Hadron Physics with ALICE at the LHC

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ALICE Physics Programme

• Characterize the quark gluon plasma, a deconfined state of matter at high temperatures

• Formed in heavy-ion collisions at the LHC
  – Temperature of the order $10^{12}$ K or $\sim 1$ GeV

• (Almost) all observations rely on the detection of final state hadrons
  – i.e. pions, kaons, protons, hyperons …
A Pb-Pb collision

Over 2000 particles can leave tracks in the detector
Schematic of the collision evolution
ALICE Detector

Time Projection Chamber (TPC)

Time-of-flight barrel (TOF)
ALICE Particle Identification

- In TPC gas, energy loss vs momentum
- Time of flight vs momentum
Hadron Physics

• How and where can ALICE contribute to **hadron physics**?

• Final hadronic yields described by a statistical model with minimal parameters
  – includes also light nuclei
Thermal model

- Model(s) describe hadron yields over several orders of magnitude.
- $T \approx 156$ MeV.
- Deviations typically less than $2\sigma$ and/or 20%.
Hadron Physics

• How and where can ALICE contribute to hadron physics?
• Final hadronic yields described by a statistical model with minimal parameters
  – includes also light nuclei

• ‘Factory’ for antimatter and hypernuclei
• Hadron phase with many hadronic interactions
LHC Heavy-ion collisions as an anti-matter and exotic hadron factory
Nuclei and anti-nuclei detection

\[ \frac{dE}{dx_{TPC}} \text{ (a.u.)} \]

\[ \text{p/z (GeV/c)} \]

\[ ^4\text{He} \quad ^3\text{He} \]

\[ 10^2 \quad 10^3 \]

\[ \text{ALICE} \]

\[ \text{Pb-Pb, } \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

\[ 2011 \text{ data taking} \]
Nuclei production – momentum dependence

- Both d and $^3$He transverse momentum spectra measured for different centrality (system size)
- Shows that they participate in collective dynamics
Nuclei production – mass dependence

• Production follow an exponential decrease
  – Predicted by simple thermal model

• In Pb-Pb collisions ‘penalty factor’ for adding one baryon is ~300
  – In p-Pb ~600
Mass Difference between light nuclei and anti-nuclei

\[ \frac{\Delta \mu}{\mu} = [-1.2 \pm 0.9 \text{ (stat.)} \pm 1.0 \text{ (syst.)}] \times 10^{-3} \]

\[ \frac{\Delta \mu}{\mu} = [0.9 \pm 0.5 \text{ (stat.)} \pm 1.4 \text{ (syst.)}] \times 10^{-4} \]

- Highest precision direct measurements of mass differences in the nuclei sector
- One to two orders of magnitude improvement over the results from 40+ years ago

*Nature Phys. 11 (2015) 811*
Mass Difference between light nuclei and anti-nuclei

\[ \Delta \varepsilon_{A\bar{A}} = Z \Delta m_{p\bar{p}} + (A - Z) \Delta m_{n\bar{n}} - \Delta m_{A\bar{A}} \]

\[ \frac{\Delta \varepsilon}{\varepsilon} = -0.04 \pm 0.05 \text{ (stat.)} \pm 0.12 \text{ (syst.)} \quad d-\bar{d} \]

\[ \frac{\Delta \varepsilon}{\varepsilon} = 0.24 \pm 0.16 \text{ (stat.)} \pm 0.18 \text{ (syst.)} \quad ^{3}\text{He}-^{\bar{3}}\text{He} \]

- Constraint improved by factor 2 for deuteron case
- First \( \Delta \varepsilon \) determination for \(^{3}\text{He}\)

*Nature Phys. 11 (2015) 811*
CPT Experimental Tests

- Comparison of experimental limits for different possible CPT violating sectors
- Additional tests since 2015 include anti-hydrogen charge and 1s-2s transition
Hypertriton $^3\Lambda H \rightarrow ^3\text{He} + \pi^-$

- Lightest hypernucleus: $pn\Lambda$
- Reconstruct weak decay with displaced vertex

- Small binding energy, $\Lambda$ separation energy
  - $130\pm50$ keV
Hypertriton model comparison

- Branching ratio (B.R.) not so well determined
- Shows yield \( \times \) B.R. vs B.R. around preferred value of 25%
- Equilibrium model with \( T=156 \) MeV gives consistent description

\[ {}_\Lambda^3H \rightarrow {}^3\text{He} + \pi^- \]

\[ \text{Pb-Pb} \quad s_{NN} = 2.76 \text{ TeV} \]

\[ 0-10\% \text{ centrality} \]


\[ \text{ALICE} \]

\[ dN/dy \times \text{B.R.} \]

\[ 10^{-4} \]


\[ \text{Hybrid UrQMD Model} \]

\[ \text{GSI - Heidelberg} \]

\[ \text{SHARE} \]

\[ \text{Thermal models} \]


Hyperttriton lifetime

- New 2015 Pb-Pb data
- Two methods for estimation
- Most accurate lifetime determination to date
Hypertriton lifetime

- World average unexpectedly below the free $\Lambda$ lifetime
- Further improvements on precision are possible in future
Strange di-baryon searches

\[ (\Lambda n)_b \rightarrow \bar{d} + \pi^+ \]

- Weak decay searches
  - H-dibaryon with ΛΛ bound state
  - Λn bound state (as antiparticle)

**ALICE**

**Pb-Pb**

**S_{NN} = 2.76 TeV**

**Upper limits (99% CL, 0-10% central)**

**Thermal model prediction (156 MeV)**

**Decay length of free Λ**

**dN/dy**

**dN/dy**


\[ (\Lambda\Lambda)_b \rightarrow \Lambda + p + \pi^- \]
Strange di-baryon searches

- Comparison of limit to predicted yields $\times$ B.R. from thermal model
- Only very small B.R. values are not ruled out
- Or production is not thermal

The hadronic phase
Evidence for hadronic phase

• Factor 2 reduction in $K^*(892)/K$ ratio from pp to central Pb-Pb collisions

• Evidence for scattering of $\pi$ and $K$ decay products

$\langle dN_{ch}/d\eta_{lab} \rangle^{1/3} < 0.5$
Evidence for hadronic phase

- Factor 2 reduction in $\Lambda^*(1520)/\Lambda$ ratio from pp to central Pb-Pb collisions

- Evidence for scattering of p and K decay products
Hadron-hadron correlations - concept

M. Lisa et al., Annu. Rev. Nucl. Part. Sci. 55 (2005), 357

\[ C(q) = 1 + \lambda \cos(q \cdot r) \]

- Correlation function \( C(q) \)
- \( R \) is the “HBT radius”
- Correlation function inversely proportional to \( R \)

\[ q = p_a - p_b, \quad q = 2 \cdot k^* \]

\[ r = T_a - T_b \]
Hadron-hadron correlations - examples

- Experimentally
  \[ C(q) = \frac{A(q)}{B(q)} \]
  where A is formed by pairs from same event and B background pairs from mixed events

Identical pions

Identical neutral kaons

Identical charged kaons

PRC 92 (2015) 054908
Hadron-hadron correlations - examples

- Experimentally, $C(q) = A(q)/B(q)$ where $A$ is formed by pairs from same event and $B$ background pairs from mixed events.

- Figure shows 3-d decomposition of $q$ and $R$.

- Demonstrates dependence of width on centrality (system size).

- It is possible to measure volume and lifetime of system.

**PRC 93 (2016) 024905**
Extracting interaction parameters

\[ C(q) = \int S(r) |\Psi(q,r)|^2 d^4r \]

- Measured correlation
- Emission function (size and shape)
- Pair wave function (includes cross section)

• Following derivation, assuming final state interaction (FSI), by Lednicky & Lyuboshitz
• 3 parameters characterize \( C(q) \)
  - radius \( R \)
  - Scattering length \( f_0 \)
  - Effective radius \( d_0 \)
Non-identical kaon correlations

- Correlations sources
  - Quantum statistics - \(K_0^S K_0^S\) and \(K^\pm K^\pm\)
  - Coulomb FSI - \(K^\pm K^\pm\)
  - Strong FSI - \(K_0^S K_0^S\) via \(f_0(980)\) and \(a_0(980)\) resonances

- What about \(K_0^S K^\pm\) pairs?
  - Only strong FSI and only \(a_0\) has isospin=1
  - Possibility to study \(a_0\)
  - Fits to data using \(a_0\) FSI parameterization

\[k^* (\text{GeV/c})\]

arXiv:1705.04929
Baryon-(anti)baryon correlations

- Multiplicity of $p$, $\Lambda$ and their anti-particles permit correlation studies
- Three correlations functions formed as $b$—anti-$b$ are combined
- This is an example for one centrality interval at one centre-of-mass energy
Baryon correlations - extracted parameters

- Interaction parameters extracted from simultaneous fits to correlation functions in different centralities and energies
  - $R$ will vary but interaction parameters have to be common

- Results favour slightly repulsive interaction between baryons and antibaryons
Baryon correlations - extracted parameters

- $d_0$ vs $\text{Re}(f_0)$
  - Comparison to other experimental results and to model
- $\text{Im}(f_0)$ vs $\text{Re}(f_0)$
  - Comparison to experiment
Baryon-meson correlation (example)

- Can learn about $\Lambda$-$K$ interactions too
- All combinations of $\Lambda$, anti-$\Lambda$ and $K^+$, $K^-$, $K^0_S$ available
Outlook and conclusion

• ALICE has demonstrated ability to use high-energy collisions to make some unique measurements in
  – Properties of exotic hadrons
  – Constraining matter–anti-matter differences
  – Measuring hadron-hadron interaction properties

• Many of these became feasible, or were much improved, during LHC Run 2 (2015-present)

• Expect further progress in Run 3 (2020-) when ALICE will be upgraded to record up to 100 times more data!
Stay tuned and thank you