FROM SMALL TO LARGE COLLIDING SYSTEMS: LESSONS LEARNED AND FUTURE PERSPECTIVES

F. Bellini (CERN)
for the ALICE, ATLAS, CMS, and LHCb Collaborations
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“Small” and “large” systems

Colliding system size

\[ \text{pp (min bias)} \]

\[ \text{p-Pb} \]

\[ \text{Xe-Xe} \]

\[ \text{Pb-Pb} \]

Resulting system size

\[ \rightarrow \text{charged particle multiplicity} \]

\[ \langle dN_{\text{ch}}/d\eta \rangle_{|\eta|<0.5} \]

J.M. Jowett et al.

F. Bellini, LHCP 2018

6.06.2018
Small systems much more than a reference

First lesson learned at the LHC:

pp, p-nucleus collisions much more than a “reference” for heavy-ion collisions

Focus of today’s talk:

1. Smooth evolution of particle composition across collision systems
2. Signatures of emergent collectivity in pp, p-Pb collisions
3. Collectivity without energy loss?

via a selection of (few) well known and (mostly) new experimental results, as well as some open points and perspectives (apologies if biased)!
Smooth evolution of hadro-chemistry

Particle composition evolves smoothly across collision systems, depending on charged particle multiplicity.

Common origin in all systems?
Strangeness production

Enhancement of strangeness from low to high multiplicity pp, p-Pb collisions, until saturation in Pb-Pb [ALICE, Nat. Phys. 13, 535–539 (2017)]

confirmed with new data from LHC Run II

Ongoing efforts to explain behavior with models
- Lund string, color ropes (PYTHIA, DIPSY)
- core-corona (EPOS-LHC)
- thermal-statistical (canonical suppression) [V. Vislavicius, A. Kalweit, arXiv:1610.03001]

- Conventional pp generators successful, with MPI + CR generating some collectivity, but now cracks.
- Need new framework for baryon production.

T. Sjostrand, Quark Matter 2018
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… and with more data, by measuring production of \( \phi \)-meson (hidden strangeness) in small systems!
Collectivity (in short)

“Loose” definition: correlations of (more than 2) particles across rapidity due to a common source

Origin of collectivity:

• **Initial state** correlations $\rightarrow$ among hadrons in the final state arise from momentum correlations at partonic level
  [gluon saturation, CGC, see B. Schenke’s talk]

• **Final state** correlations $\rightarrow$ anisotropies and correlations in space converted into anisotropies in momentum space, e.g. via hydrodynamic flow
  [established in Pb-Pb collisions]
The hallmarks of flow in heavy-ion collisions (1)

Increase in mean $p_T$ with increasing centrality
→ Push from radial flow affects low $p_T$ part of spectra

Baryon-to-meson ratios (with $\Delta m$)
→ sensitive to particle production mechanisms (radial flow at low $p_T$, recombination at mid-$p_T$)
The hallmarks of flow in heavy-ion collisions (2)

Centrality / multiplicity dependence 
→ reflects the degree of “anisotropy” in the initial geometry of the collision

Non-zero higher-order flow coefficients (“harmonics”) 
→ sensitivity to fluctuations of initial geometry

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The hallmarks of flow in heavy-ion collisions (3)

Mass scaling of flow coefficients
→ Expansion under a common velocity field

Correlations between harmonics
→ Sensitivity to fluctuations in initial geometry ($v_2, v_3$) and medium-transport properties ($v_2, v_4$)

Increasing mass

ALICE, arXiv:1805.04390

CMS, PRL 120, 092301 (2018)
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 these long-range correlations coming from (hydrodynamic) flow?

→ Investigated with new measurements with run 2 data, new analysis techniques
The challenge of removing “non-flow”

In **small systems** the contribution of **non-flow** cannot be neglected:
- Different contribution from jets
- Larger fluctuations in the number of particle sources

A word of **caution**:  
- Sensitivity to the event class definitions used in analysis  
  [ATLAS, EPJ C (2017) 77-428]  
- Sensitivity to strategy for non-flow background subtraction

**Non-flow subtraction / suppression is a delicate business in pp, p-Pb!**  
Big effort ongoing in defining “smart” observables / new techniques
If collectivity, it involves more than 2 particles

Measure elliptic flow $v_2$ using correlations among $k$ particles in a single event, subtracting correlations from smaller number of particles

[A. Bilanzic et al., PRC 83 (2011) 044913]

Multi-particle cumulants, $c_n\{k\}$

$$
c_n\{2\} = \langle \langle 2 \rangle \rangle = \langle \cos(n(\varphi_1 - \varphi_2)) \rangle
$$

$$
c_n\{4\} = \langle \langle 4 \rangle \rangle - 2 \langle \langle 2 \rangle \rangle^2
$$

$$
c_n\{6\} = \langle \langle 6 \rangle \rangle - 9 \langle \langle 4 \rangle \rangle \langle \langle 2 \rangle \rangle + 12 \langle \langle 2 \rangle \rangle^3
$$

Related to the flow harmonics, $v_n\{k\}$

$$
v_n\{2\} = \sqrt{c_n\{2\}}, \quad v_n\{4\} = \sqrt[4]{-c_n\{4\}}
$$

$$
v_n\{6\} = 6^{1/2} c_n\{6\} / 4.
$$
If long-range, correlations stay across sub-events

**Whole event**
Jets (short-range) contribute to correlations (e.g. 4-particle corr.)

≥ 2 Sub-events
If long range, particles are correlated across subevents

Figures from M. Zhou, QM 2017
J. Jia et al., PRC 96, 034906 (2017)
True collectivity in small systems!

\[ v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \rightarrow \text{true collectivity (even) in smallest systems} \]

\[ v_2\{2\} \text{ larger } \rightarrow \text{residual "non-flow"} \]
Light-flavor particle $v_2$

Clear **mass ordering** at low $p_T$ in p-Pb from new results on $v_2^{sub}$ for identified hadrons

$\rightarrow$ Consistent with hydrodynamics (and AA)
Light-flavor particle $v_2$

Clear **mass ordering** at **low** $p_T$ in $p$-Pb from new results on $v_2^{sub}$ for identified hadrons

→ Consistent with hydrodynamics (and AA)

**BUT** it could also be due to other effects
- Initial stage effects (CGC + PYTHIA)
- Parton escape (AMPT)
- Hadronic rescattering (UrQMD)

Is mass ordering no longer an exclusive product of hydrodynamic flow?
Heavy-flavor particle $v_2$ in p-Pb

Strange and charm hadrons show large azimuthal anisotropy in p-Pb collisions, up to 7-8 GeV/c.

Charm, beauty to leptons

Both light- and heavy-flavour hadrons show large azimuthal anisotropy in p-Pb collisions, up to 7-8 GeV/c.
Across the three systems the baryon-to-meson ratios evolve with multiplicity in a qualitatively similar way.
Baryon-to-meson production – heavy-flavor sector

MC generators fail in reproducing the measured $\Lambda_c/D^0$
Heavy flavor baryon-to-meson ratio similar to light-flavors ($\Lambda/K_{S}^0$)
Measurements in forward rapidity region provide further input for understanding charm fragmentation
Collectivity but no jet quenching?

**Similarities** are observed for flow observables between peripheral Pb-Pb and high multiplicity p-Pb collisions.

New and more precise measurements from ALL experiments on nuclear modification factors.

In (minimum bias) $p$-$Pb$, no suppression at high-$p_T$ is observed, contrary to **peripheral Pb-Pb**.

$\rightarrow$ *Do we understand this?*
Nuclear modification in very peripheral collisions

Strong change of behaviour of $R_{AA}$ beyond 80% centrality

→ reproduced by HG-PYTHIA with biases in event selection and collision geometry, and no nuclear modification.

Considering this, the jet quenching signal is smaller than typical systematics above ~80% centrality → consistent with $R_{pPb}$
Look for jet quenching in p-Pb by
- comparing jet-hadron correlations in low and high multiplicity p-Pb events
  [C. Klein-Boesing – HIN, Fri. 15:30]
- checking how much energy is transferred “out-of-cone” by jet-quenching
  [ALICE, arXiv:1712.05603]
- caution with biases in centrality selections

If existing at all, jet quenching in p-Pb is a very small effect.

Beware of selection biases!
**Conclusions and outlook**

**Continuity in chemistry and dynamics** across collision systems (dependence on charged particle **multiplicity**) is observed.

Many **new** precise measurements, new techniques and efforts to provide “bullet-proof” **observables** to measure collective effects in small systems.

**MC generators** can generate collective-like behaviour but **fail in the details** of hadron (baryon) production as a function of multiplicity.

**Absence of jet-quenching** in small systems remains as the main **challenge to the final-state effect interpretation**.

**Origin** of collectivity in small systems is still **to be understood**.
Strangeness enhancement in small systems

\[ \frac{h(\pi)}{h(\pi)_{\text{inel}}} \]


\[ \Lambda/K^0_s \]

\[ p/\pi \]

Baryon to meson ratio

\[ \langle dN_{ch} / d\eta \rangle_{|\eta|<0.5} \]
Blast-Wave model fits to particle spectra


A simplified hydrodynamic model with 3 free fit parameters,
- $T_{\text{kin}}$: kinetic freeze-out temperature
- $\langle \beta_T \rangle$: transverse radial flow velocity
- $n$: velocity profile
to describe particle production from a thermalized source + radial flow boost

Simultaneous fit to the $\pi$, $K$, $p$ spectra
- increase of $\langle \beta_T \rangle$ with centrality in AA
- Xe-Xe and Pb-Pb consistent
- in pp and p-Pb, similar evolution of the parameters towards high multiplicity
- at similar multiplicity, $\langle \beta_T \rangle$ is larger for smaller systems
Harmonic correlations in pp

ATLAS

ATLAS-CONF-2018-012
First measurement of $v_3$ with 4-particles in p-Pb

$\frac{v_n(4)}{v_n(2)}$ larger for $v_2$ than $v_3 \rightarrow$ global geometry dominates for $v_2$

$\frac{v_n(4)}{v_n(2)}$ similar for $v_2$ than $v_3 \rightarrow$ initial state fluctuations as important
Comparison to hydro models: $\pi v_n$

ALICE, arXiv:1805.04390
Comparison to hydro models: $p\nu_n$

ALICE, arXiv:1805.04390