An Overview of Recent Results from the ALICE Experiment

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A Quick Introduction to Heavy-Ion Physics and ALICE
QCD Phase Diagram

- Schematic phase diagram of strongly interacting matter for temperature and baryon chemical potential
- At LHC energies: most particles produced during the collision → very low baryon chemical potential
Quark-Gluon Plasma (QGP): phase of deconfined quarks and gluons

- QGP behaves as a perfect fluid
  - Well described by ideal hydrodynamics
  - Viscosity near quantum lower limit ($\eta/s > 1/4\pi$)

- Phase transition near 170 MeV
- Crossover or 1st-order phase transition between QGP and hadron gas
- Critical point?
  - RHIC Energy Scan
Collision Geometry

- Centrality: amount of overlap between nuclei
- Impact parameter: distance between centers of nuclei
- Cannot measured impact parameter directly; measure
  - Charged particle multiplicity (mostly $\pi^\pm$, $K^\pm$, p, and $\bar{p}$)
  - Number of spectator neutrons (pass through the collision unaffected)
  - Use models to map these measurements into impact parameter

“Central”
Small impact parameter
Large volume of QGP

“Peripheral”
Large impact parameter
Small volume of QGP
Time Evolution

Hydrodynamic Evolution

Pre-Equilibrium Phase ($< \tau_0$)

QGP

Mixed Phase?

Hadron Gas

Chemical Freeze Out

Freeze Out

Beam Rapidity

Mid Rapidity

time

$\pi, K, p, ...$

$T_{fo}$

$T_{ch}$

$T_c$

Incoming nuclei

Collision

sQGP

Mixed phase

Hadron gas
ALICE Detector

- ALICE: cylindrical geometry, 0.5-T solenoidal magnetic field
- Central barrel: $|\eta| < 1$, tracking, PID, calorimeters
- Muon spectrometer: $-4 < \eta < -2.5$
- Forward detectors: triggering, centrality, timing
ALICE Pb–Pb Collision

Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV

run: 137171, 2010-11-09 00:12:13
Recent Results from ALICE
Mass Difference of (Anti-)nuclei

- Test of CPT invariance of residual nuclear force by measuring mass difference of nuclei and anti-nuclei
- Highest precision measurements of mass difference in nuclei
  - First measurement of binding-energy difference for $^3\text{He}$
- Confirms CPT invariance for light nuclei

Nature Phys. 11
811-814 (2015)
Direct Photons

- \( p_T > 5 \text{ GeV/c} \): model calculations agree with data
- Low-\( p_T \) excess over models (\( 2.6\sigma \) for central collisions)
- At low \( p_T \), photon spectrum dominated by thermal contribution
- \( T_{\text{eff}} \): inverse slope of low-\( p_T \) direct-\( \gamma \) distribution
  - \( T_{\text{eff}} = (304 \pm 11 \pm 40) \text{ MeV} \) in central collisions
  - 30\% higher than at RHIC (\( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \))
  - Relation to medium temperature is complicated

\[
\frac{d^2N_{\gamma}}{dp_T dy} \propto \begin{cases} 
\exp(-\frac{p_T}{T_{\text{eff}}}) & \text{for central collisions} \\
\exp(-\frac{p_T}{T_{\text{RHIC}}}) & \text{for RHIC} 
\end{cases}
\]
Jet Shapes

- Variables to characterize jet-core shapes:
- Radial moment \( g \): \( p_T \)-weighted width of jet: more collimated \( \rightarrow \) low \( g \)
  - Pb–Pb: indication of more collimated jets than in pp, PYTHIA
Jet Shapes

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    - Pb–Pb: indication of more collimated jets than in pp, PYTHIA
  - $p_T D$: dispersion of jet constituents: fewer constituents $\rightarrow$ higher $p_T D$
    - Pb–Pb: indication of fewer jet constituents and larger $p_T$ dispersion
  - Quark and gluon jets have different $g$ and $p_T D$ distributions
Nuclear Modification Factor

- Quantify particle suppression
- Nuclear modification factor:

\[ R_{AA} = \frac{Y(A-A)}{Y(pp) \times \langle N_{\text{coll}} \rangle} \]

- \( \langle N_{\text{coll}} \rangle \) calculated from models of nucleus-nucleus collisions
- If \( R_{AA} = 1 \): A–A collision is an incoherent superposition of N–N collisions
- If \( R_{AA} \neq 1 \): new physics: suppression or enhancement in A–A collisions w.r.t. N–N collisions
- For low momentum (\( p_T < 2 \text{ GeV/c} \)) particle production not expected to scale with \( \langle N_{\text{coll}} \rangle \)
Heavy-Flavor $R_{AA}$

- Unique probes: heavy quarks experience full evolution of the system
- Energy loss expectation: $\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b)$
  \[ \rightarrow R_{AA}(\text{light flavor}) < R_{AA}(\text{charm}) < R_{AA}(\text{bottom}) \]
- Observe: $R_{AA}(J/\psi \leftrightarrow B) > R_{AA}(D)$: consistent with expectations
- $R_{AA}(D) \approx R_{AA}(\pi)$: reproduced by models with more advanced treatment of parton $p_T$ distributions and fragmentation functions
- Hint of $R_{AA}(D^+_s) > R_{AA}(D^0, D^+, D^{*+})$: if true, would indicate charm hadronization through recombination in medium (due to enhanced strangeness)
**Very Low-$p_T$ J/$\psi$**

- In peripheral Pb–Pb colls.: large excess of J/$\psi$ for $0 < p_T < 0.3$ GeV/c
- Models that describe J/$\psi$ yield at high $p_T$ do not predict this.
- **Hypothesis:** coherent photo-production of J/$\psi$ in Pb–Pb collisions
  - STARLIGHT calculation in ultra-peripheral colls. in good qualitative agreement
  - Data favor scenario where only the **spectator region** (protons that pass through without colliding) contributes to the photo-production

![Graphs showing R_AA and p_T distributions](image-url)
Azimuthal Anisotropy

- Reaction plane: plane containing beam direction and centers of nuclei
- Anisotropy of particle emission
- Hydrodynamic description: spatial anisotropy $\rightarrow$ momentum anisotropy
  - Larger pressure gradients $\rightarrow$ more particles emitted in plane (“elliptic flow”)
- Quantify anisotropy: Fourier decomposition of azimuthal distribution (w.r.t reaction plane): coefficients $v_2, v_3, v_4, \ldots, v_n$

$\phi_{lab} - \Psi_{plane}$

$\Psi_{plane}$

$X$

$\event{14}$ $\event{46}$

$\delta \phi_{024}$ $\delta \phi_{1}$

$\delta \phi_{1.02}$

$\phi_{Acos}(2, 2.76 \text{ TeV}, 4-5\% \text{ central}) + B \text{ fit}$

$\phi_{Acos}(3, \ ldots)$

Dominated by: $v_2, v_3$
Mass ordering for $p_T<2$ GeV/$c$: $\pi>K>p$

For $p_T>2$ GeV/$c$: $n_\pi$ ordering changes with centrality
  - For central collisions: $v_3>v_4>v_2$: geometry is not an important effect
  - For mid-central collisions: $v_2>v_3>v_4$
Heavy Flavor $v_2$

- Positive $v_2(D)$: similar to charged particle $v_2$
- Confirms significant interaction of charm quarks with the medium
- Suggests collective motion of low-$p_T$ charm quarks in the fireball
Flow Harmonic Correlations

- \( SC(m,n) \): correlation coefficient between \( v_m \) and \( v_n \)
  - Sensitive to initial conditions and/or \( \eta/s \)
- Studies with HIJING model (no flow) give \( SC(m,n)=0 \)
- \( v_2 \) correlated with \( v_4 \), anticorrelated with \( v_3 \)
  - Existing calculations cannot quantitatively describe centrality dependence
- \( SC(m,n) \) more sensitive to \( \eta/s \) than \( v_n \) alone
Event Shape Engineering

- Select events based on eccentricity, study other observables w.r.t. that selection
- Ratios of spectra from large (small) eccentricity events to spectra from unbiased events
  - Spectra are harder in events with larger eccentricity
  - Positive correlations between $<v_2>$ and $<p_T>$
  - Blast-wave study implies correlation between elliptic and radial flow

\[
\frac{1}{N_{ev}} \frac{d^2N}{dp_T^2} \text{(ESE-selected)} \quad \frac{1}{N_{ev}} \frac{d^2N}{dp_T^2} \text{(unbiased)}
\]

ALICE 30-40% Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
$\Delta \langle \beta_T \rangle = 0.41\%$

- $\pi^+\pi^-$
- $K^+K^-$
- $p+p$
- Blast Wave model ($\pi^+\pi^-$)
- Blast Wave model ($K^+K^-$)
- Blast Wave model ($p+p$)

Statistical uncertainty
Systematic uncertainty

ALICE 30-40% Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
$\Delta \langle \beta_T \rangle = -0.22\%$

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- Blast Wave model ($K^+K^-$)
- Blast Wave model ($p+p$)

Statistical uncertainty
Systematic uncertainty

arXiv:1507.06194
A nuclear medium could still affect particle distributions, even in the absence of a QGP.

Study p–A (or d–A) collisions to quantify “Cold Nuclear Matter” effects.
- Nuclear PDFs are different w.r.t. free nucleons (“shadowing”)
- Coherent energy loss of partons in nuclear medium
- Breakup of c$\bar{c}$ pairs in nuclear medium

Also looking for evidence of collective effects in these small systems.

Bin in charged-particle multiplicity of events: higher mult. $\rightarrow$ more nucleons participating in collisions.

$Q_{pPb}$: nuclear modification factor (like $R_{AA}$)
Charmonium in p–Pb

- $J/\psi \rightarrow \mu^- \mu^+$, $\psi(2S) \rightarrow \mu^- \mu^+$ measured at forward/backward $y$
- Pb-going direction: different trends for $J/\psi$ and $\psi(2S)$; $\psi(2S)$ suppressed
- p-going direction: Indications of smaller $Q_{pPb}$ for $\psi(2S)$ relative to $J/\psi$

### Pb-going direction

![Graph showing Pb-going direction]

### p-going direction

![Graph showing p-going direction]
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- Break-up due to interactions with hadronic resonance gas (“comovers”) is possible explanation for $\psi(2S)$ suppression
- Models with QGP and Hadron Resonance Gas in fair agreement with data
• Increase from low multiplicity (peripheral) to high multiplicity (central) collisions seen in pp, p–Pb, and Pb–Pb systems

• In Pb–Pb the enhancement at intermediate $p_T$ can be explained by collective flow and/or quark recombination from QGP

• Same qualitative behavior seen in pp and p–Pb, but with smaller magnitude

![Graph of $\Lambda/K^0_S$ Ratio]
Strangeness Production

- **Pb–Pb:** $\Lambda/\pi$ and $\Omega/\pi$ (and other ratios) reach Grand Canonical saturation value (thermal models)
- **pp** and **p–Pb:**
  - Follow similar trends as functions of multiplicity; strong disagreement with PYTHIA predictions
  - Approach (or reach) Pb–Pb values and GC saturation values
  - Do we see the lifting of canonical suppression of strangeness production in high-multiplicity pp and p–Pb collisions?

\[ \langle dN_{\text{ch}} / d\eta \rangle_{|\eta|<0.5} \]

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Canonical Suppression

- Double ratio: \(\frac{[h/\pi]_{\text{system}}}{[h/\pi]_{pp\\text{inel}}}\): magnitude of enhancement increases with number of strange quarks
- \(p/\pi\) ratio is constant → the effect is related to strangeness, not baryon number
- Decrease from high to low multiplicity is qualitatively described by models with canonical suppression
Hadronic Resonances

• \( p/\phi \) ratio vs. \( p_T \): information on particle production mechanisms
  – Pb–Pb: \( p/\phi \) constant for \( p_T < 4 \) GeV/c: consistent with hydrodynamic interpretation, but can be reproduced by some recombination models
  – p–Pb: similar to peripheral Pb–Pb and pp
    • Hint of flattening for \( p_T < 1 \) GeV/c for high-multiplicity bin

• \( p_T \)-integrated ratios:
  – \( K^{*0}/K \) is significantly suppressed in central Pb–Pb, \( \phi/K \) not suppressed
  – Different resonance lifetimes: decay products of \( K^{*0} \) re-scatter in hadronic phase
  – Can be used to study temperature and lifetime of hadronic phase

\[ \text{ALICE Preliminary} \]
\[ \text{Pb-Pb } \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}, \ -0.5 < y < 0 \]
\[ \text{V0A Multiplicity Event Classes (Pb-Side)} \]
\[ \text{ALICE, Pb-Pb 2.76 TeV} \]
\[ \text{ALICE, pp 7 TeV} \]
\[ \text{ArXiv:1404.0495} \]
\[ \text{Eur. Phys. J. C 72, 2183} \]
Conclusions

- Confirm **CPT invariance** in light nuclei
- Excess of low-$p_T$ direct $\gamma$: inverse slope $T_{\text{eff}}$ 30% higher than at RHIC
- Jet shape analyses: **Pb–Pb jets more collimated**, fewer constituents, more $p_T$ dispersion
- Heavy flavor: $R_{AA}(J/\psi \leftrightarrow B) > R_{AA}(D) \approx R_{AA}(\pi)$: new constraints for models
- Indication of collective motion of low-$p_T$ heavy quarks
- Measurements of $\nu_n$ and $\nu_m - \nu_n$ correlations: new constraints for models
- Event shape engineering: **correlations between radial and elliptic flow**
- Measurements of $Q_{pPb}$: initial-state effects not sufficient to describe $\psi(2S)$
- Striking **qualitative similarities** in strange particle production in $pp$, $p$–$Pb$, and $Pb$–$Pb$ collisions
- Lifting of **canonical suppression** for high-multiplicity $pp$ collisions?
- Resonances used to study particle production and hadronic phase

- Run 2 of LHC under way: just finished taking new, higher-energy Pb–Pb data
Additional Material
KE\_T\!/n_q Scaling

- Scale both axes: instead of \( v_n \) vs. \( p_T \), plot \( v_n/n_q \) vs. \( KE\_T/n_q \)
  - Proposed at RHIC, suggests quark coalescence as hadron production mechanism
- \( v_2 \) in mid-central colls.: \( KE\_T/n_q \) scaling works within ±20% for \( p_T > 0.8 \) GeV/c
- \( KE\_T/n_q \) scaling works better for \( v_3 \)
Deuteron $v_2$

- $v_2$ does not scale with $A$ or $n_q$ from protons to deuterons
  - Simple coalescence does not work for deuteron $v_2$
- Blast-wave model (hydro): fit $\pi, K, p$ and predict $d$: good agreement

10-20% most central

mid-central