{\mu\nu} - 2\eta \sigma^{\mu\nu} \]

\[ J^\mu = q u^\mu + \kappa \nabla^\mu_\perp (\mu/T) \]

Figs. from Rezzolla and Zanotti, 2013
Shear viscosity

Shear viscosity (expressed as viscosity over entropy, $\eta/s$) washes out initial-state anisotropies

- Larger consequences on higher-order harmonics
- Larger $\eta/s$ reduces flow

Measured $v_2$ is described very well by hydrodynamic models → QGP behaves as a ~perfect liquid!
QGP properties from flow 1/2

Bayesian analysis of yields, mean $p_T$, flow harmonics measured by ALICE has been used to extract the QGP properties.

Diagonals: prob. distrib. of each param. Off-diagonal: shows interdependence among parameters

QGP properties from flow 2/2

Bayesian analysis of yields, mean $p_T$, flow harmonics measured by ALICE has been used to extract the QGP properties.

Shear viscosity $\eta/s(T) \in 0.08 - 0.2$

Bulk viscosity

Bulk particle abundances are described by the statistical hadronization model assuming chemical equilibrium and with \( T_{\text{ch}} \approx 156 \text{ MeV} \).

The QGP expands rapidly under radial flow. Spatial anisotropy of the initial collision region causes anisotropic flow.

Spectra and flow coefficients are well described by viscous hydrodynamics with a very low shear viscosity \( (\eta/s \sim 0.08 - 0.16) \) → “perfect liquid”

The success of SHM and hydrodynamic description also supports the idea of a medium in local thermodynamical equilibrium.
Can we produce a QGP also in pp collisions?
Discovery of collectivity in small systems

The first indication of the presence of collective phenomena in high-multiplicity pp collisions came from the study of two-particle correlations vs $\Delta \eta$ and $\Delta \varphi$.

A ridge is observed in high multiplicity pp but not in minimum bias pp collisions! The ridge is not reproduced by pp Monte Carlo generators, e.g. PYTHIA.
The “ridge” in pp, p-Pb collisions

Signs of collectivity in small systems “discovered” at the LHC in terms of long-range \((2 < |\Delta \eta| < 4)\) near-side \((\Delta \phi = 0)\) “ridge” in 2-particle correlations, visible in high multiplicity pp, p-Pb, Pb-p collisions

Are the long-range correlations in high-multiplicity pp coming from (hydrodynamic) flow?
Collectivity correlates many particles over a wide $\eta$ range

Elliptic flow from multi-particle correlations:

$$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} > 0$$

- subtract jets and other physical 2-particle correlations due to non-flow
- measure with rapidity gap

In AA collisions, collectivity originates from the presence of a strongly-interacting QGP

OPEN QUESTION: what is the origin of the emerging collectivity in pp, p-Pb collisions?
Chemistry from small to large systems

Multi-strange to non-strange yield ratios increase significantly and smoothly with multiplicity in pp and p-Pb collisions until saturation in Pb-Pb

- strangeness enhancement relative to pp suggested in the 1980’s as QGP signature

→ Particle composition evolves smoothly across collision systems, depending only on final-state multiplicity

OPEN QUESTION: “emergence” in hadron production mechanism, from microscopical hadron production mechanisms (string overlap, color reconnection) to the onset of a QGP (thermalization, equilibration)?
→ A challenge for models!
No energy loss in small systems?

Not observed so far.

- Strong change of behaviour of $R_{AA}$ beyond 80% centrality is reproduced considering biases in event selection and collision geometry, and no nuclear modification → not a medium effect!

OPEN QUESTION: when (which system “size”) does energy loss sets in?

Outlook to Runs 3 and 4:

→ Search for energy loss effects with light ion collisions (e.g. O-O, Ar-Ar, low $N_{\text{part}}$, multiplicity similar to p-Pb, known geometry)
Soft probes probe the bulk of the system as a whole.

**Particle chemistry:**
- continuity observed across collision systems
- depends on charged particle multiplicity
- Strangeness production in enhanced in presence of a QGP in AA collisions
- In small systems, strangeness enhancement observed with increasing multiplicity

**Collective dynamics**
- Radial and anisotropic flow
- Flow up to higher harmonics in heavy-ion collisions
- Discovery of collective phenomena in small systems at the LHC, whose origin is to be understood.
Experimental probes and evidence for a QGP formed in heavy-ion collisions
- Strong jet quenching and medium-induced modification
- Quarkonium suppression → Melting of states as a function of temperature
- Regeneration and partial thermalisation of charm
- Radial and anisotropic flow → Collective behavior of a QGP with very low shear viscosity ($\eta/s$),
- High temperatures, mostly statistical particle production ($T_{\text{chem}}, T_{\text{kin}}$)
- Heavy-ion-like effects observed in pp and p-Pb collisions

A new frontier
- Is there QGP in small systems?
- Can we explain these effects without a QGP?
- Can we describe these emerging phenomena in one unified picture across systems?

Big progress towards a quantitative characterisation of the properties of the QGP with still open questions to be addressed in Run3 and beyond.
Further readings:


• [future] CERN Yellow Report on QCD with heavy-ion beams at the HL-LHC, arXiv:1812.06772


+ many more reviews on specific topics available on arXiv

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What’s next?

Heavy-ion program at the LHC in Runs 3+4 – An appetizer
## Recall: Heavy-ion physics at the LHC

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### Major upgrades for ALICE and LHCb

**ALICE 3**

- Next-generation HI experiment
- All-Si MAPS tracker
- Ultimate vertex detector
- Minimal mass (essentially only sensor)
- 5 mm from beam (LHC aperture)

**Physics focus:**

- Low-p$_T$ heavy-flavour
- Electromagnetic radiation from QGP

**ATLAS and CMS phase II**

**ALICE 3:** A whole new dedicated HI detector! LHCb upgrade II

**ALICE 3:** ITS3 and FoCal

**High luminosity LHC**
Runs 3+4 - Nuclei and small systems

(anti-)nuclei and (anti-)(hyper-)nuclei up to A = 4

- Clarify formation mechanisms of nuclear bound states from a dense partonic state
- Determine $T_{ch}$ even more precisely

A “small systems” programme to study collectivity, strangeness/chemistry, hadronisation

- Investigate the onset of QGP like features
Runs 3+4 – Dileptons and chiral symmetry

Lattice QCD predicts chiral symmetry restoration to occur around the same temperature as the confined/deconfined transition → but no experimental observation yet!

→ Search for signatures of chiral symmetry restoration at the QCD phase boundary by measuring intermediate mass dilepton spectrum

Di-lepton mass distribution

$dN/dm_{ee}$

\[ \pi^0, \eta, \omega, \eta', \phi - Dalitz \]

\[ \rho, \omega, \phi \]

DD

BB

J/ψ

omega/phi region: chiral symmetry and rho-a_1 mixing
Runs 3+4 – Dileptons and early QGP temperature

Measurements of dilepton spectrum:

→ **Search for signatures of chiral symmetry restoration** at the QCD phase boundary by measuring intermediate mass dilepton spectrum

→ **Access the temperature of QGP in the early stages** by measuring the mass spectrum of dileptons in the large mass range and dilepton excess due to electromagnetic radiation emitted by the QGP

Bonus in Runs 3 and 4:
- statistics
- reduced, well-known material
- heavy-flavour rejection

Di-lepton mass distribution

\[ \pi^0, \eta, \omega, \eta', \phi - \text{Dalitz} \]

Very low mass: conductivity

omega/phi region: chiral symmetry and rho-a1 mixing

Large mass: very early times
 Runs 3+4 – Dileptons

Measurements of dilepton spectrum:

→ **Search for signatures of chiral symmetry restoration** at the QCD phase boundary by measuring **intermediate mass** dilepton spectrum

→ **Access the temperature of QGP in the early stages** by measuring the mass spectrum of dileptons in the **large mass range** and dilepton excess due to electromagnetic radiation emitted by the QGP

Bonus in Runs 3 and 4:
- statistics
- reduced, well-known material
- heavy-flavour rejection
Runs 3+4 - More charm

Higher precision for rarer probes in the HF sector

- Low-\(p_T\) production and \(v_2\) of several HF hadron species
- first measurements of \(b\) at forward \(y\) down to zero \(p_T\) (main focus of ALICE)
- \(B\) hadrons and \(b\)-jets (main focus of ATLAS and CMS)

→ Study mass dependence of energy loss, in-medium thermalization of heavy-flavours
→ Access to the medium transport properties, e.g. charm diffusion coefficient
Runs 3+4 - More beauty

Higher precision for rarer probes in the HF sector

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• first measurements of \(b\) at forward \(y\) down to zero \(p_T\) (main focus of ALICE)
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→ Study mass dependence of energy loss, in-medium thermalization of heavy-flavours

→ Access flavor-dependence of in-medium fragmentation functions with jet measurements

Example: \(B^+ \rightarrow D^0\pi^+\) (displaced) channel down to low \(p_T\) accessible in the ALICE central barrel thanks to the upgraded ITS

Baryon/meson in \(b\) sector

\(R_{AA}\) in the beauty sector
Runs 3+4 – More quarkonia

Measure charmonium and bottomonium spectrum with increased precision

- Nuclear modification $R_{AA}$
- $\psi(2S)/J/\psi$, $Y(2S)/Y(1S)$
- explore feeddown

→ constrain models
→ probe melting and regeneration of quarkonia
→ probe deconfinement
→ access the medium temperature

Further reading: CERN Yellow Report on QCD with heavy-ion beams at the HL-LHC
arXiv:1812.06772
ALICE 3: a new dedicated HI experiment in Run 5 and beyond

ALICE 3: a new dedicated heavy-ion experiment at the LHC
- replace ALICE between Run 4 and Run 5
- Expression of Interest submitted in 2019 (ESPPU), arXiv:1902.01211
- Letter of Intent submitted to the LHCC: CERN-LHCC-2022-009

Physics from pp to Pb-Pb:
- Vertexing accuracy and tracking down to $p_T = 0$ (w/ retractable inner tracking layers)
- Particle identification
- Wide rapidity coverage
- Extreme acquisition rates for soft probes
Unique physics with a fast ultra-light detector

- **Multi-HF states production to investigate hadronization from the QGP**
  Multi-charm baryon production expected to be enhanced by a factor of $10^2$-$10^3$, low $p_T$ B, $\chi_c$, X, ...

- **Dilepton radiation** from various phases of the collision

- **Effect of chiral symmetry restoration** (predicted by lattice QCD) on the dielectron spectrum

- **QGP parameters** (diffusion coefficients, conductivity properties, …) with unprecedented precision

- **Ultra-soft ($p_T \sim 10$ MeV) photon** production relative to hadron production (Low’s theorem, non-pert. QCD)

…and more new unique windows opened at the LHC!
Bonus material
Characteristics of a heavy-ion detector: ALICE

ALICE is the dedicated heavy-ion detector at the LHC, designed and built specifically for this purpose.

**Solenoid:** magnetic field $B = 0.5$ T

**Inner Tracking System + Time Projection Chamber:** vertexing and tracking + identification (TPC) down to very low $p_T \sim 0.1$ GeV/c

**Time-Of-Flight, TRD, HMPID, etc.:** Particle identification detectors

**Electromagnetic calorimeters**

**+ Forward rapidity detectors and ZDC:** trigger, centrality, event time determination, …
Particle identification

- Direct identification: $\pi$, $K$, $p$, light (anti)nuclei
- Electron identification using calorimeters and transition radiation detectors
- Strange and heavy-flavour hadrons:
  - reconstruction of secondary vertex and weak decay topology
  + PID + invariant mass reconstruction
- Photons detected in calorimeters and through pair production
- Quarkonia through leptonic decays

Energy loss of long lived particles in TPC

Particle velocity from TOF measurement and momentum
Light ions at the LHC

From A. Mazeliauskas, EPS-HEP 2021:

- High achievable luminosity.
- Short oxygen run planned in LHC Run 3.
- pO: strong interest from cosmic ray physics.
- OO comparable to pPb, but better geometry control.
- Many physics opportunities see OppOstLHC [online]

Experimental projections and theory calculations show measurable energy loss signal in 10 GeV < p_T < 50 GeV.

Opportunity to discover jet quenching in small systems.
Hydrodynamical modeling (details)

Describe the expanding medium macroscopically.

Input

- Initial conditions
- equation-of-state (EOS) $\varepsilon = \varepsilon(P)$ from latticeQCD
- bulk $\zeta$ and shear viscosity $\eta$, charge diffusion, $\kappa$

Output

- Any other relevant observable, e.g. spectra, jet quenching, …

### Flow observables

are related to the response of the system to the initial spatial anisotropies

$\rightarrow$ Can be used to deduce conclusions on initial conditions, EoS and transport coefficients by data comparison

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**arXiv:1712.05815**

<table>
<thead>
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<th>$\epsilon(P)$</th>
<th>Gauge/Gravity</th>
<th>Kinetic (BGK)</th>
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| Refs. | [19, 28, 29] | [28, 119, 120] | [121-123] | [124-127] |
|       | [128, 129]   | [130]          | [131, 132] |           |

Table 2.1: Compilation of leading-order results for transport coefficients in various calculational approaches, see text for details.
Searching for the “ridge” in the smallest systems

A long-range (2 < |Δη| < 4) near-side (Δφ = 0) “ridge” in 2-particle correlations discovered in high multiplicity pp, p-Pb, Pb-p collisions

→ First signs of collectivity in small systems discovered at the LHC

Checked in e+e- using ALEPH archived data:
→ No ridge observed

Latest result:
→ ridge observed in low-multiplicity pp collisions

Are these long-range correlations in pp coming from (hydrodynamic) flow?
Hadronisation by fragmentation and recombination

Ratios of baryon to meson production spectra are sensitive to competing particle production mechanisms, depending on transverse momentum.

**Fragmentation** (a) of high-$p_T$ partons into mid-$p_T$ hadrons

**Recombination** (b,c) of low-$p_T$ partons close in phase space into mid-$p_T$ hadrons via coalescence

+ influence of **collective flow**
At intermediate $p_T$, a baryon/meson enhancement is observed for $p/\pi$, $\Lambda/K_0^S$ → interplay of radial flow and recombination

$\Lambda_c/D^0$ enhancement possibly due to the recombination of charm quarks traveling through the QGP with light quarks from the QGP.
Flow of identified hadrons

Light flavour hadrons exhibit “textbook” flow
- Mass dependence at low $p_T$
- Interplay of production mechanisms at mid-$p_T$
  (baryon/meson separation $\rightarrow$ recombination)

Charm $v_2>0$
- charm partially thermalised with the QGP
- recombination with LF at hadronisation

No significant evidence of flow of beauty
Strangeness production in a hadron gas

In a hadron gas at high temperature (e.g. hadronic phase of HIC, $T = 150$ MeV $< T_c$), (multi-)strange hadron production is an energy threshold problem.

By multi-step hadronic processes

e.g. $\pi + n \rightarrow K + \Lambda$, $E_{th} \sim 540$ MeV
$\pi + \Lambda \rightarrow K + \Xi$, $E_{th} \sim 560$ MeV

- Requires longer medium lifetime
- under-saturation of strangeness

By direct production

e.g. $\pi + \pi \rightarrow \pi + \pi + \Lambda + \Lambda$-bar, $E_{th} \sim 2200$ MeV
$\pi + \pi \rightarrow \pi + \pi + \Xi^- + \Xi^+$-bar, $E_{th} \sim 2600$ MeV

- Have to happen very early
- By non-thermalised hadrons

The strangeness quantum number has to be conserved locally and exactly in a finite system (e.g. pp), which reduces the phase space available for particle production.


→ canonical suppression due to quantum number conservation
→ Relaxation of canonical suppression with increasing $\sqrt{s}$ (and number of particles)
Strangeness production in a QGP

Strangeness is produced dominantly by fusion of thermalized gluons (a) in the QGP. Energy threshold for s-sbar: ~200 MeV (if $m_s^{\text{QCD}} \rightarrow m_s^{\text{Higgs}}$ by restoration of chiral symmetry).

The backward reaction of (b) depends on the s quark density, thus on the QGP lifetime. → saturation of strangeness abundance reached on the time scale of ~ 1-few fm/c

Strangeness enhancement in HIC relative to pp was historically proposed as a signature of the presence of a deconfined Quark--Gluon Plasma.

$gg \rightarrow s\bar{s}$

$q\bar{q} \rightarrow s\bar{s}$

Abundance of s quark relative to baryon number

Observation of strangeness enhancement at SPS

Yields normalised to $N_{\text{wound}}$ relative to p-Be

$\Rightarrow$ Not just an effect of having more participants in Pb-Pb!

$p$-Be used as a proxy for pp since $N_{\text{wound}}$ is close to 2 (as in pp)

Enhancement observed in Pb-Pb collisions wrt p-Pb, p-Pb for multi-strange (anti)baryons

$\rightarrow$ Anti-baryons less enhanced than baryons $\rightarrow$ quarks (not anti-quarks!) in the initial stage

$\rightarrow$ **Hierarchy** of the enhancement with the strangeness content

$\rightarrow$ **Increase** of the enhancement with the **centrality** of the collision


$\sqrt{s_{\text{NN}}} = 17.3$ GeV

Yields normalised to $N_{\text{wound}}$ relative to p-Be

$\Rightarrow$ Not just an effect of having more participants in Pb-Pb!

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Strangeness production from RHIC to LHC

RHIC: $\sqrt{s_{NN}} = 200$ GeV (empty markers)
LHC: $\sqrt{s_{NN}} = 2.76$ TeV (full markers)

Observation of
• increase of strangeness production relative to strange-less $\pi$ in pp collisions with increasing $\sqrt{s}$
• strangeness enhancement in HIC relative to minimum bias pp collisions
• saturation of strangeness from peripheral to central Pb-Pb

→ Prompted more differential studies in pp collisions as a function of charged particle multiplicity
Discovery of strangeness enhancement in pp collisions

Multi-strange to non-strange yield ratios increase significantly and smoothly with multiplicity in pp and p-Pb collisions until saturation in Pb-Pb collisions.

Enhancement in pp is larger for hadrons with larger strangeness content.
Initial stage of heavy ion collisions

Color Glass Condensate: at high energy and small x, the hadron content is dominated by gluonic matter “packed” into high density.

Saturation (momentum) scale:

\[ Q_{\text{sat}} = \text{inverse size scale of smallest gluons which are closely packed} \]

→ gluons of size larger than \(1/Q_{\text{sat}}\) no longer fit.

L. McLerran, [https://bib-pubdb1.desy.de/record/296833/files/ismd08_mcl_intro-corr.pdf](https://bib-pubdb1.desy.de/record/296833/files/ismd08_mcl_intro-corr.pdf)

+ more reviews in literature.