An Overview of Heavy-Ion Physics in Small Collision Systems at the LHC

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on behalf of ALICE, ATLAS, CMS, & LHCb
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Introduction

• Why study small systems?
  – Baseline for A–A (vacuum processes, “cold nuclear matter”)
  – Study “turn-on” of collective effects
  – Could there be a QGP?

• Modelling

pp Models
Single hard scatterings
vacuum processes
+ multiparticle interactions
color reconnection, color ropes, …

A–A Models
QGP, hydrodynamics (radial & elliptic flow), statistical models

• Disclaimer: there are of course many more results than what I show here.
Strangeness Production

- Smooth evolution of particle production with charged-particle multiplicity across pp, p–Pb, Xe–Xe, and Pb–Pb collisions
  - No energy dependence
  - Hadron chemistry is driven by the multiplicity (system size)

- Increase of strange-particle production for small systems, saturation around thermal-model values for large systems
  - Magnitude of strangeness enhancement increases with strange-quark content

\[ |S| = 0 \]
\[ |S| = 1 \]
\[ |S| = 2 \]
\[ |S| = 3 \]
• Near-side, long-range correlations observed in Pb–Pb, p–Pb, and pp collisions
• Extends over at least 4 units of $\eta$
• Collective behavior in small systems?
• Near-side, long-range yields:
  – Negligible for $N_{\text{trk}} < 40$, then $\sim$linear increase
  – Collision system: for given multiplicity $Y_{pp} < Y_{pPb} < Y_{PbPb}$

• Yields described by Glasma model for $N_{\text{trk}} < 100$
  – Gluon saturation, initial collimated gluon emission
  – No collision energy dependence
  – Model overestimates associated yields at high multiplicity
• ATLAS studied ridge in Z-tagged pp collisions
  – Presence of $Z \rightarrow$ hard scattering in event ($\text{high } Q^2$)
  – Proposal: presence of $Z \rightarrow$ smaller impact parameter ($b$) \rightarrow smaller initial eccentricity \rightarrow smaller $v_2$ (cf. inclusive pp sample)
  – Template fits remove back-to-back dijets, corrections for pileup
  – **No significant difference** between results in Z-tagged and inclusive events: presence of hard scattering does not affect ridge formation
• Ridge also observed at forward & backward rapidity (p- and Pb-going directions)
• Size of near-side ridge increases with multiplicity
• Structures at forward and backward rapidities have similar magnitudes for similar multiplicities

PLB 762 473 (2016)
**$\nu_n$ Measurements**

- **A–A Collisions**
  - Strong $N_{\text{ch}}$ dependence
  - Ordering: $v_2 > v_3 > v_4$ (except for highest $N_{\text{ch}}$)
    - Expected due to collision geometry ($v_2$), fluctuations ($v_3, v_4$)
    - Hydrodynamic calculations describe data well except for $v_2$ at low $N_{\text{ch}}$

- **Small Systems**
  - Weak $N_{\text{ch}}$ dependence (similar values to A–A)
  - Ordering: $v_2 > v_3 > v_4$
  - Multi-particle results ($v_2\{4\}$ & $v_2\{6\}$) less influenced by non-flow
  - Results cannot be explained by non-flow effects alone (PYTHIA)

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**Graphical Abstract**

- **Graph (a)**: 
  - PYTHIA 8
  - Hydro
  - ALICE
  - Data points and curves for $v_2$, $v_3$, and $v_4$ across different $N_{\text{ch}}$ and $s_{\text{NN}}$ values.

- **Graph (b)**: 
  - ALICE
  - Data points and curves for $v_2$ at different $p_T$ bins and $\eta$ values.

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**Figure Legend**

- ALICE
- $v_2(2,|\eta| > 1.4)$
- $v_2(2,|\eta| > 1.0)$
- $v_2(3,|\eta| > 1.0)$
- $v_4(2,|\eta| > 1.0)$

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**Additional Information**

- arXiv:1903.01790
$v_2$ of Identified Hadrons

- A–A collisions
  - Mass ordering of $v_2$ for low $p_T$
  - Baryon-meson grouping for high $p_T$
- Indications of similar behavior in p–Pb
Evolution of $\rho_T$ Spectra

- Hadron $\rho_T$ spectra become harder with increasing multiplicity ($\langle \rho_T \rangle$ increases)
- Qualitative similarities for pp, p–Pb, and Pb–Pb
- pp & p–Pb: modification mostly for $\rho_T < 3$ GeV/c
• A–A collisions: mass ordering of $\langle p_T \rangle$ (see $p$ and $\phi$)
  – Consistent with hydrodynamic flow

• Small Systems:
  – Mesons ($K^*$, $\phi$) have greater $\langle p_T \rangle$ than baryons w/ similar masses
  – More rapid increase in $\langle p_T \rangle$ with multiplicity
  – $\langle p_T \rangle$ values in high-mult. pp & p–Pb reach those seen in Pb–Pb

See also:
CMS *PLB* 768 103 (2017)
Blast-Wave Fits

- Simultaneous blast-wave fits of $p_T$ spectra
  - ALICE: $\pi$, $K^{\pm}$, & $p$
  - CMS: $K^0_S$ & $\Lambda$

- A–A collisions
  - $T_{\text{kin}}$ decreases, flow velocity $\langle \beta_T \rangle$ increases w/ centrality

- Small systems
  - Large increase of $\langle \beta_T \rangle$ w/ mult.
  - Higher $T_{\text{kin}}$ values than A–A
  - Similar multiplicities: $\langle \beta_T \rangle$ (and $\langle p_T \rangle$) greater in smaller systems

- Change of $\langle p_T \rangle$ vs. multiplicity qualitatively consistent with expanding fluid, but MPIs and/or color reconnection are possible explanations in small systems

Caveats: fit results sensitive to particles included & fit ranges
J/ψ in p–Pb

- Prompt J/ψ from initial hard scatterings
  - Modification due to initial-state effects (gluon density in nucleus, initial-state energy loss) or final-state effects (co-movers)
- Low $p_T$: suppression of prompt J/ψ
- High $p_T$: $R_{pPb}$ consistent with unity
  - Possible weak decrease from backward to forward $y$
  - Suppression in Pb–Pb not due to cold nuclear matter effects
- $R_{pPb}$ in good agreement with model predictions

Also: ATLAS *EPJC* 78, 171 (2018); ALICE *EPJC* 78, 466 (2018)
• More suppression of $\psi(2S)$ compared to ground state
  – Different nuclear effects on $J/\psi$ vs. $\psi(2S)$
  – Decent agreement with GCG + color evaporation model (in p-going direction), co-movers
  – Co-movers expected to affect $\psi(2S)$ more than $J/\psi$, this difference greater in Pb-going direction

• Observed suppression pattern consistent w/ final-state effect
Y(nS) Suppression

- Y(1S) suppressed at low $p_T$
- Y(2S) suppressed w.r.t Y(1S)
- Suppression in forward (p-going) direction w.r.t. backward
  - Consistent w/ two predictions with nPDFs
Y(nS) Suppression

- Y(2S) & Y(3S) suppressed w.r.t Y(1S)
- More suppression with increasing multiplicity
- Final-state suppression mechanisms that affect excited Y states more than ground state?
- Y suppression pattern quite similar to situation for J/ψ and ψ(2S)
• SMOG system
  – Low-density noble gas injected into VELO vessel (~100x higher pressure than LHC vacuum)
  – Allows LHCb to operate in fixed-target mode

• Measurements of $\bar{p}$ yields in p–He collisions
  – Uncertainties smaller than spread among various theoretical models
  – Will help shed light on $\bar{p}$ excess observed by AMS-02 and PAMELA: do those $\bar{p}$ come from cosmic-ray interactions with interstellar medium, or from Dark Matter annihilation?

• ALICE studies of $\bar{d}$ and $^{3}\text{He}$ also useful for Dark Matter searches
Direct Photons

- $R_{pPb}$ of isolated direct $\gamma$:
  - Consistent with unity at positive $\eta$
  - Modest modification in Pb-going direction (more d quarks)
  - Data consistent with modification of PDFs, disfavor initial-state energy loss

![Graph showing $R_{pPb}$ as a function of $E_T^\gamma$](image-url)
Dijet Correlations

- Shapes of dijet angular correlation distributions and conditional yields are sensitive to gluon saturation at low $x_A$
- Azimuthal correlation functions:
  - Wider for dijets with large rapidity separation
  - No significant broadening from $pp \rightarrow p + Pb$
- Conditional yields suppressed by ~20% for forward-forward dijets
  - Can constrain nuclear effects in low-$x$ region (e.g. saturation)

$19p + Pb$

Knospe

arXiv:1901.10440
Conclusions

• Strangeness production evolves smoothly with multiplicity
  – No energy or collision-system dependence
  – Magnitude of enhancement increases with strangeness content
  – Small systems: rope hadronization, core-corona effects?

• Near-side ridge in small systems

• $v_2$ in small systems not explained by non-flow effects alone

• $p_T$ spectral shapes:
  – Increasing $\langle p_T \rangle$ and $\langle \beta_T \rangle$ with multiplicity (MPIs, color reconnection, flow?)
  – Mass ordering of $\langle p_T \rangle$ in central A–A → violated in small systems (different trends for baryons vs. mesons?)

• Quarkonia
  – Suppression at low $p_T$
  – Excited states more suppressed than ground states (final-state effects)
  – Multiplicity dependence of $Y(nS)$ suppression

• Measurements of $\bar{p}$ production in $p$–He collisions will illuminate the excess observed by PAMELA and AMS-02
Additional Material
The $\phi$ meson ($s\bar{s}$) is a key probe in studying strangeness production
- Does $\phi$ evolve as $S=0$ particle, or as if it had open strangeness?

Large systems: $\phi$ production described by thermal models

Small systems: increase in $\phi/\pi$ ratio with multiplicity
- Inconsistent with simple canonical suppression
- Qualitatively explained by rope hadronization (DIPSY) and core/corona (EPOS)
  - Connected to strong color fields/high density

Ratios $\phi/K$ and $\Xi/\phi$ fairly flat across wide multiplicity range
- The $\phi$ has “effective strangeness” of 1–2 units
• Small systems: particles with open strangeness subject to canonical suppression, while $\phi$ is not
• ALICE observes increase in $\phi/\pi$ with multiplicity in pp
  – Not expected for simple canonical suppression
  – Does system drop out of equilibrium?
• Groups of overlapping strings fragment with higher effective string tension
  – Enhances strange-particle production
  – Enhancement of $\phi$ similar to open-strangeness hadrons
  – DIPSY (color ropes) qualitatively describes increase of $\phi/\pi$ with multiplicity
Core/Corona Effects

- EPOS: describes pp, p–A, and A–A collisions with common framework
  - Collision divided into a core (QGP) and a corona of jets
  - Core evolves hydrodynamically
  - Hadronic phase with re-scattering and regeneration (UrQMD)

![Diagram showing low-multiplicity pp, peripheral A–A, high-multiplicity pp, and central A–A collisions with corresponding plots for EPOS 3.210 and ALICE (black).]
• A–A collisions: mass ordering of $\langle p_T \rangle$ (see $p$ and $\phi$)
  – Consistent with hydrodynamic flow
• Small Systems:
  – Mesons ($K^*$, $\phi$) have greater $\langle p_T \rangle$ than baryons w/ similar masses
  – More rapid increase in $\langle p_T \rangle$ with multiplicity
  – $\langle p_T \rangle$ values in high-mult. pp & p–Pb reach those seen in Pb–Pb

CMS | 6.2 pb$^{-1}$ ($\sqrt{s} = 7$ TeV) | 35 nb$^{-1}$ ($s_{NN} = 5.02$ TeV) | 2.3 μb$^{-1}$ ($s_{NN} = 2.76$ TeV)

| pp | $|y_{cm}| < 1$ | pPb | PbPb | $|y_{cm}| < 1$ |

$\langle K^* \rangle$ vs. $N_{\text{trk}}$
Baryon-to-Meson Ratios

- Baryon-to-meson ratios vs. $p_T$ allow us to study the interplay of hydrodynamics and recombination.
- Compare Xe–Xe & Pb–Pb: consistent results for similar multiplicities.
- $p/\phi$ ratio is useful: baryon and meson with almost the same mass.
  - Flat with $p_T \rightarrow$ consistent with hydrodynamic behavior, but can also be described by some recombination models.

[V. Greco et al, *PRC* 92 054904 (2015)]
Baryon/Meson Ratios

• From low multiplicity (peripheral) to high multiplicity (central):
  – Baryon/Meson ratios depleted at low $p_T$
  – Enhanced at intermediate $p_T$

• Qualitative similarities between $pp$, $p-$Pb, & Pb–Pb
Baryon/Meson Ratios

- Baron/meson ratios in different $p_T$ regions:
  - Low-$p_T$ depletion and intermediate-$p_T$ enhancement
- Similar behavior for the three systems

**Graphs**

- $p/\pi$ ratios in different $p_T$ regions:
  - Low-$p_T$ depletion and intermediate-$p_T$ enhancement
  - Similar behavior for the three systems

**Equations**

$$\frac{p}{p}(p + K^0 S)/(\pi^0 + \pi^-)$$

**Experiment Data**

- ALICE: $7$ TeV, $|y| < 0.5$
- CMS: $5.02$ TeV, $0 < y < 0.5$
- $NN$: $2.76$ TeV, $|y| < 0.5$
  - $c < 3.00 \text{ GeV}/c$
  - $p < 0.80 < 1.00 \text{ GeV}/c$

**Gluon-Gluon**

- $p/\pi$: $6.50 < p_T < 8.00 \text{ GeV}/c$
- $p$: $6.00 < p_T < 8.00 \text{ GeV}/c$
- $Pb$: $6.50 < p_T < 8.00 \text{ GeV}/c$

**K/\pi**

- $p$: $0.50 < p_T < 0.55 \text{ GeV}/c$
- $p$: $2.40 < p_T < 2.60 \text{ GeV}/c$
- $p$: $10.00 < p_T < 15.00 \text{ GeV}/c$

**ALICE**

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**PRC 99 024906 (2019)**
Baryon/Meson Ratios

- Baron/meson ratios in different $p_T$ regions:
  - Low-$p_T$ depletion and intermediate-$p_T$ enhancement
- Similar behavior for the three systems
- Trend in pp described qualitatively by color reconnection (PYTHIA) and color ropes (DIPSY); over-predicted by collective radial expansion in EPOS
**Baryon/Meson Ratios**

\[
\frac{N_{\Lambda}}{N_{K^0}} = \frac{1}{1 + \frac{p}{p^+} (p + 5 + 10 + 15 + 20)}
\]

where \( N_{\Lambda} \) is the number of \( \Lambda \) baryons and \( N_{K^0} \) is the number of \( K^0 \) mesons. This ratio is shown for different energy scales and collision systems.

**ALICE**

- **pp** collision at 7 TeV, \(|y| < 0.5\): ALICE \( N_{\text{pp}} \) = 21.3 \( \pi_0 \) per event.
- **p-Pb** collision at 5.02 TeV, \( 0 < y < 0.5 \): ALICE \( N_{\text{p-Pb}} \) = 5.02 \( \pi_0 \) per event.
- **Pb-Pb** collision at 2.76 TeV, \(|y| < 0.5\): ALICE \( N_{\text{Pb-Pb}} \) = 21.3 \( \pi_0 \) per event.

**ALICE Multiplicity Classes**

- **V0M Class I**
- **V0M Class X**

**CMS**

- **pp** collision at 5.02 TeV, \( 0 < y < 0.5 \): CMS \( N_{\text{pp}} \) = 21.3 \( \pi_0 \) per event.
Baryon/Meson Ratios

\[
\frac{N(\mu+\bar{\mu})}{N(\pi+\bar{\pi})} = 7 \text{ TeV, } |y| < 0.5
\]

\[
\frac{N(K^+ + K^-)}{N(\pi^+ + \pi^-)} = 5.02 \text{ TeV, } 0 < y_{\text{cut}} < 0.5
\]

\[
\frac{N(p + \bar{p})}{N(p + p)} = 2.76 \text{ TeV, } |y| < 0.5
\]

\[
\frac{N(c + \bar{c})}{N(\pi + \bar{\pi})} < 0.80 \text{ GeV/c}
\]

\[
\frac{N(c + \bar{c})}{N(\pi + \bar{\pi})} < 2.90 \text{ GeV/c}
\]

\[
\frac{N(c + \bar{c})}{N(\pi + \bar{\pi})} < 8.00 \text{ GeV/c}
\]
Baryon/Meson Ratios

\[ \frac{p + \bar{p}}{\pi^+ + \pi^-} \]

\[ \frac{K^+ + K^-}{\pi^+ + \pi^-} \]

\[ \frac{\Lambda}{K^0} \]

\[ \frac{\Lambda}{\bar{K}^0} \]

\[ \frac{S}{K_L} \]

\[ \frac{dN}{d\eta} |_{|\eta| < 0.5} \]

\[ \text{ALICE pp } \sqrt{s} = 7 \text{ TeV, } |y| < 0.5 \]

\[ \text{Pythia8 Monash NoCR} \]

\[ \text{Pythia8 Monash WithCR} \]

\[ \text{DIPSY Color Ropes} \]

\[ \text{EPOS LHC} \]

\[ \text{HERWIG7} \]

arXiv:1807.11321
Nuclei

- **Thermal models**
  - Hadrons emitted in statistical equilibrium with chemical freeze-out temperature $T_{ch}$
  - Yields proportional to $\exp(-m/T_{ch})$

- **Coalescence**
  - Nuclei formed by baryons close in phase space after kinetic freeze-out
  - Nuclei may break up and re-form during hadronic phase

- **Deuterons:**
  - Coalescence in small systems and thermal production in $A-A$
  - Smooth transition between systems
  - Production controlled by system size

- **$^3$He:** factor of 5 difference in $^3$He/p ratio from $p$–Pb to Pb–Pb
  - But also a large gap in multiplicity
  - More data needed…

\[ \frac{dN}{d\eta} \quad |\eta| < 0.5 \]

\[ \frac{dN_{ch}}{d\eta} \quad |\eta| < 0.5 \]

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\[ \frac{dN_{ch}}{d\eta} \quad |\eta| < 0.5 \]
Deuteron Coalescence

- Coalescence parameter for nucleus $i$ with mass number $A$:

$$E_i \frac{d^3 N_i}{dp_i^3} = B_A \left( E_p \frac{d^3 N_p}{dp_p^3} \right)^A$$

$$B_2 = \frac{E_d \frac{d^3 N_d}{dp_d^3}}{\left( E_p \frac{d^3 N_p}{dp_p^3} \right)^2}$$

- Simple coalescence
  - Flat $B_2(p_T)$
  - Simple relationship between d & p $v_2$:
    - $v_2^d(p_T) = 2v_2^p(2p_T)$

- Simple coalescence does not describe ALICE deuteron measurements in Pb–Pb
  - Describes lower energy A–A data
  - $B_2$ flatter for smaller collision systems
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- Simple coalescence does not describe ALICE deuteron measurements in Pb–Pb
  - Describes lower energy A–A data
  - $B_2$ flatter for smaller collision systems
  - $B_2$ evolves smoothly with system size
• LHCb: first measurement of charm production in fixed-target mode at LHC
  – $D^0$ and prompt $J/\psi$ in $p$–He and $p$–Ar collisions
• Does the proton contain intrinsic charm?
• Production cross-sections compared to calculations without intrinsic (valence-like) charm contribution
  – No effect seen
  – Proves large Bjorken $x$:

Since $x \approx \frac{2mc}{\sqrt{s_{NN}}} e^{-y^*}$,

large $x \to$ negative $y^*$

Figure: 
- LHCb data for $D^0$ and $J/\psi$ production in $p$–He collisions at $\sqrt{s_{NN}} = 86.6$ GeV.
- Comparison with calculations using CT14NLO+nCTEQ15.

Source: *PRL 122, 132002 (2019)*
Mid-Rapidity $J/\psi$ $R_{pPb}$

**EPJC 78 171 (2018)**

**ATLAS**
- $p+$Pb, $\sqrt{s_{NN}} = 5.02$ TeV, $L = 28$ nb$^{-1}$
- $pp$, $\sqrt{s} = 5.02$ TeV, $L = 25$ pb$^{-1}$

**EPJC 78 466 (2018)**

**ALICE**
- Prompt $J/\psi$
- $p-$Pb $\sqrt{s_{NN}} = 5.02$ TeV

**LHCb**
- Prompt $J/\psi$
- $p-$Pb $\sqrt{s_{NN}} = 5.02$ TeV

- $-1.37 < y_{\text{cms}} < 0.43$