Recent results* from the ALICE experiment

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for the ALICE Collaboration

* a biased selection
ALICE overview

• **Design considerations**
  – High multiplicity environment
    • see next picture
  – Particle identification (PID)
  – Low $p_T$ coverage ($B = 0.5$ T)

• **Datasets**

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Pb-Pb (2010)</td>
<td>2.76 TeV</td>
<td>10 $\mu$b</td>
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<tr>
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<td>2.76 TeV</td>
<td>0.1 nb</td>
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<tr>
<td>pp (2010)</td>
<td>7 TeV</td>
<td>11 nb-1</td>
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<td>pp (2011)</td>
<td>7 TeV</td>
<td>4.8 pb-1</td>
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<tr>
<td>pp (2012)</td>
<td>8 TeV</td>
<td>9.7 pb-1</td>
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<tr>
<td>p-Pb (2013)</td>
<td>5.02 TeV</td>
<td>15 nb</td>
</tr>
<tr>
<td>Pb-p (2013)</td>
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<td>15 nb</td>
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Light flavour hadrons and (anti-)nuclei
Production of light flavour hadrons

• Thermal model fits
• Measurements of Nuclei
  – $^3$He and hypertriton ($^3\Lambda$H)
  – $\bar{\alpha}$ observation
  – Limits on exotic di-baryon particle production
A Large Ion Collider Experiment

Statistical model for particle yields

- $dN/dy$ of particle species well described in Pb-Pb
- Single temperature ~156 MeV
- Discrepancy $K^*$ and $p$
  - evidence for interactions with final hadronic stage

| Particle                | $dN/dy$ | ALICE Preliminary
<table>
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<tbody>
<tr>
<td>$\pi^+\pi^-$</td>
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<tr>
<td>$K^+K^-$</td>
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</tr>
<tr>
<td>$K^0\bar{K}^0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^+\bar{K}^-$</td>
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<tr>
<td>$p+p$</td>
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<tr>
<td>$\Lambda$</td>
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<tr>
<td>$\Omega+\bar{\Omega}$</td>
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<tr>
<td>$d$</td>
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<tr>
<td>$\frac{3}{2}H+\frac{3}{2}H$</td>
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<tr>
<td>$\frac{3}{2}He$</td>
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<table>
<thead>
<tr>
<th>Model</th>
<th>$T$ (MeV)</th>
<th>$V$ (fm$^3$)</th>
<th>$\chi^2$/NDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSI-Heidelberg</td>
<td>156 ± 2</td>
<td>5330 ± 505</td>
<td>17.4/9</td>
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</tbody>
</table>

ALI-PREL-75448
**K* suppression with centrality**

- K*/K ratio shows clear suppression going from peripheral and pp collisions to central Pb-Pb
- ϕ/K does not show this
  - also others not shown
- Favoured explanation is re-scattering of decay daughters with final state hadrons
  - \( T_{K^*} \sim 4 \text{ fm/c} \)
Light nuclei measurements

Pb-Pb, 2011 run, $\sqrt{s_{NN}} = 2.76$ TeV

TPC ionization signal (a.u.)

$\frac{p}{Z}$ (GeV/c)
\(^3\)He measurement

- Measurements over large \(p_T\) range
- Fits with overall model of hydrodynamic expansion

\[
\frac{1}{N_{ev}} \frac{d^2N}{d^2p_T} ((GeV/c)^2)\]

ALICE preliminary

\[^3\text{He}\]

\begin{align*}
\text{Pb-Pb, } \sqrt{s_{NN}} = 2.76 \text{ TeV} \\
\text{0-20\%} & \quad \text{20-80\%} \\
\text{blast-wave fits} & \\

\end{align*}
Hypertriton measurement

- Extracted $^3_\Lambda$H signal
- Branching ratio not well known

- Described in thermal model even though weakly bound $B_\Lambda = 130$ keV
- Favours equilibrium model
\( \bar{\alpha} \) production

- First observed in heavy-ion collisions at RHIC
- ALICE measures in defined centrality interval to compare to other light nuclei
Exotic di-baryon limits

- Success of thermal model encouraged searches for other states
- H-dibaryon ($\Lambda-\Lambda$)
- Bound state ($\Lambda-N$)
- Weak decay modes
- 99% limits are factor of ~10 below the predictions
Momentum spectra, nuclear modification factors and $p_T$-dependent
Momentum spectra

- Pb-Pb and p-Pb compared
- low-$p_T$
- mid- to high-$p_T$
- $R_{pPb}$, Cronin, no high-$p_T$ enhancement
- ie no effects from nuclear p.d.f2
Charged particle nuclear modification factor

\[ R_{pPb} = \frac{dN_{pPb}/dp_T}{N_{coll} dN_{pp}/dp_T} \]

- ALICE finds no evidence for \( R_{pPb} \neq 1 \) at high \( p_T \)

![Graph showing charged particle nuclear modification factor](image-url)
R_{pPb} high-p_T comparisons

- CMS and ATLAS see rise to values > 1
- However jets do not show this rise
- Need more data including $\sqrt{s}=5$ TeV pp collisions
“Cronin” enhancement - identified particles

- Enhanced production at moderate $p_T$ (~3 GeV/c)
- First observed, at lower $\sqrt{s}$, Cronin et al PRD 11, 3105 (1975)
- Traditionally explained by multiple soft scattering prior to hard interaction
“Cronin” enhancement - identified particles

- Effect absent for $\pi$, larger for $p$
“Cronin” enhancement

- Effect absent for $\pi$, larger for $p$
- K are very close to $\pi$
- Clear mass-dependence to effects
“Cronin” enhancement

- Apparently reaches even higher values for $\Xi$
- Mass ordering reminiscent of collective behaviour (hydrodynamics?)

\[ R_{p\text{Pb}} \]
**R_{pPb} of \phi at mid-rapidity**

- However...
- \( m_{\phi} > m_p \) so this is not following this trend
\( R_{pPb} \) of \( \phi \) away from mid-rapidity

- \( \phi \) is the only particle for which we can perform measurements at different rapidities, via \( \mu \mu \) channel
- Picture is obviously more complicated
Possible collective effects

- Investigate collective effects
- $p_T$ dependent particle ratios have centrality dependence in Pb-Pb …
- … and also a multiplicity dependence in p-Pb
Particle ratio in jets

• Investigate role of hard and soft mechanisms in the enhancement

• Ratio \((\Lambda+\bar{\Lambda})/2K_s\) measured in jets with \(\sum p_T\) charged > 10 GeV/c

\[ \frac{\Lambda^0 + \bar{\Lambda}^0}{2K_s} \]

\[ p_{T,V} > 10 \text{ GeV/c}, \ anti-k_T \]

\[ |\eta_{\text{jet}}| < 0.75 - R, |\eta| < 0.75 \]

\[ s_{NN} = 5.02 \text{ TeV} \]

0-10%, V0A Multiplicity Class (Pb-Side)

ALICE Preliminary

ALI-DER-89401
Further interesting results (in brief)
Ultra peripheral collisions (b>2r)
• LHC as γPb, γp and γγ collider to study
  – (Pb-Pb) exclusive vector meson (J/ψ) cross sections to investigate the gluon distribution in the nuclei
  – (Pb-Pb) results agree with EPS09 gluon distribution, favouring the presence of gluon shadowing
  – (Pb-Pb) ψ’ vector meson photo-production measured
  – (Pb-Pb) γγ cross section constraints QED processes

• 3 ALICE papers
  – arXiv:1406.7819, accepted PRL (J/ψ photo-production off protons in ultra-peripheral p-Pb collisions)
Quantum Coherence

• Extend $\pi\pi$ interferometry (HBT, aka femtoscopy) to 3- and 4-pion correlations
  – Increased sensitivity to coherent emission
• Measure $r_3$ ratio of $3\pi$ to $2\pi$ quantum correlations
• extrapolate $Q3 \rightarrow 0$
• fully chaotic means $r_3$

$P_{RC\ 89\ (2014)\ 024911}$

$\frac{r_3}{Q_{3}} = c_{3}(Q_{3}) - 1 \sqrt{(C_{2}^{2}\ QS_{12}(Q_{12}) - 1)(C_{2}^{2}\ QS_{13}(Q_{13}) - 1)(C_{2}^{2}\ QS_{23}(Q_{23}) - 1)}$
Summary

• ALICE measurements in Pb-Pb imply a picture where:
  – overall particle yields, even rare ones, closely match statistical thermal model
  – momentum spectra (and their harmonic decomposition) support collective effects described by hydrodynamics
  – hadrons at high-$p_T$ from partons fragmentation are suppressed, regardless of colour charge

• p-Pb collisions show several surprising features analogous to Pb-Pb

• Heavy-ion collisions can serve as a laboratory for interesting physics not directly related to the quark gluon plasma
Backup
Statistical model - pp collisions

\[ \frac{\pi^+ + \pi^-}{2}, \frac{K^+ + K^-}{2}, K^0, \frac{K^+_s + K^-_s}{2}, \phi, \frac{p + \bar{p}}{2}, \Lambda, \frac{\Xi^+ + \Xi^-}{2}, \Omega + \bar{\Omega}, d, \frac{^3H + ^3H}{2}, ^3\text{He} \]

\[ dN/dy \]

Not in fit

ALICE Preliminary
pp \( s = 7 \) TeV

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<tr>
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<th>V (fm)</th>
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<td>146 ± 2</td>
<td>25 ± 2</td>
<td>1 (fix)</td>
<td>78.2/7</td>
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<td>150 ± 2</td>
<td>23 ± 2</td>
<td>0.88</td>
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\[ \frac{\text{(mod.-data)} - \text{mod.}}{\text{mod.}} \]

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ALI-PREL-74533
$\bar{\alpha}$ extraction with TOF

ALICE preliminary
Pb-Pb $\sqrt{s_{\text{NN}}} = 2.76$ TeV
negative particles

$\frac{p}{Z}$ (GeV/c)