Particle production in Pb-Pb collisions with the ALICE experiment at the LHC

F. Bellini* for the ALICE Collaboration
*Università di Bologna, I.N.F.N Sez. di Bologna – Italy

Heavy Ion physics session
Melbourne, 6th July 2012
Outline

The ALICE experiment at LHC

Physics of heavy ion collisions

• How to probe medium evolution by measuring particle production

Results in Pb-Pb collisions

• Particle spectra
• Particle ratios
• Strangeness enhancement
• Light hadrons $R_{AA}$
• Baryon anomaly

Summary and conclusions

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06th July 2012
The ALICE detector at LHC

- Unique PID capabilities: $dE/dx$, time-of-flight, Cherenkov, decay topology (V0, cascades), ...
- Central region with the smallest material budget at the LHC

Central barrel: $|\eta| < 0.9$, $B = 0.5$ T

Inner Tracking System – ITS: Primary vertex, PID via $dE/dx$

Time Projection Chamber – TPC: Global tracking, PID via $dE/dx$

Time Of Flight system – TOF: PID via time-of-flight measurement

**Centrality in Pb-Pb collisions:**
Glauber model analysis of large-$\eta$ V0 scintillator amplitudes, alternatively from ZDC, Pixel, TPC.
The ALICE detector at LHC

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**Centrality in Pb-Pb collisions:**
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Heavy Ion collisions and medium evolution

Hadronic states provide many useful observables to characterize medium produced in ultra-relativistic heavy ion collisions and its evolution

**Kinetic freeze-out**
- stop elastic interactions

**Chemical freeze-out**
- stop inelastic interactions
- Fix particle ratios

**QGP expansion (lifetime @ LHC ~ fm/c)**
- hadronization and re-scattering

**Hydrodynamics, thermalization**
- radial and anisotropic flow

**Quark-Gluon Plasma formation**
(t ~ 1 fm/c after collision)

**Parton hard scattering/Jets**
- pQCD regime

**Pre-equilibrium state**
Identified particle $p_T$ spectra and ratios

The thermal parameters of the system at freeze-out can be extracted through a hydrodynamic-inspired (Blast-wave) fit to the $p_T$ spectra of the primary identified particles.

**Particle ratios** are compared with **thermal models** (statistical approach) which assume that particles are created in thermal equilibrium governed by a scale parameter defined as “temperature”.

**Collective expansion** of the medium produced in HI collisions can be described by simple hydrodynamical models in terms of different flow terms.

**Radial flow** describes the expansion in the transverse plane and is derived by the measurement of primary particles average $p_T$.

Anisotropic flow: see Talks by Carlos Perez Lara, Anitha NYATHA
Each species spectrum has been fitted with a Blast-Wave* function to extract integrated yields and $\langle p_T \rangle$

$$\frac{dN}{p_T dp_T} \propto \int_0^R rdrm \int_0^\infty r drm I_0 \left( \frac{p_T \sinh \rho}{T_{kin}} \right) K_1 \left( \frac{m_T \cosh \rho}{T_{kin}} \right)$$

$$\rho = \tanh^{-1} \beta \quad \beta = \beta_s (r/R)^n$$

Comparison with hydro models:
Yields and shape of primary $\pi$, $K$ and $p$ are in good agreement with hydrodynamic models

Comparison with Au-Au at RHIC:
Harder spectra and flatter protons than at RHIC indicate a stronger radial flow at LHC
Blast-wave fit to $\pi/K/p$ spectra

*Global Blast-wave* fit to extract (kinetic) freeze-out temperature ($T_{fo}$) and average radial flow $\langle \beta \rangle$

$T_{fo}$ parameter of the model depends on $\pi$ fit range, resonances effect to be investigated

$\langle \beta \rangle \approx 0.66 \text{ c} \sim 10\%$ higher than at RHIC

$T_{fo}$ seems slightly lower than at RHIC

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Au-Au STAR, PRC 79, 034909 (2009)
Particle ratios vs thermal model

At LHC anti-particle/particle ratios at mid-rapidity are compatible with 1, as expected due to $\mu_B \sim 0$


At LHC anti-particle/particle ratios at mid-rapidity are compatible with 1, as expected due to $\mu_B \sim 0$

Difficult to reproduce all ratios simultaneously

This unexpected deviation is still to be understood

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The disappearance of strangeness suppression (i.e. strangeness enhancement) in HI collisions was one of the first signals predicted for the QGP.

The abundance of strange quarks in the medium favours the production of hyperons.

**Strangeness enhancement** is defined with respect to pp collisions as:

\[
E_i = \frac{Yield_{i}^{AA}}{\langle N_{\text{part}} \rangle} \frac{\langle N_{\text{part}} \rangle}{Yield_{i}^{pp}} / 2
\]
Strangeness enhancement with respect to pp collisions increases following hierarchy of strangeness content (valence quarks) of baryons.

ALICE results compared with lower energy data (SPS, RHIC):
- enhancement decreases as energy increases
- same trend observed from RHIC to SPS

Light hadrons suppression in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV

High $p_T$ partons coming from hard-scattering processes (pQCD) undergo energy loss in the medium.

The nuclear modification factor is defined as:

$$R_{AA} = \frac{d^2N^{AA} / dp_T d\eta}{\langle N_{coll}\rangle d^2N^{pp} / dp_T d\eta}$$

to compare Pb-Pb and pp collisions scaled with number of binary collisions.

$R_{AA} = 1$ if no medium effect

$$\langle N_{coll}\rangle = \langle T_{AA}\rangle \cdot \sigma^{INEL}_{pp}$$

$\langle T_{AA}\rangle$ = Nuclear overlap function from Glauber model (related to the number of binary collisions)

$\sigma^{INEL}_{pp} = 64 \pm 5 mb$
Suppression of high-$p_T$ particles in central collisions is stronger than that observed RHIC → a very dense medium is formed in central Pb-Pb collisions at the LHC.

$R_{AA}$ decreases with centrality
Minimum of $R_{AA}$ occurs at 6-7 GeV/c for all centralities
Identified light hadrons $R_{AA}$

For central collisions and high $p_T (> 8\text{GeV/c})$, the $R_{AA}$ of light hadrons is compatible

→ No strong flavour dependence of $R_{AA}$ is observed
→ Baseline for understanding heavy quark energy loss (talk by Andrea Dainese)

$K^0_s$: similar behavior as charged particles, meson suppression up to high $p_T$
$\Lambda$: enhancement at intermediate $p_T$ and suppression at high $p_T$
→ Related to the so-called “baryon anomaly”
$\Lambda/K^0_s$ ratio and the “baryon anomaly”

"Baryon anomaly": baryon/meson ratio vs. $p_T$ increases from pp to a value $>1$ for central Pb-Pb collisions at intermediate $p_T \rightarrow$ production via coalescence

$\Lambda/K^0_s$ Magnitude increases with both centrality and beam energy from RHIC to LHC.
ALICE provides many observables to study the particle production in different energy regimes in heavy ion collisions at the LHC

- $\pi/K/p$ spectra measurement provided indication for a **stronger radial flow at the LHC** than at RHIC
- **Anti-particle/particle ratio $\sim 1$**, as expected for $\mu_B \sim 0$ at the LHC
- **thermal model predictions** for particle ratios seem to be valid although some additional work is needed on proton yields
- **strangeness enhancement** has been observed and compared to results at lower energy
- **suppression of light hadrons ($R_{AA}$)** shows no obvious flavour dependence
- the “**baryon anomaly**” provides insight on the interplay between soft and hard particle production mechanisms

... and more in other talks at this conference or yet to come...
Thank you for your attention!
ITS – Inner tracking system

### ITS:
- 6 silicon layers, 3 technologies: pixel, strip, drift

**Primary vertex reconstruction (SPD)**
- Standalone tracking
- PID via dE/dx measurement in silicon with resolution of 10-15% in PbPb

### Table: ITS Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Silicon Pixel</th>
<th>Silicon Drift</th>
<th>Silicon Strip</th>
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</thead>
<tbody>
<tr>
<td>Spatial precision $\phi$ ((\mu m))</td>
<td>12</td>
<td>35</td>
<td>20</td>
</tr>
<tr>
<td>Spatial precision $z$ ((\mu m))</td>
<td>100</td>
<td>25</td>
<td>830</td>
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<tr>
<td>Two track resolution $\phi$ ((\mu m))</td>
<td>100</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>Two track resolution $z$ ((\mu m))</td>
<td>850</td>
<td>600</td>
<td>2400</td>
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<tr>
<td>Cell size ((\mu m^2))</td>
<td>50 x 425</td>
<td>202 x 294</td>
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<tr>
<td>Active area per module ((mm^2))</td>
<td>12.8 x 69.6</td>
<td>72.5 x 75.3</td>
<td>73 x 40</td>
</tr>
<tr>
<td>Readout channels per module</td>
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<td>2 x 256</td>
<td>2 x 768</td>
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<tr>
<td>Total number of modules</td>
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<td>260</td>
<td>1698</td>
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<tr>
<td>Total number of readout channels</td>
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<tr>
<td>Total number of cells</td>
<td>9.84</td>
<td>23</td>
<td>2.6</td>
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<tr>
<td>Max. occupancy for central Pb-Pb (inner layer) (%)</td>
<td>2.1</td>
<td>2.5</td>
<td>4</td>
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<tr>
<td>Max. occupancy for central Pb-Pb (outer layer) (%)</td>
<td>0.6</td>
<td>1.0</td>
<td>3.3</td>
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<tr>
<td>Power dissipation in barrel (W)</td>
<td>1350</td>
<td>1060</td>
<td>850</td>
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<tr>
<td>Power dissipation end-cap (W)</td>
<td>30</td>
<td>1750</td>
<td>1150</td>
</tr>
</tbody>
</table>

**dE/dx vs. p (GeV/c)**
- ITS stand-alone tracks
- PP @\(\sqrt{s} = 7\) TeV (2010 data)

**ALICE Performance**
- 9/5/2011
TPC – Time Projection Chamber

PID via $dE/dx$ measurement in gas with resolution of 5% in PbPb

ALICE Performance
Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV min. bias
18/05/2011

PID for high-$p_T$ particles via simultaneous $4\sigma$ fit of TPC signal on the relativistic rise of $dE/dx$ Bethe-Bloch
The ALICE Time-Of-Flight system:

- Based on Multi-Gap Resistive Plate Chamber
- \( r_{\text{in}} = 370 \text{ cm} \), \( 0^\circ \leq \phi \leq 360^\circ \), \( |\eta| < 0.9 \)
- 18 sectors, >153,000 readout channels

**PID via gaussian unfolding of TOF signal**

**Global* time resolution:** ~86 ps in Pb-Pb

*Includes resolution on event time zero
Tracking performance

**p_t resolution**

- **\( p_t \) resolution ~10% at 50 GeV/c**
- Small multiplicity dependence
- Estimate from track residuals

**DCA_{xy}: Transverse distance-of-closest-approach**

Good DCA_{xy} resolution

\[ \rightarrow \] control contamination from secondaries

Strict DCA_{xy} cut (< 7\( \sigma \)), small contamination

Residual contamination less than 1% for \( p_t > 4 \) GeV/c
Feed-down correction needed to eliminate contributions from weak decay of strange particle (Λ, Ξ, ...) to the primary protons spectrum.

Distance of closest approach (DCA) in the bending plane used to correct.

Correction estimated from a fit using Monte Carlo templates for distributions of primaries and secondaries
- from weak decay of strange particles
- from interaction with the material.

![Fraction of primaries](image)

- Strict DCA \(_{xy}\) cut (< 7\(\sigma\)) allow small contamination
- Residual contamination less than 1% for \(p_T > 4\) GeV/c
Multi-strange baryons analysis

- ITS vertexing + tracking
- TPC tracking + PID (dE/dx)
- Topological reconstruction of decays:
  - Selection of $\Lambda$ based on cuts on impact parameter and invariant mass
  - TPC PID for all decays products
- Signal extraction:
  - Polynomial+gaussian fit for mean and $\sigma$
  - Bin counting in ($\pm 3\sigma$) signal region
  - Integral of background fit function in signal region
  - Signal = bin counting - integral
Multi-strange baryons spectra

Pb-Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

$\Omega^-$

$\bar{\Omega}^+$

$\Xi^-$

$\bar{\Xi}^+$

Preliminary

$error = \sqrt{\text{stat}^2 + \text{sys}^2}$

$1/N_{\text{evts}} \frac{dN}{dp_T} \big|_{|y|<0.5}$ (GeV/c)$^{-1}$

$0-20\%$

$20-40\%$

$40-60\%$

$60-90\%$

$Pb-Pb$ at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

$error = \sqrt{\text{stat}^2 + \text{sys}^2}$

$1/N_{\text{evts}} \frac{dN}{dp_T} \big|_{|y|<0.5}$ (GeV/c)$^{-1}$

$0-20\%$

$20-40\%$

$40-60\%$

$60-90\%$

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Measured spectra in Pb-Pb at LHC vs RHIC

- ALICE, Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
- PHENIX, Au-Au, $\sqrt{s_{NN}} = 200$ GeV
- STAR, Au-Au, $\sqrt{s_{NN}} = 200$ GeV
- STAR (TOF, feed-down corr.)

ALICE Preliminary
0-5% most central

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Hydro models

VISH2+1:  
* viscous hydrodynamic model (2+1)  
* assumes longitudinal boost-invariance  
* assumes thermal yields ($T_{ch} = 165$ MeV)  
* no explicit description of the hadronic phase

HKM:  
* hydrokinetic model + hadronic cascade model (UrQMD)  
* the hydrokinetic model is based on dynamical decoupling described by escape probabilities

Krakow:  
* viscous hydrodynamics (3+1) with shear and bulk viscosities  
* assumes no longitudinal boost-invariance  
* ansatz to describe deviation from equilibrium due to viscosity corrections in the transition from hydrodynamics to particles

EPOS 2.17v3:  
* quantum mechanical multiple scattering approach for particle and jet production in high-density environment (energy loss) based on flux tubes (parton ladders)  
* hydrodynamical (3+1) evolution + hadronic cascade  
* Introduced to account for bulk matter, jets, and their mutual interaction
Blast-wave function

\[ \frac{dN}{p_{\perp} dp_{\perp}} \propto \int_0^R r dr m_{\perp} I_0 \left( \frac{p_{\perp} \sinh \rho}{T_{\text{kin}}} \right) K_1 \left( \frac{m_{\perp} \cosh \rho}{T_{\text{kin}}} \right) \]

\[ \beta = \beta_s (r/R)^n \quad \rho = \tanh^{-1} \beta \]

Free parameters: \( T_{\text{kin}}, \beta_s, n \)
- \( T_{\text{kin}} \): kinetic (thermal) freeze-out temperature in the model
- \( \beta \): transverse radial flow velocity
- \( \beta_s \): surface transverse flow velocity
- \( n \): velocity profile
- \( \rho_r \): transverse boost
- \( R \): transverse geometric radius of the source at the freeze-out
At the LHC anti-particle/particle ratios at mid-rapidity are compatible with 1, as expected \( \rightarrow \mu_B \sim 0 \)

*STAR, PRC 79, 034909 (2009)*
*PHENIX, PRC 69, 03409 (2004)*
*BRAHMS, PRC 72, 014908 (2005)*
Particle ratios – from RHIC to LHC

K/π and p/π ratios at LHC and RHIC exhibit similar centrality dependence.

K/π slightly increases with dN_{ch}/dη from pp to very central events.

STAR, PRC 79, 034909 (2009)
PHENIX, PRC 69, 03409 (2004)
BRAHMS, PRC 72, 014908 (2005)
Pions $R_{AA}$

ALICE Preliminary

pp reference used is measured pp in $\sqrt{s} = 2.76$ TeV (ALICE 2011 data)
Kaons and protons $R_{AA}$

$0-5\% \text{ Pb-Pb } \sqrt{s_{NN}} = 2.76 \text{ TeV}$
- Charged
- $p + \bar{p} + K^+ + K^-$

$5-10\% \text{ Pb-Pb } \sqrt{s_{NN}} = 2.76 \text{ TeV}$
- Charged
- $p + \bar{p} + K^+ + K^-$

$10-20\% \text{ Pb-Pb } \sqrt{s_{NN}} = 2.76 \text{ TeV}$
- Charged
- $p + \bar{p} + K^+ + K^-$

$20-40\% \text{ Pb-Pb } \sqrt{s_{NN}} = 2.76 \text{ TeV}$
- Charged
- $p + \bar{p} + K^+ + K^-$

$40-60\% \text{ Pb-Pb } \sqrt{s_{NN}} = 2.76 \text{ TeV}$
- Charged
- $p + \bar{p} + K^+ + K^-$

$60-80\% \text{ Pb-Pb } \sqrt{s_{NN}} = 2.76 \text{ TeV}$
- Charged
- $p + \bar{p} + K^+ + K^-$

$\text{pp reference used is measured pp in } \sqrt{s} = 2.76 \text{ TeV (ALICE 2011 data)}$