Event-shape, multiplicity-, and energy-dependent production of (un)identified particles in pp collisions with ALICE at the LHC

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Motivation

ALICE at the CERN LHC is optimized for heavy-ion physics

→ Also, **important contributions** to the LHC **pp physics** program
→ Provides baseline for the measurements of heavy ions

1) **Studies of particle production** at high energies in pp collisions aim

- to constrain fragmentation functions (Ref. Daniel de Florian *et. al*, Phys. Rev. D 95, 094019)
  in perturbative *QCD calculations* based on the factorization theorem
  → “**hard**” scattering regime
- to constrain *phenomenological (Monte Carlo) models*
  → “**soft**” scattering regime
Motivation

2) Understanding collective-like effects seen at 7 TeV:
smooth evolution of yield ratios in p–Pb and Pb–Pb collisions

Study the evolution of particle production with the center-of-mass energy ($\sqrt{s}$) and multiplicity by measuring identified particle production

→ To disentangle the energy and multiplicity dependences, for a given multiplicity class, the $p_T$ distributions are measured at new collision energies of 5.02 TeV and 13 TeV
Motivation

2) **Understanding collective-like effects** seen at 7 TeV:
smooth evolution of yield ratios in p–Pb and Pb–Pb collisions

Study the evolution of particle production with the center-of-mass energy ($\sqrt{s}$) and multiplicity by measuring identified particle production

3) Using the observable *transverse spherocity*

- to differentiate between soft and hard scattering domains of particle production
- to investigate the importance of jets in high multiplicity pp collisions
The ALICE apparatus

THE ALICE DETECTOR

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Muon Trigger
15. Dipole Magnet
16. PMD
17. AD
18. ZDC
19. ACORDE

• Trigger and event characterization:
  V0A and V0C: forward/backward detectors
• Measurement of charged-particle multiplicity:
  1) “V0M” estimator (V0A“+”V0C):
     → to avoid auto-correlation bias, we measure the multiplicity via slices of percentiles of V0M amplitudes
  2) Mid-rapidity (|η|<0.8) estimator (SPD tracklets) applied in the analysis of charged particles
Results I.

Transverse momentum ($p_T$) spectra of (un)identified hadrons as a function of collision energy and charged-particle multiplicity
**$p_T$ spectra of identified hadrons in INEL pp collisions**

New: LHC Run 2

**ALICE Preliminary**

$\sqrt{s} = 5.02$ TeV (INEL)

- $\pi^+ + \pi^-$
- $K^+ + K^-$
- $p + \bar{p}$

Normalization uncertainty 2.51%

Uncertainties: stat. (bars), sys. (boxes)

$\sqrt{s} = 13$ TeV

$\sqrt{s} = 5$ TeV

ALICE Preliminary

pp $\sqrt{s} = 13$ TeV (INEL), $|y| < 0.5$

Normalisation uncertainty: 2.55%

- $\pi^+ + \pi^-$
- $K^+ + K^-$
- $K_S^0$
- $p + \bar{p}$ ($\times 2$)
- $\Lambda + \bar{\Lambda}$ ($\times 2$)
- $K^{*0} + \bar{K}^{*0}$ ($\times 2$)
- $\phi$ ($\times 2$)
- $\Xi^- + \bar{\Xi}^+$ ($\times 2$)
- $\Omega^- + \bar{\Omega}^+$ ($\times 2$)

ALI-PREL-130556
Energy dependence of $p_T$-spectra

1) Progressive hardening of the spectra with increasing $\sqrt{s}$
2) Ratios of spectra at different $\sqrt{s}$ evidence the two different $p_T$ ranges:
   - soft regime ($p_T < 1$ GeV/$c$): small increase with little or no $p_T$ dependence
   - hard regime (at high $p_T$): very significant dependence on $\sqrt{s}$

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**New: LHC Run 2**
Energy dependence of $p_T$-differential particle ratios

1) Kaon-to-pion ratios:
   - No $\sqrt{s}$ dependence observed within uncertainties

2) Proton-to-pion ratios:
   - For $p_T < 10$ GeV/c: modest $\sqrt{s}$ dependence is seen
   - In the intermediate $p_T$ region the peak with increasing $\sqrt{s}$ shifts towards higher $p_T$
   - For $p_T > 10$ GeV/c: no evidence of evolution with $\sqrt{s}$ within uncertainties
$p_T$ spectra of **unidentified** charged hadrons

as a function of **charged-particle multiplicity**

New:

LHC Run 2
$p_T$ spectra of **unidentified** charged hadrons as a function of **charged-particle multiplicity**

New: LHC Run 2

Ratios to minimum bias (INEL>0)

→ spectra become harder as the multiplicity increases

→ $p_T < 1$GeV/c: the ratios are flat

→ $p_T > 1$GeV/c: the ratios exhibit a strong dependence on $p_T$ (more pronounced towards higher multiplicities)

**Mid-rapidity estimator**

**“V0M” estimator**
$p_T$ spectra of identified hadrons as a function of charged-particle multiplicity

1) $p_T$ spectra become **harder** as the multiplicity increases

2) Ratio to MB (INEL>0): above $p_T = 2\text{GeV/c}$ only modest change with charged-particle multiplicity

3) Similar results have been reported for (multi-)strange hadrons at QM 2017
**Multiplicity dependence of $p_T$-differential particle ratios**

**Kaon-to-pion ratios:**
- No apparent modifications is observed in the reported multiplicity classes
- Result is compatible with the observations reported at 7 TeV

**Proton-to-pion ratios:**
- A characteristic depletion is observed at high multiplicity and at low $p_T$ values
- Enhancement at intermediate $p_T$ => consistent with the presence of an expanding medium (radial-flow)
- Particle dynamics is similar to p–Pb and Pb–Pb systems
Results II.

Yield $dN/dy$ and average transverse momentum of identified hadrons

as a function of collision energy and charged-particle multiplicity
15

Smooth evolution across different collision systems

→ hadrochemistry is dominantly driven by charged-particle multiplicity

- Soft particle production in pp collisions is similar to that in p-Pb and Pb-Pb collisions
Integrated hadron yields

as a function of charged-particle multiplicity

Study the validity of multiplicity scaling at different collision energies

New: LHC Run 2 – 13 TeV

Hadrochemistry is dominantly driven only by the charged-particle multiplicity

Same patterns observed for 7 and 13 TeV at similar multiplicity

Energy scaling property applies for the yields of \( \pi^+ \), \( K^+ \), and \( p \) → similar observation for (multi-)strange hadrons
Average transverse momenta as a function of charged-particle multiplicity

- Average $p_T$ for $\pi^+$, $K$ and $p$ indicates a **hardening** going from 7 to 13 TeV at comparable multiplicities.

- Similar trends are seen for (multi-)strange hadrons and for all charged hadrons at lower collision energies.

Scaling with multiplicity is **not valid** → similar observation for (multi-)strange hadrons.
Results III.

(Un)identified particle production as a function of transverse spherocity ($S_0$) in high-multiplicity pp collisions at 13 TeV
Investigations of particle production using event shapes

- **Aim:** Study the importance of jets in high multiplicity pp collisions
- **Tool:** Transverse spherocity (to isolate “jetty”-like and “isotropic” events associated with underlying event (UE) suppressed or enhanced activity)

![Diagram](image)

By definition, transverse spherocity is sensitive to soft physics:

$$ S_0 \equiv \frac{\pi^2}{4} \min_{\hat{n}_s} \left( \frac{\sum_i^{N_{\text{ch}}} |\vec{p}_{T,i} \times \hat{n}_s|}{\sum_i^{N_{\text{ch}}} p_{T,i}} \right)^2 $$

“Jetty”: $S_0 = 0$, “Isotropic”: $S_0 = 1$

- **Collective effects evidenced in the soft QCD regime**
  → event shape observables are ideally suited to better distinguish the underlying physics of a pp collision

- **For the studies of (un)identified particles, events are selected:**
  with more than (2) 10 charged particles within $|\eta| < 0.8$ and $p_T > 0.15$ GeV/c
  → to minimize sensitivity to particle loss
Unidentified particle production – average $p_T$ vs multiplicity and spherocity

- **For jetty events:**
  steeper rise, systematically larger $\langle p_T \rangle$ as compared to the 0 – 100% ($S_0$-unbiased) case → expected from jet production

- **For isotropic events:** systematically lower $\langle p_T \rangle$ than the $S_0$-unbiased case

- **So-integrated results:** consistent to measurements at lower collision energies → No apparent energy dependence observed

- **Model comparison:** $S_0$-unbiased (0 – 100% $S_0$)
  → PYTHIA and EPOS-LHC models describe well the data (EPOS-LHC: small deviation at low $N_{ch}$)
PYTHIA and EPOS LHC describe the $<p_T>$ evolution moderately well (minor deviations for EPOS at very low $N_{ch}$)

- PYTHIA overestimates $<p_T>$ for all $N_{ch}$ (the contribution of underlying event is significantly underestimated)
- EPOS LHC gives the best description (overestimate the rise of $<p_T>$ at low multiplicities, it agrees very well with the data for $N_{ch} > 15$)
**Identified particle spectra as a function of multiplicity and spherocity**

- **Only** the 10% highest V0M multiplicity events are considered
  
  → 97% of the events have at least ten charged tracks

- 20% of events with the highest (lowest) measured $S_O$
  
  → **isotropic**, $0.76 < S_O < 1$  
  (jetty, $0 < S_O < 0.46$)

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New: LHC Run 2
13 TeV
Identified particle spectra as a function of multiplicity and spherocity

→ Isotropic events: spectra are enhanced at low $p_T$ (compared to $S_o$-unbiased) and suppressed for $p_T > 2.5$ GeV/c for $\pi^+ \pi^-$ and $K^+ K^-$

→ Jetty events: spectra are suppressed at low $p_T$ and enhanced at intermediate $p_T$

→ Crossing of “jetty” and “isotropic” spectra: increase towards larger $p_T$ for heavier particles

=> mass-dependent spectral modifications
Identified particle ratios as a function of multiplicity and spherococity

**Isotropic events:**
- Kaon-to-pion ratio: consistent with those measured in the $S_0$-unbiased case.
- Proton-to-pion ratio: apparent shift in $p_T$, similar to the multiplicity dependent modifications; collective-like effects can be further enhanced.

**Jetty events**
- Kaon-to-pion ratio: signatures of a suppression.
- Proton-to-pion ratio: suppression can be attributed to the production mechanisms of protons in jets.
Comparison to models
Particle ratios as a function of multiplicity and spherocity

**Ratios to $S_0$ unbiased (V0M class I – III)**

- **Kaon-to-pion ratios (left)**
  - Double ratios are well-described by both PYTHIA 8 and EPOS-LHC generators (only fragmentation)

- **Proton-to-pion ratios (right):**
  - PYTHIA 8: predicts the observed trends, but underestimates the magnitude of the modification
  (Similar to evolution of average $p_T$
  - Deviation might originate from underestimated underlying event)
  - EPOS-LHC:
    - Double ratio is described the best
    - Absolute ratio: further tuning is needed
Summary

Light-flavor hadron production studied as a function of

- $\sqrt{s}$ and charged-particle multiplicity $N_{ch}$
  $\rightarrow p_T$-spectra and particle ratios exhibit a clear evolution with $N_{ch}$
  $\rightarrow p_T$-integrated hadron yields scales with $N_{ch}$ across different $\sqrt{s}$ and colliding systems: hadrochemistry is dominantly driven by multiplicity
  $\rightarrow$ Average $p_T$ grows with $\sqrt{s}$ at similar $N_{ch}$: dynamics of particle production might be different at different $\sqrt{s}$

- $\sqrt{s}$ and charged-particle multiplicity $N_{ch}$ and transverse spherocity $S_0$
  $\rightarrow$ Particle ratios: collective-like effects can be controlled with transverse spherocity
  $\rightarrow$ Average $p_T$ is larger (smaller) in jetty (isotropic) events hinting at different dynamics of particle production

Microscopic (Pythia 8, DIPSY) and macroscopic (EPOS-LHC) models describe several aspects of data; in most cases EPOS-LHC does a better job.

Thank you for your attention!

Gyula Bencedi (Wigner RCP, Hungary)
Backup slides
A Large Ion Collider Experiment (ALICE) at the LHC

- ALICE at the LHC is optimized for heavy-ion physics
- ALICE aims to study the formation of the strongly interacting QCD matter, the Quark-Gluon Plasma (QGP) created in high energy heavy-ion collisions

Time evolution of the matter produced in heavy-ion collision

- Hot and dense system is created by colliding heavy ions (Pb ions)
  - high energy density ($>> 1$ GeV/fm$^3$) over large volume ($>> 1000$ fm$^3$)

- Transition from nuclear matter into deconfined phase at high $T$
- Collective expansion of the system $\rightarrow$ multiple interactions of partons
- Chemical freeze-out ($T_{ch}$)
  - end of inelastic scatterings
- Kinetic freeze-out ($T_{f_0}$)
  - end of elastic scatterings

Thermal model:
- Particles in HI collisions are produced in apparent chemical equilibrium
- Description based on thermal-statistical models
- Particle abundances $\propto \exp(-m/T_{ch})$ with $T_{ch}$ being $\sim 156$ MeV
Particle Identification in ALICE

- Tracking + standalone reconstruction: PID via dE/dx from SDD and SSD
- Standalone tracking in the low-\(p_T\) region (down to 100 MeV/c)

- PID via velocity measurement in the intermediate momentum region

- Track-by-track ID (n-\σ cut) in the \(1/\beta^2\) region
- PID in the relativistic rise using a statistical approach

- PID using RICH technique in the intermediate momentum region on a track-by-track basis
Measurement of light flavor particle $p_T$-spectra

- **Primary particles** \([1]\): particle with $c\tau > 1$ cm, which is either a) produced directly in the interaction, or b) from decays of particles with $c\tau < 1$ cm, restricted to decay chains leading to the interaction – that is to the primary collision.

- **Long-lived particles**
- **Topological identification of weakly-decaying strange hadrons**

- **Invariant-mass**

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<table>
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<tr>
<th>Particle</th>
<th>Valence Content</th>
<th>Mass (MeV/$c^2$)</th>
<th>$c\tau$ (fm)</th>
<th>Decay</th>
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<td>$\pi^+$</td>
<td>ud</td>
<td>139.57</td>
<td>7.8</td>
<td>$\pi^+ + \pi^-$</td>
</tr>
<tr>
<td>$K^+$</td>
<td>us</td>
<td>493.68</td>
<td>3.7</td>
<td>$K^+ + K^+$</td>
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<tr>
<td>$K^{0}_S$</td>
<td>$1/2(d\bar{s} + s\bar{d})$</td>
<td>497.61</td>
<td>2.68</td>
<td>$K^{0}_S + \pi^+ + \pi^-$</td>
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<tr>
<td>$K^{*0}$</td>
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<td>4.16</td>
<td>$K^{*0} + \pi^+ + \pi^-$</td>
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<td>1672.45</td>
<td>2.46</td>
<td>$\Omega^- + p + \pi^-$</td>
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</tbody>
</table>

\[1\] ALICE-PUBLIC-2017-005, The ALICE definition of primary particles
Similarities among different colliding systems

Low-$p_T$: < 2 GeV/c; Mid-$p_T$: 2 < $p_T$ < 10 GeV/c; High-$p_T$: > 10 GeV/c
Light flavor particle $p_T$-spectra in $pp$

$\sqrt{s} = 7$ TeV

- Events classified according to event activity measured in the backward/forward region (by “V0M” estimator), in order to avoid auto-correlation biases.

- Charged-particle multiplicity measured at mid-rapidity for each event class

“V0M” multiplicity classes:

- Inclusive
  $\rightarrow (dN/d\eta)_{INEL > 0} \approx 6.0$

  $I \rightarrow dN/d\eta \approx 3.5 \times (dN/d\eta)_{INEL > 0}$

  $X \rightarrow dN/d\eta \approx 0.4 \times (dN/d\eta)_{INEL > 0}$
\( \sqrt{s} = 7 \text{ TeV} \)

**Light flavor particle \( p_T \)-spectra in pp**

**Evolution of spectral shapes with multiplicity**

- **High Multiplicity**
  \[ \sim 3.5 \times (dN/d\eta)_{\text{INEL} > 0} \]
  Flattening at high \( p_T \)

- **Low Multiplicity**
  \[ \sim 0.65 \times (dN/d\eta)_{\text{INEL} > 0} \]
  Flattening at Low \( p_T \)

- **Mass-dependent hardening with increasing event multiplicity**
  → hardening for baryons more pronounced than for mesons

- **In Pb–Pb**: change in spectral shape interpreted in terms of collective expansion of a locally thermalized system
$\sqrt{s}$ dependence: $p_T$-integrated particle ratios

- Saturation in K-to-pion and p-to-pion ratios observed in the LHC-energy regime
- Hint of modest increase of hyperon-to-pion ratio with increasing $\sqrt{s}$
- Can one factorize this increase to be only a function of $\langle dN_{ch}/d\eta \rangle$ regardless of $\sqrt{s}$?
$\sqrt{s}$ dependence: $\langle dN_{\text{ch}}/d\eta \rangle$

- $\langle dN_{\text{ch}}/d\eta \rangle$ follows a power law behavior as a function of $\sqrt{s}$
- Only modest change (factor of < 2) in $\langle dN_{\text{ch}}/d\eta \rangle$ over 1 order of magnitude increase in $\sqrt{s}$ (0.9 TeV → 13 TeV)
- Evolution of hyperon-to-pion ratios are consistent with the increase observed in $\langle dN_{\text{ch}}/d\eta \rangle$
- Is hadrochemistry dominantly driven by $\langle dN_{\text{ch}}/d\eta \rangle$?

**An event-multiplicity differential study is performed**

- “V0M” estimator is used to slice in percentiles of multiplicity
- $\langle dN_{\text{ch}}/d\eta \rangle$ restricted to $|\eta|<0.5$ represents the average number of charged primary particles at midrapidity
Particle production at high $p_T$: multiplicity dependence of the power-law exponent

- **Low multiplicity:**
  $\rightarrow$ plateau observed regardless of used multiplicity estimator and collision energy

- **High multiplicity:**
  $\rightarrow$ mid-rapidity estimator: decreasing trend towards higher multiplicities

  $\rightarrow$ nonlinearity: similar result seen at lower energy and for identified particles
Relative yields of charged particles as a function of V0M and tracklets multiplicity estimators, pp at 5.02 and 13 TeV

New: LHC Run 2
Multiplicity dependence: strange hadron production at different $\sqrt{s}$

Hadrochemistry is driven by multiplicity rather than $\sqrt{s}$
Significant enhancement of strange to non-strange hadron production is observed with increasing particle multiplicity in pp.

Similar behavior to that observed in p–Pb (both in terms of values and trend with multiplicity).

Similar values reached in high-multiplicity pp, p–Pb, and peripheral Pb–Pb collisions (having at similar multiplicities).

Baryon-to-meson ratios (with same strangeness content) but different masses

- No significant change with multiplicity
- → Strangeness enhancement is neither due to the difference in the hadron masses nor due to baryon nature of the particle

Monte Carlo comparison

- DIPSY \([2]\) with color ropes describes qualitatively best the increase of strange particles, but fails to describe the p/\(\pi\) ratio
- EPOS describes the evolution qualitatively

The multiplicity-dependent enhancement follows a hierarchy determined by strangeness content of the hadron.

Ω (sss)
Ξ (dss)
Λ (uds)