ALICE Status
Claude A. Pruneau
Wayne State University

Results Outline
• Single Particle Production
• Flow
• Correlation Functions
• Jet Measurements
• Heavy Flavor Jet

ALICE TPC Upgrade

with a focus on recent ALICE USA results...
ALICE by numbers

Eight years of data taking...

<table>
<thead>
<tr>
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LHC Run 2 data analysis is in full swing.
Significant increase in integrated luminosity in pp, p-Pb, and Pb-Pb collisions allows more and more precise investigation of statistics hungry probes.
Eight years of data taking...

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### ALICE by numbers

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Working Groups:
- CF: Correlations Fluctuations Bulk
- DQ: Dileptons and Quarkonia
- HF: Heavy Flavor
- GA: photon and pion working group
- LF: Light Flavor Spectra
- JE: Jets
- UD: Ultraperipheral/Diffractive

233 papers submitted as of Oct 17, 2018

QM 2018
35 talks
99 posters
16 new papers

#Papers submitted

2014 21
2015 28
2016 33
2017 34
2018 20+
QCD at High Temperature: Quark Gluon Plasma (QGP)

- **Proof of existence**
- **Properties**
  - Nature of phases (DoF) & transitions (1st, 2nd order, cross-over)?
  - Equation of state (EoS)
  - **Shear & Bulk Viscosity**
  - Electrical/Thermal conductivities
  - Heat Capacity (?!)
  - Compressibility (?!)
  - Hadrochemistry
  - Transport Properties (dE/dx)
- **Technical Questions**
  - A+A Initial conditions
- System size/lifetime
- **QGP or flow in Small systems vs. large systems?**
- Understanding hadronization
- **New states of matter**
  - Chiral Magnetic Effect (CME)
  - Disoriented Chiral Condensate (DCC)
- **Tools**
  - Correlation Functions, Flow
  - Jets
  - Heavy Flavor
  - …
FLOW Measurements

What is flow?

Spatial anisotropy  →  Momentum anisotropy

Momentum anisotropy: \( \frac{dN}{d\varphi} \propto 1 + 2 \sum_{n=1}^{+\infty} v_n \cos [n(\varphi - \Psi_n)] \)

- **Collective particle momentum anisotropies in the transverse plane** quantified by coefficients \( v_n \)
  - **Soft sector** (\( p_T < 2 \text{ GeV/c} \)): multiple interactions between partons (collective) convert initial-state (IS) spatial anisotropies into final-state momentum anisotropy,
  - **Hard sector** (\( p_T > 10 \text{ GeV/c} \)): path-length dependent parton energy-loss produces final-state anisotropy,
- **Common origin**: Spatial anisotropies determined by initial geometry of the collision, including IS fluctuations

- **Toolset**:
  - Two-particle cumulants
  - Multi-particle cumulants
    - Generic framework\(^1\)
    - Scalar Product (SP) method
  - Symmetric Cumulants (SC)
  - Decomposition of linear and non-linear contributions to flow.

\(^1\)A. Bilandzic et al., Phys. Rev. C 89, 064904 (2014)
**Collectivity in AA**

Are Correlations long-range & involving multiple particles?

\[ v_n \{4\} = 4 \sqrt{-c_n \{4\}} \]

\[ v_n \{6\} = 6 \frac{1}{4} c_n \{6\} \]

\[ v_n \{8\} = -\frac{1}{33} c_n \{8\} \]

- ALICE Preliminary
- Pb-Pb \( |s_{NN}| = 5.02 \text{ TeV} \)
- \( 0.2 < p_T < 3.0 \text{ GeV/c} \)
- \( |\eta| < 0.8 \)

\[ v_2 \{4\} \sim v_2 \{6\} \sim v_2 \{8\} \]

**Long range collectivity in Pb-Pb**
FLOW Measurements

Origin of Collectivity in Pb—Pb?! 

- Measurements of $v_n$ consistent with hydrodynamical model calculations
- Symmetric cumulants (SC) provide further constraints on the initial conditions + transport coefficients
- Together $v_n^m$ + SC$(m,n)$ provide a better handle of the model parameters than each of them independently

- Origin of collectivity in large collision systems is well understood.
Anisotropic flow of identified particles in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

Low-pT ($< 2$ GeV/c) : Mass ordering (Radial flow) ; observed at 2.72 TeV, confirmed at 5.02 TeV.
Intermediate-pT (2-7 GeV/c) : Quark number scaling
High-pT ($>7$ GeV/c): Parton energy loss
Correlations Functions

**R2 & P2 Correlations in Pb - Pb**

\[ R_2(\Delta \eta, \Delta \phi) = \frac{\rho_2(\Delta \eta, \Delta \phi)}{\rho_1(\eta_1, \phi_1) \otimes \rho_1(\eta_2, \phi_2)} - 1 \]

\[ P_2(\Delta \eta, \Delta \phi) = \frac{\langle \Delta p_T \Delta p_T \rangle (\Delta \eta, \Delta \phi)}{\langle p_T \rangle^2} \]

\[ \Delta p_T = p_{T,j} - \langle p_T \rangle \]

\[ \langle \Delta p_T \Delta p_T \rangle (\Delta \eta, \Delta \phi) = \int \int \rho_2(p_1, p_2) \Delta p_{T,1} \Delta p_{T,2} \frac{dp_{T,1}}{dp_T} \frac{dp_{T,2}}{dp_T} \]

**0-5% PbPb Collisions**

**LS**

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

**US**

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

**CI**

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

**P2**

\[ P_2(\Delta \eta, \Delta \phi) \]

**R2**

\[ R_2(\Delta \eta, \Delta \phi) \]

US: Unlike-sign pairs

LS: Like-sign pairs

CI = US + LS
Correlations Functions

Flow vs. Non-Flow

\[ v_n[P_2] = \frac{v_n^{pT}}{\langle p_T \rangle} - v_n \]

Comparison of correlators \( P_2 \) and \( R_2 \) indicates collective flow dominance at \(|\Delta \eta| > 1\) — new evaluation of non-flow effects
QGP in small systems?

Enhancement of multi-strange hadrons in pp and p-Pb

- Do we make a QGP in pp collisions??

- Reduction of $K^0$ relative to $K^-$ in central Pb-Pb consistent with increased re-scattering of decay products in hadronic phase
Flow Measurements

QGP, Collectivity in pp, p–Pb?

- $v_n \{m\}$ are sensitive to long-range multi-particle correlations.
- $v_n \{m\}$ are large in pp and p-Pb.
  - Indicates presence of long-range multi-particle correlations in this systems
  - What is their origin?
    - Initial state effects,
    - final state effects,
    - both?
- Consider measurements of SC(m,n)$_{3\text{-sub}}$. 

![Graph showing flow measurements in different collision systems and the sensitivity of $v_n \{m\}$ to multi-particle correlations.](image-url)
SC(m,n): suppression of non-flow effects

- Need to constrain initial conditions - small systems
- Need better/new measurements - Symmetric Cumulants

- Suppression of non-flow in SC w/ multiple sub-events: SC(m,n) > SC(m,n)[2-sub] > SC(m,n)[3-sub]
- Positive correlation between \( v_2 \) and \( v_4 \) in all collision systems
- Anti-correlation between \( v_2 \) and \( v_3 \) at large multiplicities — initial eccentricity correlations
- A transition to positive correlations followed by both small and large systems
- Not described by non-flow only models, but qualitatively by models with initial state
Flow coefficients in Xe — Xe Collisions

- **First measurements** of $v_2$, $v_3$, $v_4$ in Xe-Xe at $\sqrt{s_{NN}} = 5.44$ TeV
- $v_2\{4\}/v_2\{2\}$ sensitive to flow fluctuations: qualitatively described by initial conditions, some tension with hydro model predictions\(^1\)
- Models include nuclear deformation $\beta_2$, which modifies Wood-Saxon as

$$\rho(r, \theta) = \frac{\rho_0}{1 + e^{(r-R_0-R_0 \beta_2 Y_{20}(\theta))/a}}$$

$\rho_0$ density at center, $R_0$ nuclear radius, $r$ distance from center, $Y_{20}$ Bessel function of second kind, $a$ skin depth

Effect: $\sim 20\%$ larger $v_2\{2\}$ in central, decreasing towards peripheral

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Measuring/Constraining QGP properties

- Flow harmonics constrain initial conditions and transport properties: $\eta/s$, $\zeta/s$, EoS, freeze-out conditions.
- Higher harmonics probe smaller spatial scales
  - More sensitive to transport properties (e.g. $\eta/s$) and initial density profile
- Testing details of hydrodynamical response of QGP

\[ V_n = V_n^L + V_n^{NL} \quad (n > 3) \]

C.A.P., ALICE Status, Oct 25, 2018
Linear vs. Non-linear response of higher harmonics

- $V^L_n$ proportional to spatial anisotropy $\varepsilon_n$ (same order)
- $V^{NL}_n$ proportional to lower order spatial anisotropies, e.g. $\varepsilon_2$ and/or $\varepsilon_3$ when $n>3$
- $V^L_n$ and $V^{NL}_n$ statistically uncorrelated

\[ V_4 = V_4^{NL} + V_4^L = \chi_{4,22}(V_2)^2 + V_4^L \]
\[ V_5 = V_5^{NL} + V_5^L = \chi_{5,32}V_3V_2 + V_5^L \]
\[ V_6 = V_6^{NL} + V_6^L = \chi_{6,222}(V_2)^3 + \chi_{6,33}(V_3)^2 + \chi_{6,24}V_2V_4^L + V_6^L \]

Non-linear modes are more sensitive to initial state fluctuations + transport properties ($\eta/s$, $\zeta/s$)\(^{(1)}\)

For different particle species, additionally probe\(^{(2)}\)
- Effects of hadronisation mechanism, e.g. quark coalescence
- Effects of hadronic rescattering

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\(^{(1)}\) Phys.Lett. B773 (2017) 68
\(^{(2)}\) JHEP 1609 (2016) 164
Correlations Functions

Balance Functions

Two-wave quark production model:
- $\pi^\pm$: predominantly produced at late stage
- $K^\pm$: predominantly produced at early stage

Investigate if BFs for $\pi^\pm$, $K^\pm$, ..., evolve differently with centrality at LHC & RHIC (BES)

A tool for studying the chemical evolution of the quark-gluon plasma

$B(\Delta y, \Delta \phi) = \frac{dN}{d\eta} R^{CD}_{2}(\Delta y, \Delta \phi)$

Bass, Danielewicz, Pratt PRL. 85, 2689 (2000)
Bozek PLB 609 (2005) 247–251
Pratt PRL. 108, 212301 (2012)
Kapusta, Plumberg PRC 97, 014906 (2018)
Correlations Functions

Pion, Kaon Balance Functions

π⁻⁺: Considerable shape dependence on collision centrality

K⁺⁻: Modest shape dependence on collision centrality

Katarina Gajdosova on behalf of the ALICE Collaboration
Niels Bohr Institute, Copenhagen

C.A.P., ALICE Status, Oct 25, 2018
Hadron, Pion, Kaon Balance Functions — Pb-Pb

**BF Widths**

- **ALICE Preliminary**
  - Pb-Pb $|s_{NN}| = 2.76$ TeV
  - $0.2 \leq p_t \leq 2$ GeV/c

- Narrowing
- ~invariant

**BF Yields**

- **ALICE Preliminary**
  - Pb-Pb $|s_{NN}| = 2.76$ TeV
  - $0.2 \leq p_t \leq 2$ GeV/c

- Kinematical focusing

**Correlations**

- Large radial flow in PbPb
- Delayed hadronization(?!)

**Constraints on**
- QGP expansion dynamics
- Hadro-chemistry of the QGP

C.A.P., ALICE Status, Oct 25, 2018
Correlation Functions

Momentum Correlator $G_2$

$G_2(\Delta \eta, \Delta \phi) \equiv \frac{\int \rho_2(\vec{p}_{1}, \vec{p}_{2})p_{T,1}p_{T,2}dp_{T,1}dp_{T,2}}{\rho_1(\eta_1, \phi_1) \otimes \rho_1(\eta_2, \phi_2)} \left\langle p_{T,1} \right\rangle \left\langle p_{T,2} \right\rangle$

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV  ALICE Preliminary
CI, 30-40%

\begin{itemize}
  \item Broadening of $G_2$ w/ centrality
  \item Less broadening at LHC
  \item In progress: using longitudinal broadening to estimate the shear viscosity at LHC
\end{itemize}

M. Sharma & C.P. et al (STAR), PLB704, 467 (2011)
Jet - Medium Interactions

p+p collisions

- Use jets from p+p collisions as “calibration”
- Use jets in A+A collisions as self-generated probes to study the properties of the matter produced.
- Initially, such studies were conducted with leading particles.
- Today, studies are carried out with charged jets, full jets, and even heavy-flavor jets.

A+A collisions

- Topics of interest
  - Jet suppression (energy-loss)
  - Jet modification by medium
  - Medium modification (recoil) by jet.
Jet Measurements

Jet cross-section in $p + p$ collisions @ 5.02 TeV

$40 < p_{T,\text{Jet}} < 140$ GeV/c

Jet reconstruction w/ Anti-$k_T$; cone sizes: 0.2, 0.4

Measurements consistent with POWHEG + Pythia8
Jet Measurements

Jet cross-section: 0-10% Pb + Pb collisions

40 < $p_{T,\text{Jet}}$ < 140 GeV/c  
Jet reconstruction w/ Anti-$k_T$; cone sizes: 0.2, 0.4

ALICE Preliminary
Pb-Pb 0-10%  $\sqrt{s_{NN}} = 5.02$ TeV

Anti-$k_T$ $R = 0.2$ \( |\eta| < 0.5 \)

$\rho_{\text{lead,ch}}^{\text{lead,ch}} > 5$ GeV/c

ALICE Preliminary
Pb-Pb 0-10%  $\sqrt{s_{NN}} = 5.02$ TeV

Anti-$k_T$ $R = 0.4$ \( |\eta| < 0.3 \)

$\rho_{\text{lead,ch}}^{\text{lead,ch}} > 7$ GeV/c

First full jet measurement at $p_{T,\text{Jet}} < 100$ GeV/c at 5.02 TeV
Jet Measurements

Jet $R_{AA}$

$R_{AA}$ Definition: 

$$R_{AB}(p_t) = \frac{d\sigma_{AB} / dy d^2 p_t}{\langle N_{bin} \rangle d\sigma_{NN} / dy d^2 p_t}$$

ALICE Preliminary
Pb-Pb 0-10% $\sqrt{s_{NN}} = 5.02$ TeV
pp $\sqrt{s_{NN}} = 5.02$ TeV

Anti-$k_T$ $R = 0.2 \mid |\eta_{\text{jet}}| < 0.5$
$p_{T,\text{lead,}\text{ch}} > 5$ GeV/c

Similar suppression observed in $R=0.2$ and $R=0.4$
Jet Measurements

Jet \( R_{AA} \)

**\( R_{AA} \) Definition:**

\[
R_{AB}(p_t) = \frac{d\sigma_{AB}/dyd^2p_t}{\langle N_{bin} \rangle d\sigma_{NN}/dyd^2p_t}
\]

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**Results — Jet**

The first full jet \( R_{AA} \) measurement at \( p_T^{jet} < 100 \text{ GeV/c} \) at 5.02 TeV. Similar suppression observed in \( R = 0.2 \) and \( R = 0.4 \). Consistent with ATLAS \( R = 0.4 \) jet \( R_{AA} \). Also verified that full jet \( R_{AA} \) consistent with Charged jet \( R_{AA} \) (backup slides).

**Similar suppression observed in \( R=0.2 \) and \( R=0.4 \)**

Consistent with ATLAS \( R = 0.4 \) jet \( R_{AA} \).

Also verified that full jet \( R_{AA} \) consistent with Charged jet \( R_{AA} \) (backup slides).
Jet Measurements

Full Jet $R_{AA}$

**$R_{AA}$ Definition:**

$$R_{AB}(p_t) = \frac{d\sigma_{AB} / dy d^2 p_t}{\langle N_{\text{bin}} \rangle d\sigma_{NN} / dy d^2 p_t}$$

**ALICE Preliminary**

- **Pb-Pb** 0-10% $\sqrt{s_{NN}} = 5.02$ TeV
- **pp** $\sqrt{s_{NN}} = 5.02$ TeV

**Anti-$k_T$** $R = 0.2$ | $|\eta_{\text{jet}}| < 0.5$

$$p_{T,\text{lead,ch}} > 5 \text{ GeV/c}$$

**$R_{AA}$**

**ALICE Preliminary**

- **Pb-Pb** 0-10% $\sqrt{s_{NN}} = 5.02$ TeV
- **pp** $\sqrt{s_{NN}} = 5.02$ TeV

**Anti-$k_T$** $R = 0.4$ | $|\eta_{\text{jet}}| < 0.3$

$$p_{T,\text{lead,ch}} > 7 \text{ GeV/c}$$

All models qualitatively describe the measured $R_{AA}$

But tension with the data remain for most models.
Jet Measurements

D⁰ Jets in pp, p+Pb at $\sqrt{s} = 5.02$ TeV

D⁰ Jet Reconstruction

- D⁰ Meson
  - Decay channel: $D⁰ \rightarrow K^- \pi^+$, BR = 3.89% [PDG PRD 96 (2018) 030001]
  - TPC dE/dx + TOF PID for K/π discrimination
  - Topological selections (secondary vertex)
  - $p_{T,D} > 3$ GeV/c

- Jet finding
  - D⁰ meson candidates replace the decay products in the jet finding
  - Track-based
  - anti-$k_T$, $R = 0.3, 0.4$
  - $p_{T,\text{Jet}} > 5$ GeV/c

No evidence for jet suppression in p-Pb

$R_{PbPb} \approx 1$ within uncertainties
**Jet Measurements**

**R_{AA} of D0-Meson Jets in Pb–Pb at √s_{NN} = 5.02 TeV**

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**D0-Jet RAA ~ 0.2 in 5 < \( p_{T,\text{ch-jet}} \) < 20 GeV/c**

Similar to D meson (non-photonic electrons) and inclusive jets.
A US-DOE contribution to ALICE

ALICE Barrel Tracking Upgrade -

Upcoming LHC Run-3 will see **factor 10+ increase in beam luminosity**
ALICE will operate in continuous read-out mode, **sampling all collisions at 50 kHz**

**ALICE-USA institutions collaborating towards:**

- **New** TPC “**Inner Readout Chambers**” (IROC)
  - Build 40 + spares stacks of high-precision **Gas Electron Multiplier (GEM)** chambers
- **New** TPC **read-out electronics** based on the ‘**SAMPA**’ chip
- **New** “**Inner Tracking System**” w/
  - 10 m² of silicon, 12.5 Gigapixels
  - middle layers and readout electronics
Construction of all IROC chambers complete in ~2 months
Entire project complete in less than 1 year.

First framed foil at Wayne State

Complete IROC in test & shipping vessel at Yale

Complete half-barrel of ITS

IROC “Alubody” at UT-Austin

New TPC FEE at UT-Knoxville
Summary

• A wealth of results…
  • 4 collisions systems; several beam energies
  • 233 papers as of Oct 17, 2018
  • ~ 30 papers/annum
  • 100s of conference contributions/annum

• Homing in on some properties of the QGP
  • Initial state conditions
  • Shear viscosity
  • Hadro-chemistry
  • Transport coefficients

• Increasing evidence of collective behavior in large multiplicity p+p and p+Pb collisions but origin of behavior (initial/final state) still debated.
  • Much more to come w/ Run 2 and w/ Run 3 ALICE upgrade…
A shameless plug…

- A large fraction of measurements in Heavy Ion are based on **correlation observables**.
- Correlation observables are all inter-connected.
- They measure/emphasize different aspects of the physics we seek to understand.

Learn more about correlation functions here….

For basic intro, see:

www.cambridge.org/9781108416788

### Topics

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Available on amazon.com