The limits of QGP-like effects towards smaller systems
from Pb-Pb down to pp and fixed-target collisions

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Nicolò Jacazio (Bologna University and INFN) On behalf of ALICE, ATLAS, CMS and LHCb
Relativistic AA collisions: the QGP

**Initial state:** collision of two Lorentz-contracted nuclei

- Fast thermalization $\Rightarrow \tau \approx 1 \text{ fm/c}$
- Phase transition (cross-over) to hadron gas ($T_c = 156.5 \pm 1.5 \text{ MeV}$ P. Steinbrecher et al. Nucl. Phys. A 982 (2019) 847)

  $\Rightarrow$ Color confinement: **hadronization**

- Chemical freeze-out ($T_{ch} \approx 153 \text{ MeV}$)

  $\Rightarrow$ inelastic collisions stop: **particle abundances fixed**

- Kinetic freeze-out ($T_{fo} \approx 100 \text{ MeV}$)

  $\Rightarrow$ elastic collisions stop: **particle spectra fixed**

- Particles fly towards detectors

nicolo.jacazio@cern.ch

Nuclear Physics A 987
QGP in AA collisions

Collectivity: radial and anisotropic flow described by hydro models
**QGP in AA collisions**

- **Partonic energy loss**: jet quenching and energy loss hierarchy \( R_{AA}^{\pi} \sim R_{AA}^{D} \leq R_{AA}^{B} \)

  - Non prompt J/\( \psi \) produced from B decays

\[
R_{AA} = \frac{1}{\langle N_{\text{Coll}} \rangle} \frac{d^2N/dydp_T}{d^2N/dydp_T}_{|_{pp}}
\]
QGP in AA collisions

Suppression of quarkonium: increases from peripheral to central AA collisions
QGP in AA collisions

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

A. Timmins Quark-gluon plasma properties from LHC data 22 May 2023, 18:15

nicolo.jacazio@cern.ch
Pre LHC: pp, pA and AA

- **At the LHC**: QGP is formed in AA collisions → clear signatures (e.g. flow, strangeness enhancement, nuclear modification factor, jet suppression, ...)

- p—Pb → control experiment, disentangle cold nuclear matter effects

- pp collisions → reference for Pb—Pb
Collective evolution: two particle correlation

- Collective expansion translates into **long range** modulation of particle emission in **azimuth**

\[ \phi_1, \phi_2, \Delta \eta, \Delta \phi \]

Away side

Near side

CMS PbPb \( \sqrt{s_{_{NN}}} = 2.76 \text{ TeV}, 220 < N_{\text{off}} < 260 \)

1 < \( p_T^{\text{frag}} \) < 3 GeV/c
1 < \( p_T^{\text{assoc}} \) < 3 GeV/c

Long range

CMS PLB 724 (2013) 213

nicolo.jacazio@cern.ch
Collective evolution holding until pp?

- Collective expansion translates into **long range** modulation of particle emission in **azimuth**

- Also observed in p-Pb and pp → "small systems" is born

- Collective expansion also at play? Under which conditions does this not happen?
Small systems post LHC

• Tentative definition: "system a priori too small to show characteristics of heavy ion physics and however in which we observe them" → **small systems are defined from AA**

• **Nota bene:** with this definition a system "too small" is not defined a priori → sometimes a final state looking like a large system, at least for charged particle multiplicity

• Minimum Bias pp **still holds as the reference** → high-multiplicity events $\sim O(10^{-4})$ of the total cross section

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Decreasing systems size

nicolo.jacazio@cern.ch
Collective motion in small systems

- High multiplicity $\rightarrow$ many partonic interactions $\rightarrow$ many color strings $\rightarrow$ color string shoving!

**String shoving leads to collective motion**

PYTHIA8 string shoving, pp 13 TeV
100 $\leq N_{ch}$$< 120$
$1<p_T$$< 2$ GeV/c

C. Bierlich et al.
MCnet-16-48, LU-TP 16-64

- PYTHIA with string shoving can reproduce long range angular correlation
- Explains presence in high-multiplicity hadron-hadron collisions

J. Kim et al.
arXiv:2108.09686

nicolo.jacazio@cern.ch
• No significant long range correlation is found in $e^+e^-$ collisions around $\Delta \phi = 0$
And at the LHC?

- No significant long range correlation is found in $e^+e^-$ collisions around $\Delta \phi = 0$

- At the LHC we can lower the multiplicity in pp collisions
  - Correlation in pp is larger than that of $e^+e^-$ at similar multiplicity
Anisotropic flow of identified particle

- $v_2 > 0$ in small systems:
  - low $p_T \rightarrow$ consistent with mass ordering
  - intermediate $p_T \rightarrow$ particle type grouping

- Described by hydro with quark coalescence and jet fragmentation

$v_2 > 0$ implies some energy loss yet no jet quenching? $\rightarrow$ to be solved!
Going smaller at the LHC: UPCs

- Coulomb fields of moving charges equivalent to a flux of photons boosted to high energies
  - \( \gamma \) energies of \( \sim 10 \)s GeV with a 2.5 TeV Pb beam
  - High multiplicity events \( \rightarrow \) no clear near side ridge

nico1o.jacazio@cern.ch
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  - \( \gamma \) energies of \( \sim 10 \)s GeV with a 2.5 TeV Pb beam
  - High multiplicity events \( \rightarrow \) no clear near side ridge
  - Non-zero \( v_2 \) but lower than hadron-hadron collisions!
  - Caveat: \( v_2 \) coefficients vulnerable to (residual) non-flow
"Baryon-to-meson"

• In Pb-Pb collisions mass-dependent hardening of the spectra
  low-\(p_T\) depletion
  intermediate-\(p_T\) enhancement

• protons are shifted towards higher momenta
  \(\rightarrow\) interpreted as radial flow
  common velocity field (\(p=mγβ\))
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- Remarkable consistency across systems as a function of multiplicity

- high-\(p_T\) : recovery of universal behavior?
"Baryon-to-meson" ratio with HF probes

- $\Lambda^+_c/D^0$ enhanced at intermediate $p_T$ in central Pb-Pb collisions (also measured up to high $p_T$ CMS-PAS-HIN-21-004)

- $\Lambda^+_c/D^0$ in $p-$Pb does not depend on the final-state multiplicity → similar values observed in peripheral Pb-Pb collisions (LHCb-PAPER-2021-046)

- Comparison to $\Lambda/K_s^0$ might indicate coalescence of heavy quarks saturates earlier than for light quarks in small systems
Strangeness enhancement in small systems

- One of the original traces of the QGP $\rightarrow$ thermal production via gluon fusion
- Enhanced production of strange hadrons wrt $\pi$ $\rightarrow$ increasing with multiplicity
- Hierarchy with strangeness content: $K_S^0 < \Lambda(1s) < \Xi(2s) < \Omega(3s)$
- Strangeness increases with multiplicity following a universal trend
Strangeness enhancement: more differential

Relative strangeness production:

- Increases with multiplicity at midrapidity
- Decreases with forward energy
- Same hierarchy with strangeness content observe vs multiplicity and forward energy!
- Can we disentangle the effects?

ALI-PREL-506610

Zero Degree Calorimeter (ZDC)
Forward calorimeters counting collision remnants
Strangeness enhancement: more differential

At fixed multiplicity:

Relative $\Xi$ yield increase with forward activity

- Increase in the average fraction of strange hadrons with increasing multiplicity and decreasing ZDC energy
Strangeness enhancement with beauty?

- Measurement of $B^0_s$ and $B^0$ at forward rapidity ($2 < y < 5$) in pp at 13 TeV

- **Significant increase in** $B^0_s/B^0$ **with multiplicity** when measured in the same rapidity range

- $b\bar{b}$ pair production at hadron colliders dominated by hard parton-parton interactions → set in the initial stages

- Possibly due to quark coalescence → enhanced $B^0_s/B^0$ ratio with increasing particle multiplicity
Smaller systems with fixed target

- SMOG → unique opportunity to access pA and AA collisions with smaller nuclei at the LHC
- $J/\psi$ showing no discontinuity from p–Ne to central Pb–Ne
- More data and more collision systems required to complete the picture
  - SMOG2 will be taking data in Run 3 → more nuclei, x1000 increase in luminosity

<table>
<thead>
<tr>
<th>Integrated luminosity</th>
<th>SMOG largest sample p–Ne@68 GeV</th>
<th>SMOG2 example p–Ar@115 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute integrated luminosity</td>
<td>~100 nb$^{-1}$</td>
<td>100 pb$^{-1}$</td>
</tr>
<tr>
<td>Relative error on luminosity</td>
<td>6–7%</td>
<td>2.3%</td>
</tr>
<tr>
<td>$J/\psi$ yield</td>
<td>1.5k</td>
<td>335M</td>
</tr>
<tr>
<td>$D^0$ yield</td>
<td>200k</td>
<td>335M</td>
</tr>
<tr>
<td>$D^+$ yield</td>
<td>1k</td>
<td>3.5M</td>
</tr>
<tr>
<td>$Y(1S)$ yield</td>
<td>150</td>
<td>400k</td>
</tr>
<tr>
<td>Low-mass $5 &lt; M_{D^{0}} &lt; 9$ GeV/c$^2$ Drell-Yan yield</td>
<td>5</td>
<td>20k</td>
</tr>
</tbody>
</table>

Z. Citron et al. 
CERN-LPCC-2018-07
Conclusions

Small systems exhibit features typical of AA collisions
• Soft boundaries between small and large systems

Dynamics
• Correlations in the smallest systems ($\gamma p$, $\gamma Pb$) show no long range effect but overall positive flow
• Precision measurements of identified hadron flow show mass effect in small systems
• Baryon-over-meson ratio showing universal evolution among systems in the LF sector

Hadrochemistry
• Strangeness enhancement observed in small systems with light and heavy flavors
• More differential measurements of the initial state effects on strangeness

Pushing the limits to understand small systems
Future data will help us in understanding → going smaller, more differential, larger
Crucial role of the LS2 upgraded detectors