ALICE overview

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ALICE = A Large Ion Collider Experiment

- Dedicated heavy ion experiment in CERN LHC
- Excellent tracking down to low $p_T \sim 100$ MeV
- Very good particle identification (PID) capabilities
PID in ALICE

dE/dx: silicon tracker (top left)
Flight time to TOF (bottom left)

TPC gas (top right)
Cherenkov angle in HMPID (bot. right)
Spectra in proton-proton

Tuning of event generators.

General motivation in LHC: significant QCD background in electroweak physics
\[ \pi^0 \]'s in p+p and Pb+Pb

ALICE can reconstruct \( \pi^0 \)'s with calorimeters PHOS and EMCal (and DCal from run2 on), or using conversion photons from TPC gas and ITS material.

**Top right:** NLO calculations barely agree, typical scale choice factor of 2 off.
Excellent tracking has enabled ALICE to make the best determination of the differences in mass and binding energy between light ions and anti-ions.

Based on CTP symmetry, both differences should be zero. For mass differences, ALICE results show this to hold within 0.1 % level.
**Heavy ion collisions - motivation**

Bjorken estimate for energy density after primary interactions in LHC:

\[ \varepsilon_{Bjorken} \sim \frac{\langle m_T \rangle}{\pi R_A^2 \tau_0} \frac{dN}{dy} = \frac{1}{A \tau_0} \frac{dE_{\text{measured}}}{dy} \sim 16 \text{ GeV/fm}^3, \]

using \( \tau_0 = 1 \text{ fm/c} \)  

*J.Phys. G38 (2011) 124040*

Substantially larger than critical energy density \( \varepsilon_c \sim 1 \text{ GeV/fm}^3 \) from lattice-QCD
Thermal model in Pb + Pb

Bulk particle production from fireball is well described by thermal models. “Small” (important?) deviations, room for details and developments.
Instead of full hydrodynamical calculation, parametrize the radial velocity at the constant time freeze-out (~last scattering) surface:

\[ \beta_T = \beta_T(r) = \beta_{\text{max}} \left( \frac{r}{R} \right)^\alpha \quad \text{and} \quad \gamma_T = \gamma_T(r) = \left[ 1 - \beta_T^2(r) \right]^{-1/2} \]

This results in following \( p_T \)-spectrum

\[
\frac{1}{p_T} \frac{dN}{dp_T dy} \propto \sqrt{p_T^2 + m^2} \int_0^R dr I_0 \left( \frac{\gamma_T p_T \beta_T}{T_{\text{kin}}} \right) K_1 \left( \frac{\gamma_T \sqrt{p_T^2 + m^2}}{T_{\text{kin}}} \right)
\]

3 free parameters (for shape): \( \alpha, \beta_{\text{max}} \) and \( T_{\text{kin}} \).

**BW model:** *Phys.Rev. C48 (1993) 2462-2475*

**BW model:**
- no dynamics
- orders of magnitude
- qualitative trends
\( \rho_T \) spectra in Pb+Pb

**Qualitative message using BW:**
In more central collisions, smaller \( T_{\text{kin}} \) with larger \( \langle \beta_T \rangle \) indicates longer collective evolution up to stronger radial flow.
**$p_T$ spectra in p+Pb**

BW fits works ok at low $p_T$

BW parameters show similar trends as in the heavy ion with increasing multiplicity

Is this a sign of collectivity in proton-lead?

Note: PYTHIA with color reconnections shows similar trend. **PRL 111 (2013) 042001**
Jet quenching, $R_{AA}$

Heavy ion collision, medium created

Bunch of independent proton-proton

Nuclear modification factor:

$$R_{AA} \equiv \frac{(\text{Yield measured in Pb + Pb})}{(\text{Number of collisions}) \times (\text{Yield in p + p})} = \frac{dN_{Pb+Pb} / d\eta}{N_{bin} dN_{p+p} / d\eta} = \frac{\langle T_{AA} \rangle d\sigma_{p+p} / d\eta}{\langle T_{AA} \rangle d\sigma_{p+p} / d\eta}$$

Standard interpretation:

If $R_{AA} < 1$ at high $p_T$, partons lose energy while traversing the hot medium.
Clearly $R_{AA} < 1 \iff$ energy loss by the dense medium

At high $p_T$, the suppression of all particle species is the same. At mid-$p_T$, protons are less suppressed. Question: is hydrodynamics + jet quenching enough to explain this, or does one need e.g. recombination processes?
$R_{AA} -$ jets in Pb + Pb

ALICE jet reconstruction: tracks down to 150 MeV, clusters to 300 MeV.

Jet suppression compatible with charged hadron results.

Push down to low $p_{T,\text{jet}}$ (where medium more important), include PID.
D-meson spectra in Pb+Pb

\[ \text{D}^0 \rightarrow K^- \pi^+ \]

\[ \text{D}^+ \rightarrow K^- \pi^+ \pi^+ \]

\[ \text{D}^{**} \rightarrow \text{D}^0 \pi^+ \]

Invariant Mass (GeV/c)

\[ \text{PbPb}, \langle s_{NN} \rangle = 2.76 \text{ TeV} \]

Centrality: 0-7.5%

\[ \mu = 1.869 \pm 0.001 \quad S/\text{B} (3\sigma) = 1845 \pm 156 \]

\[ \sigma = 0.013 \pm 0.001 \quad S/\text{B} (3\sigma) = 0.881 \]

\[ \text{PbPb}, \langle s_{NN} \rangle = 2.76 \text{ TeV} \]

Centrality: 0-7.5%

\[ \text{D}^{**} \rightarrow \text{D}^0 \pi^+ \]

Invariant Mass (GeV/c)

\[ \text{S}/\text{B}(3\sigma) = 0.09 \]

\[ \mu = 600 \pm 74 \text{ MeV/c}^2 \]

\[ \sigma = 600 \pm 74 \text{ MeV/c}^2 \]

Systematic uncertainties

from Data

from B feed-down subtr.

\[ \text{D}^0 \text{ meson} \]

\[ \text{D}^+ \text{ meson} \]

\[ \text{D}^{**} \text{ meson} \]
$R_{AA}$: D-mesons in Pb + Pb

"Dead cone" effect (Phys. Lett. B519 (2001) 199) and smaller coupling to medium would hint to reduce energy loss, resulting $R_{AA,D} > R_{AA,\pi}$.
$R_{AA}$: $J/\psi$ in Pb + Pb - forward

Surprise: $J/\psi$ is more suppressed in RHIC as compared to LHC.

Note: ALICE forward, PHENIX mid-rapidity. Does that make a difference?
Now both measurements at mid-rapidity. Still smaller suppression at RHIC, not rapidity!

Interpreted as sizable regeneration of J/ψ.
**Left:** Minimum bias (MB) proton-lead collisions do not show nuclear modification at high $p_T$. **Right:** Average D-meson $R_{AA}$ compared with heavy ion results.

No **obvious** energy loss in MB. “Expected”, if $p+Pb$ seen as control measurement. (Surprises came! 😊) Supports suppression in $AA$ to be final state effect.
Elliptic flow

Fourier decomposition of invariant yield:

$$F \frac{dN}{d^3p} = \frac{dN}{p_Tdp_Tdyd\phi} \approx \frac{1}{2\pi p_T} \frac{dN}{dp_Tdy} \left(1 + 2v_2 \cos[2(\phi - \Psi_R)]\right)$$

Elliptic flow: second harmonic $v_2 = v_2(p_T)$

Secondary interactions, pressure!

Flow does not depend on $\eta$ within ALICE acceptance => flow is long range correlation

**Left:** Elliptic flow ($v_2$) for identified particles up to Omega hadron give stringent tests for the models. Note: mass ordering described by hydro.

**Right:** D-mesons have comparable $v_2$ with charged hadrons. Systematics from B-decays: $v_2$ can only be larger.
Theory challenge

JHEP 1209 (2012) 112

Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
Centrality 0-20%

$R_{AA}$ vs $p_T$ (GeV/c)

ALICE $D^0, D^+, D^{*-}$ average, $|y|<0.5$

POWLANG: Alberico et al., EPJ C71 (2011) 1666
Cao, Qin, Bass, arXiv:1308.0617
TAMU: Rapp, He et al., PRC 86 (2012) 014903

Simultaneous $R_{AA}$ and $v_2$ description difficult


$\langle T_t \rangle$ vs $v_t$ (GeV/c)

$\langle T_t \rangle$ vs $v_t$ (GeV/c)

Syst. from data
Syst. from B feed-down

POWLANG: Alberico et al., EPJ C71 (2011) 1666
Cao, Qin, Bass, arXiv:1308.0617
TAMU: Rapp, He et al., PRC 86 (2012) 014903

Simultaneous $R_{AA}$ and $v_2$ description difficult
Viscosity is a matter property, should be the same in both collision energies.

Requiring simultaneous reproduction of RHIC and LHC data help to give tighter constraints, for example here to shear viscosity.
Long range correlations also in high multiplicity p + Pb events!


Take two-particle correlation function measured in high multiplicity p+Pb and subtract the same measured in low multiplicity event. This should approximately subtract the common short range correlations (jets).

Do these **long range** correlations imply flow in p + Pb?
Flow and 2-ple correlations

How does flow show up in azimuthal correlations?

If single particle spectra has Fourier decomposition

$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \psi_n)]$$

then pair distribution $\Delta \varphi := \varphi_1 - \varphi_2$ becomes

$$\frac{dN^{\text{pair}}}{d\Delta \varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_{n\Delta} \cos(n\Delta \varphi)$$

such that

$$V_{n\Delta} = V_{n\Delta}(p_{T1}, p_{T2}) = v_n(p_{T1})v_n(p_{T2})$$

Remove jet correlations with rapidity gap, $|\Delta \eta| > 0.8$

Flow harmonics in Pb+Pb

Get pair distribution
Fourier coefficients
(previous slide)

Geometry dominates $V_{2\Delta \varphi}$
clear centrality dependence

Centrality
- 40-50%
- 20-30%
- 10-20%
- 2-10%
- 0-2%

$2 < \pT < 2.5 \text{ GeV/c}$
$1.5 < \pT < 2 \text{ GeV/c}$

Higher harmonics give connection to initial state fluctuations

Simulation: H. Niemi
Collectivity in high multiplicity p+Pb?

Mass ordering in $v_2\{2PC, sub\}$ in p+Pb, similar to lead-lead

Collectivity in high multiplicity p+Pb?

ATLAS:
Substantial $v_n$'s up to high $p_T$

arXiv:1409.1792 [hep-ex]

CMS:
Many particles correlated also in p+Pb

Collectivity in p+Pb – theory

Top: Color Glass Condensate (CGC) – no flow in p+Pb:
Two gluons scattering from the same color field give rise to contributions that are symmetric around $|\Delta \phi| = \pi/2$. These “glasma” contributions can be significantly enhanced when target gluon densities are large (saturation). *Phys. Rev. D87 (2013) 094034*

Bottom: Hydrodynamics – yes, flow in p+Pb:
Prospects

**Run 2**: 10 x statistics with upgraded detector: two new detectors; di-jet calorimeter (DCal) and ALICE diffractive detector (ADD) + added 5 TRD modules + many improvements to existing systems

**Run 3-4**: 100 x statistics, *very* significant detector upgrade

**13 TeV data coming!**

First glimpse at LHCP 2015, St. Petersburg, Russia

http://lhcp2015.com

and more in Quark Matter 2015, Kobe, Japan (Sep. 27 – Oct. 3)

http://qm2015.riken.jp
Summary

• Although a dedicated heavy ion experiment, ALICE has physics program in all LHC collision systems (+ cosmics)

• Concentrate on strengths: PID, tracking, benefits from low pile-up conditions

• Recently, ALICE made the most precise measurement on differences in mass and binding energies of light (anti-)nuclei

• Measurements of identified $v_2$ and $v_n$’s give constraints to hydrodynamical models and help e.g. constrain shear viscosity of QGP

• Simultaneous description of heavy flavour $R_{AA}$ and $v_2$ a challenge

• J/$\psi$ more suppressed at RHIC. Interpreted trough regeneration.

• Collectivity in proton-lead: hydrodynamics, Color Glass Condensate explanation or something else?
Thanks!

ALICE Contributions to ICNFP 2015:

• **Maria Vasileiou**: Identified charged hadron production in pp and Pb-Pb collisions with ALICE at the LHC

• **Yasser Morales**: Identified hadron production and study of collective phenomena in p--Pb collisions at the LHC with ALICE

• **Elena Rogochaya**: Bose–Einstein correlations of charged and neutral kaons in p-p and Pb-Pb collisions with the ALICE experiment at the LHC

• **Gyulnara Eyyubova**: Performance of the ALICE secondary vertex b-tagging algorithm (poster)
Backup:
“Low $p_T$ – medium (bulk), thermal physics”

Static thermal source, constant $V$ and $T$: perfect $m_T$–scaling

$$\frac{dN}{m_T dm_T} = \frac{gV}{2\pi^2} \times m_T K_1 \left( \frac{m_T}{T} \right) \sim \sqrt{m_T} e^{-m_T/T}, \text{ when } m_T \gg T$$

Include constant radial flow, $\beta_T$
(assuming longitudinal boost-invariance)

$$\frac{dN}{m_T dm_T dy} \propto m_T I_0 \left( \frac{\gamma_T \beta_T \sqrt{m_T^2 - m^2}}{T} \right) K_1 \left( \frac{\gamma_T m_T}{T} \right)$$

$$\sim e^{-m_T/T_{\text{eff}}}, \text{ where } T_{\text{eff}} = T \sqrt{\frac{1 + \beta_T}{1 - \beta_T}}$$

Basic consequences of radial flow:
• $m_T$–scaling is broken
• Spectra get blue shifted due to flow
Backup: hydro applicability


Lead – Lead collisions:

Top, left to right: 1) Knudsen number, late starting time, low viscosity 2) Knudsen number, early starting time, high viscosity 3) Inverse Reynolds number

Bottom: Knudsen number in p + PB
Charged jets in proton-proton

- Jet physics down to very low $p_T$ constituents
- Good agreement in jet xsec with ATLAS
- Example: number charged constituents as a function of $p_{T,jet}$
- Comparison with event generators, tuning

**ALICE, arXiv: 1411.4969**