QGP in small systems: overview

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**Partonic energy loss**: jet quenching and hierarchy $R_{AA}^B > R_{AA}^D$ confirmed at the LHC. First estimates of $\hat{q}$

**Quarkonium suppression**: first full exploitation of bottomonium thermometer at the LHC

Compelling evidence of QGP formation putting together SPS, RHIC and LHC results

QGP studies @LHC are entering the quantitative era

$+ SEVERAL\ OTHERS\ (LESS\ CLEAN)\ OBSERVATIONS\ POINTING\ TO\ THE\ SAME\ CONCLUSION$
Assumption-2: technicalities related to small systems...

... are ordinary business for experimentalists and theorists are also aware about!

- Geometrical bias
- Multiplicity estimation in small systems
- ...

... if that is not the case, let’s discuss
   (and check backup)
Results in small systems

...from latest to earlier stages of the evolution in HI:

- Hadrochemistry
- Collectivity
- Hard probes
...from latest to earlier stages of the evolution in HI:

Results in small systems
Measurement of relative abundances of different particle species

Light hadrons (composed by $u$ and $d$) abundantly produced in elementary collisions, but strange hadrons suppressed!

What happens in heavy-ion collisions?

- **1982 (Rafelski, Muller):** Strangeness enhancement relative to elementary collisions proposed as smoking gun for QGP formation

- **Statistical Hadronization Model (SHM):** reproduce particle yields in HI by means of a Hadron-Resonance Gas in thermal equilibrium
Measurement of **relative abundances of different particle species**
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- **Statistical Hadronization Model (SHM)**: reproduce particle yields in HI by means of a Hadron-Resonance Gas in thermal equilibrium

**QGP altered chemical composition**

Experimental evidence: strange hadrons more abundant in HI than in pp(p-Be)

MIND THE REFERENCE: strangeness production depends on $\sqrt{s}$ in small systems!

DOES IT?
Strangeness enhancement in small collision systems (pp and p-Pb)

The larger the content in strangeness of the hadron, the steeper the increase is
Strangeness enhancement in small collision systems (pp and p-Pb)

The larger the content in strangeness of the hadron, the steeper the increase is.

Multiplicity drives strangeness enhancement across different collision systems/energies...

...and this is true for all "soft" particles.
Hadrochemistry as seen by microscopic models

- **PYTHIA** (Lund string model):
  - Hadrons come from string ($\kappa = 1 \text{ GeV/fm}$) breaking. s/u fit on data
  - At high energies need MPI to describe multiplicity and re-connection of colour strings to describe $<p_T>$ VS multiplicity
  - Recently introduced:
    - Colour **ropes**: packing of strings increase $\kappa$
    - $p$-A and A-A environments

- **DIPSY** (Dipole evolution in Impact Parameter Space and rapidity)
  - Evolution of initial state and collision described in impact parameter space.
  - Strings which overlap in impact parameter space form **ropes**

CAVEAT: ropes favor baryons wrt mesons. No flavour preference!
Hadrochemistry as seen by EPOS

- **EPOS:**
  - Hard scattering: parton “ladders” + CGC-inspired saturation scale
  - At time $\tau_0$ (before hadronization) strings divided into fluid (CORE) and escaping (CORONA) according to momenta and local density
    - **CORONA:** strings can hadronize as in the Lund approach
    - **CORE:** from time $\tau_0$ evolves as a viscous hydrodynamic system. Hadronization happens statistically at a common $T_H$
  - After hadronization → afterburner (e.g. UrQMD)

Good job with version 3 of the generator! Hints to the need of “core” part in pp collisions?

High precision data from the LHC suggest that the production of strangeness is driven by the final-state multiplicity of the collision.

Independence on the collision energy

Can we extend this observation to lower energies?

High multiplicity STAR results superimpose to ALICE’s points

Can we infer something looking at the trend at lower multiplicity?

Would be interesting to complement with smaller systems results @RHIC!!
...from latest to earlier stages of the evolution:

Selected results

Hard probes → Collectivity → Hadrochemistry
Collectivity in a nutshell

According to the hydro picture, in HI the QGP is expected to develop:

- **Radial flow** (important in central collisions):
  - Common expansion velocity of partons
  - Translates into $p_T$ spectra modification
  - Baryon/meson anomaly

$p_T$ spectrum gets harder as the collision gets more central

Common $\beta \rightarrow$ larger $p$-boost to higher-mass particles ($p=m\gamma\beta$)
Collectivity in a nutshell

According to the hydro picture, in HI the QGP is expected to develop:

- **Radial flow** (important in central collisions):
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- **Anisotropic flow** (important in semi-peripheral collisions):
  - Initial spatial anisotropy translates into final momentum anisotropy (pressure gradients)
  - Measured through angular anisotropies in the momentum distribution

\[
E \frac{d^3N}{dp^3} \approx \frac{1}{2\pi p_T dp_T d\eta} \left[ 1 + 2 \sum_{n=1}^{\infty} \nu_n \cos[n(\phi - \Psi_n)] \right]
\]

$p_T$ spectrum gets harder as the collision gets more central

Common $\beta \rightarrow$ larger $p$-boost to higher-mass particles ($p=m\gamma\beta$)
baryon/meson (high/low mass) ratio: from HI...

Increase at mid-$p_T$ in all centrality classes.

Peak shifting towards the right when going more central (higher radial boost in central collisions?)

Evolution can be described by hydro at low-$p_T$
baryon/meson (high/low mass) ratio: from HI...

Increase at mid-\(p_T\) in all centrality classes.

Peak shifting towards the right when going more central (higher radial boost in central collisions?)

Evolution can be described by hydro at low-\(p_T\)

NOTE: it is not a strangeness nor baryon/meson-related effect!
baryon/meson (high/low mass) ratio: from HI...

In PRL 111 (2013) 222301 (ALICE: Pb-Pb at $\sqrt{s_{NN}}=2.76$ TeV)

- $|y|<0.5$
- $\Lambda/K_s$
- 0-5%
- 60-80%
- Systematic uncertainty

Theory 0-5%
- Hydro VISH2+1
- Recombination
- (Fries et al.)
- EPOS

Increase at mid-$p_T$ in all centrality classes.

Peak shifting towards the right when going more central (higher radial boost in central collisions?)

Evolution can be described by hydro at low-$p_T$.

NOTE: it is not a strangeness nor baryon/meson –related effect!

Hint for a similar evolution in pp from STAR?

Extensively studied in small systems at the LHC:

ALICE, Nat. Phys. 13 (2017) 535-539
ALICE, arXiv:1807.11321
ALICE, PLB 728 (2014) 25-38
CMS, PLB 768 (2017) 103
Spectra modification: baryon/meson ratio (small systems)

Same pattern in the $\Lambda/K_0^*$ measured in small systems, with different magnitude...

...but...

MIND THE MULTIPLICITY SPAN!

ALICE, arXiv:1807.11321

PLB 728 (2014) 25-38

PRL 111 (2013) 222301

ALICE Preliminary pp $s = 7$ TeV
VOM Class I, (dN$_{d\Omega}$/d$\eta$) = 21.3
VOM Class X, (dN$_{d\Omega}$/d$\eta$) = 2.3
(VOMMultiplicity Classes)

ALICE p-Pb $\sqrt{s_{NN}} = 5.02$ TeV
0-5%, (dN$_{d\Omega}$/d$\eta$) = 45.1
60-80%, (dN$_{d\Omega}$/d$\eta$) = 9.8
(VOA Mult. Classes - Pb side)

ALICE Preliminary
Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV
0-5%, (dN$_{d\Omega}$/d$\eta$) = 194.2
70-80%, (dN$_{d\Omega}$/d$\eta$) = 44.9
Spectra modification: baryon/meson ratio (small systems)

Same pattern in the $\Lambda/K^0_S$ measured in small systems, with different magnitude...

...but...

MIND THE MULTIPLICITY SPAN!

In order to make proper comparison, one can select $p_T$ ranges and look at multiplicity dependence.
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MIND THE MULTIPLICITY SPAN!

In order to make proper comparison, one can select $p_T$ ranges and look at multiplicity dependence

Clear continuity among different systems!

Is the underlying mechanism the same here?

Need to compare $p_T$ spectra to hydro ↓
Blatt wave - simplified hydro model:

- Assumes common particle expansion with $\beta_T$ and $T_{\text{kin}}$
- If assumption ok: fit (e.g.) $\pi, K, p \rightarrow$ predict $p_T$ shape of other particles
- Assumption ~ok for all collision systems
- pp and p-Pb: similar $T_{\text{kin}}-\beta_T$ progression
Radial flow: does hydro fit the picture?

Blast wave - simplified hydro model:
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- If assumption ok: fit (e.g.) $\pi, K, p \rightarrow$ predict $p_T$ shape of other particles
- Assumption ~ok for all collision systems
- pp and p-Pb: similar $T_{\text{kin}}-\beta_T$ progression
- Considering corresponding multiplicity: less “violent” expansion in A-A, but $T_{\text{kin}}$ common for all systems

Soft particles $p_T$ spectra in small systems are well reproduced by a simplified hydro model.
Anisotropic flow in a HI...

\( v_n \neq 0 \) observed in HI at RHIC and LHC

Global hydro fits to several bulk observables start appearing:

What about small collision systems?

Anisotropic flow: small systems?

\[ v_2 \neq 0 \] observed in all collision systems

**NOTE:** contribution of non-flow not easy to estimate in pp (and p-Pb)

...but does this make sense at all? Can hydro develop in so small systems?

Naïve expectation: need "large enough" and "live long enough" medium to reach thermal equilibrium and apply hydro (several interactions needed)

- \( R > \lambda \)
- \( \tau > \lambda/v \)

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08 Sep. 2018
Anisotropic flow: small systems?

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Naïve expectation: need “large enough” and “live long enough” medium to reach thermal equilibrium and apply hydro (several interactions needed)

\[
\begin{align*}
&\text{Too restrictive: hydro can be applied far from thermalization!} \\
&\text{• } R > \lambda \\
&\text{• } \tau > \lambda/v
\end{align*}
\]

First theoretical calculations involving hydro expansion of a single fluid in all collisional systems start appearing.

W. Li, arXiv: 1704.03576
Selected results

...from latest to earlier stages of the evolution:
Selected results

...from latest to earlier stages of the evolution:

Hard probes →

Collectivity →

Hadrochemistry →
Partonic energy loss

- High-$p_T$ partons produced in the early stages of the collisions ($\tau<<1\text{fm}$)
- Loose energy in the medium through:
  - elastic scattering
  - Induced gluon radiation (dominant at high-$p_T$)
- Simple prediction (dead-cone effect):
  \[ \Delta E_g > \Delta E_{\text{light-quark}} > \Delta E_{\text{heavy-quark}} \]
Hard probes: going “smaller”

\[ \langle N_{\text{part}} \rangle = 23 \rightarrow R_{AA} = 0.65 \]

Decreasing multiplicity
Hard probes: going “smaller”

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Decreasing multiplicity

\[ \langle N_{\text{part}} \rangle = 11 \rightarrow R_{AA} = 0.7 \]
Hard probes: going “smaller”

\[ R_{AA} \neq 1 \text{ in A-A down to very low } <N_{\text{part}} \text{ (hence multiplicities)} \]

But what happens in small collision systems?

Difficult to define an \( R_{AA} \) in \( pp \)....!!!

Let’s concentrate on \( p-Pb \)

\[ <N_{\text{part}} > = 23 \rightarrow R_{AA} = 0.65 \]

\[ <N_{\text{part}} > = 11 \rightarrow R_{AA} = 0.7 \]

\[ <N_{\text{part}} > = 5 \rightarrow R_{AA} = 0.8 ? \]
Hard probes: going “smaller”

$R_{AA} \neq 1$ in A-A down to very low $<N_{\text{part}}>$ (hence multiplicities)

But what happens in small collision systems?

Difficult to define an $R_{AA}$ in pp...!!!

Let’s concentrate on p-Pb.

PYTHIA (with no energy loss) describes $R_{AA}$ in very peripheral Pb-Pb collisions from ALICE!

$\rightarrow R_{AA} = 0.7$

$<N_{\text{part}}> = 5 \rightarrow R_{AA} = 0.8$?
No evidence of jet quenching in p-Pb collisions at the LHC. High-$p_T$ hadrons do also not show any suppression.
Quarkonia

- the original idea:
  quarkonium production suppressed via color screening in the QGP


Quantitative use of quarkonium as thermometer!!

CMS, arXiv:1805.09215
Kroupa and Strickland, Universe 2016, 2(3), 16
Quarkonia

- **the original idea:** quarkonium production suppressed via color screening in the QGP
  

- **(re)combination** enhanced quarkonium production via (re)combination during QGP phase or at hadronization


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**Central AA collisions** | **SPS** 20 GeV | **RHIC** 200 GeV | **LHC** 2.76TeV | **LHC** 5.02TeV
---|---|---|---|---
$N_{c\bar{c}}$/event | ~0.2 | ~10 | ~85 | ~115

Quantitative use of quarkonium as thermometer!!

CMS, arXiv:1805.09215
Krouppa and Strickland, Universe 2016, 2(3), 16
Quarkonia melting in small systems?

No F.S. suppression for $J/\psi$ in p-Pb collisions
Quarkonia melting in small systems?

No F.S. suppression for \( J/\psi \) in p-Pb collisions

...but ratio \( \psi(2S)/J/\psi \) significantly lower than 1 at large \( N_{\text{coll}} \)!!

Makes sense in the “sequential suppression scenario”: \( \psi(2S) \) should dissociate at lower T.
Quarkonia melting in small systems?

...but then, why $\Upsilon(2S)$ is suppressed in p-Pb and even pp high-multiplicity events?

**Perspective:**

$\psi(2S)/J/\psi$ versus multiplicity in pp collisions?
Conclusions
“small systems” path the way to a possibly deeper (microscopic) understanding of QGP phenomena:

- Final state multiplicity drives light flavours observables across systems and energies.
- Strangeness enhancement in pp collisions. In highest multiplicity, hadrochemistry ≈ to the one in the QGP
- $v_2 \neq 0$ in pp and p-Pb collisions at the LHC.
- No parton energy loss observed in pp and p-A
- Intriguing (and unclear) results on quarkonium suppression in p-A (and pp!) collisions
Multiplicity estimation in small systems

**y-values:**
- Measure $p_T$ spectra of strange particles and pions in pp events characterized by different multiplicities (fwd-rapidity estimator).
- Integrate spectra extrapolating at low and high $p_T$ with suitable functions.
- Calculate $Y_S/Y_\pi$

**x-values:**
- For all multiplicity class (fwd-rapidity estimator), count the number of primary charged particles at central rapidity and build-up $dN_{ch}/d\eta$ distribution.
- Take statistical average of every distribution.
Multiplicity bias in small systems

**x-values:**

- ∀ multiplicity class (fwd-rapidity estimator), count the number of primary charged particles at central rapidity and build-up dN_{ch}/d\eta distribution
- Take statistical average of every distribution
Selection bias and $R_{AA}$ in peripheral collisions at LHC

ALICE, Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV, charged particles, $|\eta| < 0.8$

Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV, charged particles, $|\eta| < 0.8$
- ALICE data, $8 < p_T < 20$ GeV/c
- HG-PYTHIA, PLB 773 (2017) 408
Resonances are powerful tools to probe the hadronic phase after chemical freeze-out.
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Lifetime [fm/c]: \( \rho [1.3] < K^* [4.2] < \Lambda^* [12.6] < \Xi^0 [21.7] < \phi [46.2] \)
Fix yield’s ratio to saturation limit. Check the evolution when decreasing the volume (multiplicity)

Qualitatively the thermal fit describes $K, \Lambda, \Xi, \Omega$

Notable exception is the $\phi$!

Slightly decreasing protons
Hint for hadronic re-scattering?
Need to evaluate degree of correlation on systematics across multiplicity!

K* normalized to peripheral value since re-scattering can blur the picture
Anisotropic flow in heavy ions

$v_n \neq 0$ observed at RHIC and LHC: means that in semi-central collisions the $p_T$ distribution of particles is anisotropic wrt the event plane...

does this mean we have flow?

Hydrodynamic models reproduce $v_n$ in all centralities by means of an “almost” perfect fluid: $\eta/s=0.2$
The Lund string model: basics

- Linear confinement potential for large distances (confirmed by lattice QCD). For short distances perturbation theory holds.

- Confined colour fields described as strings with tension $\kappa = 1$ GeV/fm.

- Breaking of strings (tunneling) give hadrons

$$P \propto e^{-\frac{\pi m_T^2}{\kappa}} = e^{-\frac{\pi m_q^2}{\kappa}} \cdot e^{-\frac{\pi p_T^2 q}{\kappa}}$$

- Flavour of hadrons determined by the Gaussian mass suppression term (which mass to put? If current $\rightarrow$ less s-suppression than observed. If constituent $\rightarrow$ too much s-suppression. s/u empirical number to be tuned on data)

- In **hadronic collisions** multiple strings needed to describe multiplicity distribution (MPI)

- In the LC Lund model each string hadronizes separately with respect to the others

- The multiplicity increases, but not the $\langle p_T \rangle$ nor the relative flavor abundancies!

- Multiple strings are close in space-time. Dynamical interaction not implemented in this model, but colour re-arrangement can happen: Colour Reconnection (CR)

- Takes place after parton shower and takes into account all SU(3) permitted configurations. **Selection parameter:** minimum total string length

- After re-arrangement of strings, hadronization takes place

- Correctly takes into account colour re-arrangement in remnant
PYTHIA: effect of CR

- 3 main parameters tuned on data: $c_{\text{time}}(\langle p_T \rangle)$, $c_j(\Lambda/K^0_S)$ and $p_T^{\text{ref}}(dN_{\text{ch}}/d\eta)$.
- The presence of junctions increases baryon production at intermediate $p_T$, but not sufficient to reproduce data.
- $\Lambda/K^0_S$ shape (magnitude is tuned!) reproduces data up to 3 GeV/$c$ → problem in spectra common to baryons and mesons?

**TAKE HOME**

CR mimics features that we traditionally attribute to collective flow, but something more is needed. Tuning?

Leading Colour strings dominate: can’t be attributed to CR

The DIPSY model: basics & ropes

- Partonic model in impact parameter space and rapidity (Dipole evolution in Impact Parameter Space and rapidity)
- Mueller dipole model (LL-BFKL)
- Proton/Nucleus structure built up dynamically from dipole splittings
- Builds-up initial state + collision in impact parameter space. Naturally treats saturation and MPI

To the question “Which are the strings that can interact?” the DIPSY model answers following the evolution of colour strings during the whole parton shower

**How do strings interact?**

Stack of colour strings close in the IP-y space:
can form colour singlets or multiplets according to the summing rules of SU(3)
Singlets correspond to simple re-arrangement of single strings,
Multiplets correspond to ROPES.

**Hadronizing a rope** means fragmenting string-by-string
with an effective string tension $\kappa > \kappa_0$

As we know from previous works,
higher string tension $\Rightarrow$ more baryons and more flavours $\neq (u,d)$

Before hadronizing a string
a “swing” mechanism further allow colour re-arrangements
(in analogy with colour re-connection)
• Hard scattering treated with the addition of several DGLAP parton “ladders” (pomerons) + a CGC-inspired saturation scale

• Parton ladders are then considered as relativistic strings, conveniently treated in a string fragmentation approach (a-la Lund)

• At time $\tau_0$ (well before hadronization) strings are divided into: fluid (CORE) and escaping (CORONA) according to their momenta and density of the string segments
  - **CORONA**: strings can hadronize as in the Lund approach
  - **CORE**: from the time $\tau_0$ evolves as a viscous hydrodynamic system. Hadronization happens statistically at a common $T_H$

• After hadronization hadron-hadron rescattering can be considered, making use of an afterburner (e.g. UrQMD)

**NOTE**: parameters governing the core-only part are 6 ($\tau_0, \rho_0, \varepsilon_{FD}, y_{rad}, f_{ecc}, \gamma_s$), to be tuned on data!!
• $\langle p_T \rangle$ increases only when introducing a flowing core

• Radial flow of the core also dominates the intermediate region of the $p_T$ spectrum

• High $p_T$ is dominated by escaping fragmenting strings

**NOTE**: the exact onset of the effect depends on tuning ($p_T$ cut-off for escaping strings)
EPOS: effects of Core-Corona (II)

Observed trends of relative particle yields reproduced thanks to interplay between core and corona (+ UrQMD)

Spectra + yields described in EPOS through evolution with multiplicity of relative importance of CORE and CORONA

TAKE HOME

- Relative importance of CORE/CORONA in the yields for long and short living resonances is strikingly different
- Mild $\Phi$ enhancement with multiplicity observed in EPOS

NOTE: Does this imply QGP in small systems? NO! May or may not be.