Studying particle production in high-multiplicity proton-proton and proton-lead collisions with ALICE

D.D. Chinellato for the ALICE Collaboration

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The role of multiplicity

High-multiplicity pp, proton-lead collisions

proton-proton (pp) collisions

lead-lead (Pb-Pb) collisions
The role of multiplicity

- 2 → 2 scatterings (LO)
- Soft physics: **multi-parton interactions** and initial and final state radiation
- MPI correlated via $b, Q^2$

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Somewhere in between…?

High-multiplicity pp, proton-lead collisions

kinematically and chemically equilibrated system: hydrodynamics and statistical principles

proton-proton (pp) collisions

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The role of multiplicity

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Disclaimer:
Multiplicity is not the only relevant variable! But let’s project on it for now...

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The role of multiplicity

How are relative particle species abundances determined? → chemistry

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The role of multiplicity

How are relative particle species abundances determined? → chemistry

How is momentum distributed? → kinematics

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Studying particle production in high-multiplicity pp and p-Pb collisions with ALICE
Specificity: low-momentum tracking and particle identification in a high-multiplicity environment
The ALICE Experiment at the LHC

**ITS** \((|\eta|<0.9)\)
- 6 Layers of silicon detectors
- Trigger, tracking, vertex, PID \((dE/dx)\)

**ITS standalone tracks**

**ALICE**

\(p_{T}\) range 10^{-1} - 10^{2} 

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**TPC** (|η|<0.9)
- Gas-filled ionization detection volume
- Tracking, vertex, PID (dE/dx)

ALICE has at its disposal practically all known particle identification techniques in a broad pT range.

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+ relativistic rise
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\[ \Xi^- \rightarrow \Lambda + \pi^- \]

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**TOF** ($|\eta|<0.9$)
- Multi-gap resistive plate chambers
- PID via velocity determination

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The ALICE Experiment at the LHC

- Event selection based on total charge deposited in the V0A and V0C detectors ("V0M")
- $\langle dN_{ch} / d\eta \rangle$ estimated as the average number of primary charged tracks in $|\eta| < 0.5$
Identified particle spectra in pp and p-Pb

In proton-lead…

…and proton-proton: a very comprehensive set of measurements

Studying particle production in high-multiplicity pp and p-Pb collisions with ALICE
Strangeness production

- One of the original traces of the QGP
- Thermal production via gluon fusion in a QGP scenario
- $K^0_S$, $\Lambda$, $\Xi$ and $\Omega$ in Pb-Pb at 5.02 TeV:
  - Production wrt to $\pi$ enhanced
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  - Strangeness increases with multiplicity following a universal trend
  - Not described by PYTHIA

- How can this be achieved?

Particle production in the Lund model

- Hadronization can be described as the breakup of color flux tubes ("strings") with constant energy density / tension
- Standard PYTHIA with MPI: no increase of strangeness production
Particle production in the Lund model

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- Standard PYTHIA with MPI: no increase of strangeness production
- New development: in high-density conditions, strings may overlap to form color ropes
  - Increased tension → increase in s production!

C. Bierlich,
https://indico.cern.ch/event/732345/contributions/3024828/attachments/1668639/2676025/cbierlich.pdf
The statistical hadronization picture: Canonical suppression

- **Statistical Hadronization Models** (e.g. Thermus) can be used to describe relative particle species abundances
- In small systems and multiplicities:
  - strangeness must be exactly conserved
  - leads to suppression of open strangeness
- Effect depends on system size; SHM description holds over certain rapidity range $k$
  - From data, $k = 1.35 \pm 0.28$
- Description OK for strangeness

ALICE, Phys. Rev. C 99, 024906
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  - From data, $k = 1.35 \pm 0.28$
- Description OK for strangeness
  - But fails for $\phi$: net strangeness zero…
  - And fails for $K^*$: affected by post-hadronization effects (rescattering)

ALICE, Phys. Rev. C 99, 024906
Strangeness in EPOS 3:
The core-corona approach

- Hard scattering: parton “ladders”
- At time $\tau_0$ (before hadronization) strings divided into fluid (CORE) and escaping (CORONA) according to momenta and local density
  - Corona: string fragmentation (Lund)
  - Core: from time $\tau_0$ evolves as a viscous hydrodynamic system. Hadronization happens statistically at a common $T_H$
- After hadronization: hadronic cascade model (UrQMD)
  - N.B.: droplet of QGP needed

K. Werner,
Modification of identified spectra

- Spectra become harder at higher multiplicities

ALICE, Phys. Rev. C 99, 024906

Spectra become harder at higher multiplicities

Studying particle production in high-multiplicity pp and p-Pb collisions with ALICE
Modification of identified spectra

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- The hardening is more pronounced for baryons than for mesons.

Studying particle production in high-multiplicity pp and p-Pb collisions with ALICE.
Modification of identified spectra

- Spectra become harder at higher multiplicities
- The hardening is more pronounced for baryons than for mesons
- (Multi-)strange baryons follow protons
  - Could the strangeness yield increase be a matter of \(<p_T>^*\)?
Proton to pion ratios

ALICE, Phys. Rev. C 99, 024906

Studying particle production in high-multiplicity pp and p-Pb collisions with ALICE
Proton to pion ratios

- Behavior known from Pb-Pb collisions
  - Interpreted as radial flow: p are pushed to a higher momentum
    - p are pushed to higher momenta by a common velocity field
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Studying particle production in high-multiplicity pp and p+Pb collisions with ALICE

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    - p are pushed to higher momenta by a common velocity field
  - Remarkable consistency across systems as a function of multiplicity
  - high p\_T: recovery of universal behavior?
Proton to pion ratios

- Behavior known from Pb-Pb collisions
- Interpreted as radial flow: p are pushed to a higher momentum
  - p are pushed to higher momenta by a common velocity field
- Remarkable consistency across systems as a function of multiplicity
- high $p_T$: recovery of universal behavior?
Proton to pion ratios vs MC predictions

ALICE, Phys. Rev. C 99, 024906

- **Color Reconnection:**
  - Implemented in PYTHIA8 Monash; hadronizing strings may be rearranged prior to fragmentation in a multiplicity-dependent way
  - Qualitative agreement with the behavior of the data

- **Collective Radial Expansion:**
  - Present in EPOS LHC
  - Includes a QGP droplet
  - Viable explanation but effect is overestimated

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EPOS LHC – T. Pierog et al., arXiv:1306.0121
Baryon to meson ratios: strangeness

- Similarities also seen in strangeness measurements
- Behavior in $\Lambda/K^0_S$ ratio for all systems a function of $N_{ch}$ only

Studying particle production in high-multiplicity pp and p-Pb collisions with ALICE
Baryon to meson ratios: strangeness $+$ charm

- Similarities also seen in strangeness measurements
- Behavior in $\Lambda/K^0_S$ ratio for all systems a function of $N_{\text{ch}}$ only

- May also be present in charm measurements in pp and p-Pb?
  - Multiplicity-differential analysis pending…
Baryon to meson ratios: strangeness + charm

- May also be present in charm measurements in pp and p-Pb?
  - Multiplicity-differential analysis pending...
- Charm production always produced in initial hard scattering, not in string breaking
  - Describing baryon production problematic
Beyond multiplicity: event shape studies

- A proton-proton interaction produces particles in
  - Jets from a (few) initial hard scattering(s)
  - A (softer) underlying event (UE): ‘the rest’

- These two can be studied more closely! A possibility: spherocity $S$

![Diagram of proton-proton interaction producing particles with jets and underlying event](image)

**Graphical Representation**

- **ALICE Simulation**
  - PYTHIA 8.212 (Monash 2013)
  - $\sqrt{s} = 7$ TeV

**Spherocity classes**

- (More than two charged particles)
  - $|\eta| < 0.8, N_{ch} \geq 15$
  - 0-10%
  - 10-20%
  - 20-30%
  - 30-40%
  - 40-50%
  - 50-60%
  - 60-70%
  - 70-80%
  - 80-90%
  - 90-100%

**High S:**
- Soft QCD-like, azimuthally isotropic, enhanced UE

**Low S:**
- Hard QCD-like, e.g. dijets

Studying particle production in high-multiplicity pp and p-Pb collisions with ALICE
The proton-to-pion ratio in jets and the UE

Dominated by jet-like behavior: baseline
Dominated by UE: (de/in)crease at (low/mid)-p_T?
The proton-to-pion ratio in jets and the UE

- The same idea can be explored using full jet reconstruction in pp
- Leads to consistent picture for $\Lambda/K^0_S$ correlated with jets and UE:
  - Baryon/meson peak from UE dynamics
  - Constraint on phase space of relevant effect

Studying particle production in high-multiplicity pp and p-Pb collisions with ALICE
Characterizing strangeness production

• Many effects can cause an increase in strangeness production…
  • How can we distinguish them?

• A first idea (C. Bierlich): look into e.g. the $\Omega/\pi$ ratio in events that contain a $\phi$ meson
  • Default string fragmentation: $\Omega$ suppressed
  • Ropes: increased tension, $\Omega$ enhanced
  • How would other models compare?

• Other ideas?

• “Beyond multiplicity” → statistics-hungry!
  • Data is/will be there…

C. Bierlich,
https://indico.cern.ch/event/732345/contributions/3024828/attachments/1668639/2676025/cbierlich.pdf
Completing the picture:

Studying Xe-Xe collisions
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- Universality of $p_T$-differential ratios again confirmed
- Important piece of the puzzle: radial flow scales with $dN/d\eta$
Completing the picture: Studying Xe-Xe collisions

Consequence of initial anisotropy

Collective expansion: Modulation in azimuth

- Universality of $p_T$-differential ratios again confirmed
- Important piece of the puzzle: radial flow scales with $dN/d\eta$ but elliptic flow does not?...
Completing the picture: Studying Xe-Xe collisions

- Results from Xe-Xe at 5.44 TeV confirm that multiplicity is the key variable for relative particle abundances.
Completing the picture: Studying Xe-Xe collisions

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- Can we study the onset of saturation? (does it always take place?)

Studying particle production in high-multiplicity pp and p-Pb collisions with ALICE Preliminary Pb-Pb, pp, Xe-Xe, 200 pb−1 at 5.44 TeV

Multiplicty slicing with mid-rapidity estimator

ALICE Upgrade projection

Multiplicty slicing with mid-rapidity estimator
Completing the picture: Studying Xe-Xe collisions

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O-O collisions: Run 3+4
Summary and outlook

- Comprehensive measurements show: **multiplicity is a key variable** when comparing pp, p-Pb, Xe-Xe and Pb-Pb
  - hadrochemistry, particle ratios: similar
  - Kinematics: not necessarily
- Fundamental constraints to theory
Summary and outlook

• Comprehensive measurements show: **multiplicity is a key variable** when comparing pp, p-Pb, Xe-Xe and Pb-Pb
  • hadrochemistry, particle ratios: similar
  • Kinematics: not necessarily
• Fundamental constraints to theory

• How can models be **reconciled and distinguished**?
  • (To) QGP or not (to) QGP?
• More development needed: baryon production mechanisms? Consider LF and HF information together?
• A lot more ahead!

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Thank you!