Recent results from the ALICE experiment at the LHC

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The standard heavy-ion collisions movie

In heavy-ion collisions (HIC) we realize high density / energy conditions
→ Strongly interacting matter → study of a deconfined state of matter (QGP)

HIC as door to a wonderland of collective phenomena (a plasma!) and unseen QCD properties

But…. We need a “baseline reference” to check differences...
→ pp collisions needed to study nuclear modification factor, particle production, tune MC...

And…. we need to get rid of any “trivial nuclear effect” that could muddy
→ p-A collisions needed to disentangle initial/final state effects
→ p-A collisions are our control experiment
The movie plot: heavy ion collision

- Thermal freeze-out: no elastic interaction $\rightarrow$ momentum spectra “fixed”
- Chemical freeze-out $\rightarrow$ Particle abundances “fixed”
- Thermalization time

Bulk of matter produced in the collision can be described in terms of hydrodynamics:
- Strongly interacting matter
- Rapid expansion & cool down
- Collective flow develops

Signatures:
- particle correlations, anisotropic flow
- $p_T$ yields mass dependent
- energy losses
This movie follows this empirical QGP script...

2. The Empirical QGP

The discovery of the gedanken QGP phase of matter in the laboratory requires an empirical definition of the minimal number of necessary and sufficient conditions in terms of experimentally accessible observables. My empirical definition is summarized by the following symbolic equation

\[
\text{QGP} = \text{P}_{\text{QCD}} + \text{pQCD} + \text{dA}.
\]

Why are three independent lines of evidence needed? The first term, \( \text{P}_{\text{QCD}} \), stands for a class of observables that provide information about its bulk thermodynamic equation of state.

- Study ‘bulk’ thermodynamic equation of state
- Short wavelength dynamics predicted by pQCD: hard processes, jets, HF,...

With Run1 ended in 2013 with p-Pb run, LHC experiments (and ALICE) completed first round of data taking to go through this equation (and the script). We completed it with confirmations, surprises and puzzles, discovered also thanks to specific ALICE detector characteristics.

(script courtesy by M. Gyulassy famous paper “The QGP discovered at RHIC” arXiv:nucl-th/0403032)
The ALICE detector

Central barrel tracking + PID $|\eta| < 0.9$

Muon spectrometer $-4 < \eta < -2.5$

New in Run2:
- TRD completed
- AD large-$\eta$ coverage (diffraction)
- EMCAL extended (DCal)

Low-momentum tracking and particle identification in a high multiplicity environment
### ALICE data taking in Run I

<table>
<thead>
<tr>
<th>System</th>
<th>Year</th>
<th>√s_{NN} (TeV)</th>
<th>L_{int}</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>2009-2010</td>
<td>0.9</td>
<td>~ 0.15 nb^{-1}</td>
</tr>
<tr>
<td>pp</td>
<td>2011</td>
<td>2.76</td>
<td>~ 1.1 nb^{-1}</td>
</tr>
<tr>
<td>pp</td>
<td>2010-2011</td>
<td>7</td>
<td>~ 4.8 pb^{-1}</td>
</tr>
<tr>
<td>pp</td>
<td>2012</td>
<td>8</td>
<td>~ 9.7 pb^{-1}</td>
</tr>
<tr>
<td>p-Pb</td>
<td>2013</td>
<td>5.02</td>
<td>~ 30 nb^{-1}</td>
</tr>
<tr>
<td>Pb-Pb</td>
<td>2010-2011</td>
<td>2.76</td>
<td>~ 0.1 nb^{-1}</td>
</tr>
</tbody>
</table>

- All main characters to play our script gathered together to make our movie
- And note large bandwidth for this ALICE movie: 1.25 GB/s for Pb-Pb events
ALICE data taking in Run II so far

<table>
<thead>
<tr>
<th>System</th>
<th>Year</th>
<th>$\sqrt{s_{NN}}$(TeV)</th>
<th>$L_{int}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>2015-2016</td>
<td>13</td>
<td>$\sim 14$ pb$^{-1}$</td>
</tr>
<tr>
<td>pp</td>
<td>2015 (4 days!)</td>
<td>5.02</td>
<td>$\sim 100$ nb$^{-1}$</td>
</tr>
<tr>
<td>p-Pb</td>
<td>2016</td>
<td>5.02</td>
<td>$\sim 3$ nb$^{-1}$</td>
</tr>
<tr>
<td>p-Pb</td>
<td>2016</td>
<td>8.16</td>
<td>$\sim 20$ nb$^{-1}$</td>
</tr>
<tr>
<td>Pb-p</td>
<td>2016</td>
<td>8.16</td>
<td>$\sim 20$ nb$^{-1}$</td>
</tr>
<tr>
<td>Pb-Pb</td>
<td>2015</td>
<td>5.02</td>
<td>$\sim 0.4$ nb$^{-1}$</td>
</tr>
</tbody>
</table>

Targets for Run II:
- pp 13 TeV $\rightarrow$ reach 40 pb$^{-1}$
- Pb-Pb $\rightarrow$ 1 nb$^{-1}$
- high statistics pp 5 TeV sample (2017) “improve the reference”

More differential studies allowed in Run II (statistics)
- Increased center-of-mass energies
- Improved detector
A review of selected ALICE results

- Intriguing (and striking) similarities between pp/p-Pb/Pb-Pb collisions
- Traditional signatures of QGP formation (in HIC) seen now in smaller systems
- Collectivity in small systems?

Do we need to change our movie?
Paradigm shift for interpretation of all hadronic collisions?

- Strangeness enhancement
- Identified particle spectra
- Anisotropic flow and correlations
- Heavy flavour production
- Parton energy loss and jets

• The traditional script
• The movie twist (if present)
• The recent result
One of the first proposed smoking guns for QGP

Strangeness Enhancement (I)

- enhancement confirmed with respect to pp as expected
- hyperon to pion ratio as expected from thermal models and larger at LHC w.r.t. RHIC

Strangeness Production in the Quark-Gluon Plasma

Johann Rafelski and Berndt Müller

PRL 48(1982) 1066

PLB 11 (2013) 48

2013

PLB 728 (2014) 216

2014

Pb-Pb at $s_{NN} = 2.76$ TeV

(a) Yield / $\langle N_{\text{part}} \rangle$ relative to pp-pBe

(b) Yield / $\langle N_{\text{part}} \rangle$ relative to pp-pBe

(c) Hyperon-to-pion ratio

$\Omega / \pi$

$\Omega^\pm$ + $\Omega^-$

\[ \frac{\Omega^{-}}{\pi} \]

\[ \frac{\Omega^{+}}{\pi} \]

$\Xi / \pi$

\[ \frac{\Xi^{-}}{\pi} \]

\[ \frac{\Xi^{+}}{\pi} \]

$\Lambda / \pi$

\[ \frac{\Lambda^{-}}{\pi} \]

\[ \frac{\Lambda^{+}}{\pi} \]

$\Sigma / \pi$

\[ \frac{\Sigma^{-}}{\pi} \]

\[ \frac{\Sigma^{+}}{\pi} \]

$\Xi / \pi$

\[ \frac{\Xi^{-}}{\pi} \]

\[ \frac{\Xi^{+}}{\pi} \]

$\Omega / \pi$

\[ \frac{\Omega^{-}}{\pi} \]

\[ \frac{\Omega^{+}}{\pi} \]
Strangeness enhancement (II)

- Studied via strange to non-strange integrated particle ratios vs $<dN_{ch}/d\eta>$
- Evolution of the enhancement driven by particle multiplicity, not by the collision system!
- MC predictions do not describe data
- Not reproduced by QCD inspired models as PYTHIA (note attempts to introduce thermodynamical model in string fragmentation model (Fischer and Sjostrand, JHEP 01 (2017) 140))
- DIPSY with color ropes (establish short range correlations) and EPOS LHC (QGP partially formed in pp) predict some trend similar to what seen in data. DIPSY (color ropes) gives qualitative description

EPOS LHC Pierog T et al., PRC 92 (2015) 034906
DIPSY Bierlich C at al., PRD 92 (2015) 094010
Strangeness enhancement (III)

- New results with data from Pb-Pb at $\sqrt{s_{NN}}=5.02$ TeV
- pp ratios at very high pp multiplicity overlaps with peripheral Pb-Pb values...
- Thermal models successful to describe Pb-Pb production (production in thermally equilibrated regime) → concepts used now in some models in pp (EPOS)
• Baryon-to-meson ratio sensitive to hadronization mechanisms and multiplicity dependent
• $p_T$ integrated yield compatible at $\sqrt{s_{NN}}=2.76$ and $\sqrt{s_{NN}}=5.02$ in PbPb $\rightarrow$ no evident energy dependence
• Tension with thermal models (if present) to be investigated (note re-analysis of Pb 2.76 TeV for $\Xi^\pm$ on-going)
• Testing hydrodynamic and pQCD inspired models
Charged particle spectra

- Pb-Pb and p-Pb spectra reasonably described by hydrodynamic models. EPOS-LHC better on p-Pb
- For pp pQCD-inspired models need extra-mechanisms providing ‘coherence’ (CR, ropes)
• In Pb-Pb collisions thermalization and fireball expansion process is standard interpretation mechanism
• Particles move in a common velocity field ("radial flow")
• Expectation of blue-shifting w.r.t. pp and mass ordering

Run I

Run II

- High precision measurement in Run II (π, K, p in 10 centrality classes)
- PID one of ALICE specialities (five different PID techniques)
  → Test models!
Identified spectra in pp as a function of multiplicity

- Hardening with multiplicity + mass ordering!
- “collectivity hint” (radial flow) in pp?
- This would entail a hydrodynamic expansion of the system
Identified spectra in pp: multiplicity and spherocity

Selection of jetty or isotropic events in high multiplicity pp to further study differentially spectra modifications

- Spectral shape modified and it is mass dependent
- Hardening at low $p_T$ larger in isotropic events (bulk production)
Hydrodynamic description: Blast-Wave model

Simultaneous fit of p, K, p spectra

Extraction of:
- $\beta_T$ radial expansion velocity
- $T_{\text{Kin}}$ kinetic freeze-out
- $n$ velocity profile

\[ E \frac{d^3N}{dp^3} = \int_0^\infty m_f I_0 \left( \frac{p_x \sinh(\rho)}{T_{\text{Kin}}} \right) K_1 \left( \frac{m_f \cosh(\rho)}{T_{\text{Kin}}} \right) r \, dr \]

\[ m_f = \sqrt{m^2 + p_T^2} \quad \rho = \tanh^{-1} |\beta_T| \quad \beta_T = \beta_r \frac{r}{R} \]

Schnedermann, Sollfrank and Heinz Phys. Rev. C 48, 2462

• Largest expansion velocity of Pb-Pb collisions
• Similar evolution for pp and p-Pb at highest multiplicity
• Higher $\beta_T$ for smaller systems at similar multiplicity
• CAVEAT: QCD effects as color reconnection can mimic radial flow!

**Global Blast-Wave fit to**
- $\pi$ (0.5-1 GeV/c), K (0.2-1.5 GeV/c), p (0.3-3.0 GeV/c)

- ALICE Preliminary, pp, $\sqrt{s}$ = 7 TeV
- ALICE, p-Pb, $\sqrt{s}_{NN}$ = 5.02 TeV
- ALICE, Pb-Pb, $\sqrt{s}_{NN}$ = 2.76 TeV

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- ALICE Preliminary, Pb-Pb, $\sqrt{s}_{NN}$ = 5.02 TeV
Collectivity: anisotropic flow

Geometrical asymmetry translates in momentum space (pressure gradients in a collective expanding medium)

\[ E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_t dp_t dy} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_{RP})] \right) \]

- Geometrically, high harmonics are sensitive to the evolution of the collision system and hydrodynamic properties of the medium (\(\eta/s\))

- RHIC legacy: QGP is an almost perfect fluid!

- Higher integrated \(v_2\) at LHC related to the \(p_T\) increase
Anisotropic flow: identified particles

- Mass ordering pattern as expected due to collective expansion in Pb-Pb
- Seen also in p-Pb! (high multiplicity)

\[ v_2 \]

\[ v_2 (p_T > 0.9 \text{fm}) \]

ALICE Preliminary

Pb-Pb \(s_{NN} = 5.02 \text{ TeV} \)

\(|y| < 0.5\)

\[ v_2 \]

\[ v_2 (|y| > 0.9) \]

ALICE Preliminary

p-Pb \(s_{NN} = 5.02 \text{ TeV} \)

0-20% (V0A) \(|y| < 0.8\)

ALI-PREL-125031

ALI-PREL-125035

ALI-PREL-134117

ICPPA - 1-5 October 2017

P. Antonioi - ALICE overview

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Mapping plasma properties with higher order flow harmonics

- $\eta/s$ obtained up to 6th order
- Ratio of $\eta/s$ at different $\sqrt{s_{\text{NN}}}$ sensitive to models (Run I+II)
- Constrain initial conditions and $\eta/s(T)$
- Data favor fixed $\eta/s=0.2$

Shear viscosity-to-entropy ratio (EKRT model)

Niemi et al., PRC 93 (2016) 014912

Global Bayesian analysis (mean $p_T$, $v_2$, $dN_{\text{ch}}/dy$ vs centrality as input)

Bass et al., arxiv:1704.07671
And heavy flavours?

**a probe of the medium from production to observation that gives a unique access to HF interactions in the QGP.**

Lifetime of QGP $\approx 10 \text{ fm/c}$

Formation time of the QGP $\leq 0.1 \text{ fm/c}$

Heavy probes easily tagged in a liquid...

production cross sections (hard scattering) calculable with perturbative QCD pp reference critical to test pQCD

We can investigate:

1. Parton **energy loss** in the QGP
2. Participation of heavy quarks in the **collective expansion** of the medium
Charm takes part in collective expansion! (I)

Recent result: now positive flow seen in p-Pb via HF-electron in the charm sector

Don’t forget double ridge structure emerging via subtraction of high/low multiplicity for unidentified and identified particles

Similar to charged particles within uncertainties

Collective expanding system in p-Pb?

PLB 726 (2013) 164-177
Charm takes part in collective expansion! (II)

- D-meson $v_2$ similar to pions
- Difference for $p_T<4$ GeV/c ?
- First $D_s$ $v_2$ measurement at LHC

All together robust evidence of strong coupling of c-quark with the medium
J/Ψ $v_2$: Pb-Pb and p-Pb

- $v_2$ for $p_T<3$ GeV/c is compatible with zero
- $v_2$ in $3<p_T<6$ GeV/c is positive with a total significance of 5σ and similar to Pb-Pb!
- Recombination expected to be negligible in p-Pb, but measured values imply J/Ψ participates in the collective behaviour

• Significant $v_2$ observed for J/Ψ in different $p_T$ and centrality ranges
• 6.6σ in $4<p_T<6$ GeV/c for 20-40%
• Comparison to transport and recombination models tend to show tensions at high $p_T$ (> 4 GeV/c)
\( J/\Psi \cdot v_2 \cdot \text{Pb-Pb and p-Pb} \)

- \( v_2 \) for \( p_T < 3 \text{ GeV/c} \) is compatible with zero
- \( v_2 \) in \( 3 < p_T < 6 \text{ GeV/c} \) is positive with a total significance of 5σ and similar to Pb-Pb!
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- Comparison to transport and recombination models tend to show tensions at high \( p_T \) (> 4 GeV/c)
Heavy flavour energy loss

Heavy flavour: testing our understanding of QCD energy loss in the medium

Casimir factors and dead-cone effect: gluon/quark hierarchy and mass hierarchy

\[ \Delta E \propto \alpha_S C_R \overline{q}L^2 \]

\[ \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \]

ALICE

Average \( D^0, D^+, D^{*+} \)

Pb-Pb, \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \), \( |y|<0.5 \)

- 0-10%
- with pp \( p_T \) extrap. reference
- 30-50%
- p-Pb, \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \), \(-0.96 < y_{\text{CMS}} < 0.04\)

\[ \text{Run I} \]

\[ R_{AA} \]

Pb-Pb, \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

- \( \pi^+ \) (ALICE) 8-16 GeV/c, \( |y|<0.8 \)
- D mesons (ALICE) 8-16 GeV/c, \( |y|<0.5 \)
- Non-prompt \( J/\psi \) (CMS)
  - 6.5-9 GeV/c, \( |y|<1.2 \)

\( \text{EPJC 77 (2017) 262} \)

(\text{empty) filled boxes: (un)correlated syst. uncert.}

(*) 50-100\% for non-prompt \( J/\psi \)

JHEP 03 (2016) 081
JHEP 11 (2015) 205
PRC 90 (2014) 034904

\[ \text{Run I} \]
$R_{AA}$ and $v_2$: now potential to constrain models

**ALICE Preliminary**

- Average $D^0$, $D^+$, $D^{*+}$, $|y|<0.5$
  - 0-10% Pb-Pb $|y|<0.5$, $s_{NN} = 5.02$ TeV
  - 0-10% Pb-Pb $|y|<0.5$, JHEP 03 (2016) 081
  - 30-50% Pb-Pb $|y|<0.5$, $s_{NN} = 5.02$ TeV
  - 30-50% Pb-Pb $|y|<0.5$, JHEP 03 (2016) 081

- Models that describe better $R_{AA}$ tend to underestimate $v_2$ and vice versa (especially at high $p_T$)!
- From $v_2$ LBT, MC@sHQ, PHSD and POWLANG models have $\chi^2$/ndf < 1, the TAMU, BAMPS-el+rad and BAMPS-el models have larger values.

**Run II**

- Better precision in Run II and higher $p_T$ reach: similar values at $s_{NN}=2.76$ and 5.02 TeV $\rightarrow$ harder spectra vs denser medium
- Models that describe better $R_{AA}$ tend to underestimate $v_2$ and vice versa (especially at high $p_T$)!
- From $v_2$ LBT, MC@sHQ, PHSD and POWLANG models have $\chi^2$/ndf < 1, the TAMU, BAMPS-el+rad and BAMPS-el models have larger values.

**Data precision starts to constrain models and extract medium parameters!**

(references for models in backup)
$R_{pPb}$: charmed mesons and baryons

- $R_{pPb}$ compatible with unity. No energy loss?
- CNM effects expected negligible at high $p_T$
- Models including nPDFs, incoherent mult. scattering describe data

- In pp $\Lambda_c$ measurement underestimated by NLO calculations
- $\Lambda_c/D^0$ baryon-to-meson ratio sensitive to hadronization mechanisms
- Larger than model predictions

Large uncertainties but compatible with unity.
Energy loss: jet quenching

One of the smoking guns at RHIC (Au-Au and d-Au)
Strong energy loss confirmed at LHC

STAR, PRL 91 (2003) 072304

With increasing $\sqrt{s_{NN}} \rightarrow$ increasing density $\rightarrow$ increasing quenching?
Comparable $R_{AA} \rightarrow$ harder spectrum compensates higher density
First measurement of $M_{\text{jet}}$ in Pb-Pb (and p-Pb)
Jet mass sensitive to virtuality of the parton
Interaction with hot medium may increase virtuality
→ larger gluon radiation
p-Pb baseline described by PYTHIA and HERWIG
Data are best described by vacuum expectations (PYTHIA) without quenching mechanisms

And p-Pb data jets at different multiplicity class don’t show any quenching
No “hard” smoking gun in p-Pb: “collective-like medium but not dense enough”?
A further final disclaimer notice + some advertisement

A lot of ALICE recent results **not** included in this presentation!

One of most precise $\frac{3}{2}H$ lifetime measurement

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**J/Ψ vs multiplicity in pp**

**J/Ψ UPC in Pb-Pb**

LHC Pb-Pb as large photon-nucleon collider

Other multiplicity studies

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And excellent opportunities **at this conference** to know better some of them:

- Viktor Riabov, Measurement of **hadronic resonances** with ALICE at the LHC
- Igor Altsybeev, **Forward-backward correlations** between event-mean transverse momentum in Pb-Pb collisions with ALICE
- Ludmilla Malinina, **Femtoscopy** with ALICE at the LHC [arXiv:1709.01731]
- Dmitri Peresunko, Measurement of neutral mesons and **direct photons** with ALICE at the LHC [arXiv:1708.08745]
- Evgeny Kondratyuk, **Charge Particle Veto** at the LHC ALICE experiment
- Grigory Feofilov, **Upgraded ITS** for ALICE at the LHC: status and plans

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+ You Zhou, Overview on HIC results
Conclusions and outlook

Standard script for a movie to explore QGP in HIC showed surprises at LHC energies:

• **traditional QGP signatures** started to show up in **pp and p-Pb collisions** (strangeness, flow-like effects, J/Ψ and Ψ(2S) yield, baryon/meson increase...)

• **multiplicity-dependent studies** show approximation of superposition of isolated scattering is not enough to describe hadronic collisions (extra final-state, multiple interactions mechanisms connected with high density of color charges?)

At ALICE, LHC Run II is providing more differential results in many observables:

• better **extracting properties of the hot medium** created in Pb-Pb collisions

• **exploring unexpected properties of pp and p-Pb collisions**
Backup: the ALICE upgrade programme

- Major upgrade of detector system during Long Shutdown 2 (2019-2020)
  - Study the thermalization of partons in the QGP, with focus on charm and beauty quarks
    → secondary vertices → improve inner tracker
  - Low-momentum charmonia dissociation (and regeneration?) to study deconfinement and medium temperature
  - Production of thermal photons and low-mass dileptons emitted by QGP to study initial temperature and equation of state of the medium
    → exploit low $p_T$ reach & PID
  - Precision study of light nuclei and hyper-nuclei

All this... difficult to trigger...
→ read everything and reconstruct/compress online!
(rate capabilities)
→ TPC with GEM readout + improved readout

All results with $\int_{\text{int}} = 10$ nb$^{-1}$ achievable only via the five joint ALICE upgrade projects
Backup (references)

**EPOS LHC**
Pierog T. et al., arXiv:1306.0121
  - minimum bias MC
  - break up parameterization of flux tubes created by initial hard scattering
  - flow parameterization as a function of volume

**Krakow**
  - collective flow in pp and p-Pb
  - hydro + non equilibrium corrections due to bulk viscosity
  - statistical hadronization at freeze-out

**DPMJET-III**
Roesler S. et al., hep-ph/0012252 (SLAC-PUB-8740)
  - QCD inspired: soft/hard components treated in a unified way
  - percolation of hadronic strings
  - doesn’t reproduce identified spectra, but it reproduce $dN_{ch}/d\eta$ in pp
Backup (references)

Boltzmann transport, Coll. Eloss, expansion

Langevin transport, Coll Eloss, recombination, hydrodynamics

**PHSD**: PR C92 (2015) 1, 014910, PR C93 (2016) 3, 034906
Parton-Hadron-String Dynamics transport, coalescence

**LBT Cao, et al.** PR C94 (2016) 014909
Boltzmann transport, radiation + coll.

**TAMU**: PL B735 (2014) 445-450
Transport, Coll. Eloss, resonant scatt. and coalescence+hydro

**MC@sHQ+EPOS2**: PR C89 (2014) 014905
Coll+Rad Eloss, recombination, EPOS-expansion

**Djorkevic**: PR C92 (2015) 024918
Coll+Rad Eloss, recombination, finite-size hydro

**CUJET 3.0** Xu et al., JHEP 02 (2016) 169
Eloss+hydro + sQGMP

**SCETM,G NLO**: arXiv: 1610.02043
Soft Collinear Effective Theory, Bjorken expansion