Soft probes in heavy-ion collisions at the LHC

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Outline

- Introduction on heavy-ion physics
- Selection of results
  - Global properties
  - Soft probes in nucleus-nucleus collisions
  - Collectivity in p-Pb collisions

This is far from being an exhaustive summary of the soft heavy-ion physics
Heavy-ion physics

study QCD matter under extreme conditions
high temperature and/or energy-density
that undergoes a phase transition
hadronic matter $\rightarrow$ deconfined quarks and gluons (QGP)

past: GSI SIS $\sim$2 GeV
      BNL AGS $\sim$5 GeV
      CERN SPS $\sim$20 GeV

present: BNL RHIC $\sim$200 GeV
          CERN LHC $\sim$5 TeV

future: CERN HI-LHC
        GSI FAIR $\sim$45 GeV
Nucleus-Nucleus collision: a process

**Hard processes:**
- Charm, Beauty, Jets
- Probe the whole evolution of the collision
- Thermalization time (RHIC) \( \tau_{th} \approx 0.6 \text{ fm/c} \)

**Soft processes:**
- high cross section
- decouple late – indirect signals for QGP

**Photons (real and virtual):**
- insensitive to the hadronization phase

**Freeze-out:**
- chemical: particle compositions is fixed (no more inel. Collisions) \( \rightarrow T_{ch} \approx 160 \text{ MeV} \)
- thermal: momentum spectra are fixed (no more elastic collisions) \( \rightarrow T_{f0} \approx 110 \pm 130 \text{ MeV} \)

(\( \pi, K, p, ... \))
Global event features
A-A collisions can be characterized by the centrality, defined through $b, N_{\text{part}}(N_{\text{spec}})$. 

Central collisions

Peripheral collisions

S. Bufalino - LHCP2016
Pb-Pb @ 2.76 TeV: charged particle multiplicity

- Charged particle multiplicity has been measured in a wide pseudo rapidity range (-3.5 < \( \eta \) < 5)
- the total number of charged particles ranges from \( 162 \pm 22 \) for centrality class 80-90% to \( 17170 \pm 770 \) for centrality class 0-5%
- in the central barrel they can be also identified over a broad momentum range


S. Bufalino - LHCP2016
Pb-Pb @ 5.02 TeV: charged particle multiplicity

- for the 5% most central collisions: $<dN_{\text{ch}}/d\eta> = 1943 \pm 54$ in $|\eta| < 0.5$
- steeper rise with the centre-of-mass energy
- centrality dependence: a factor of $\sim 1.2$ describes the increase from 2.76 to 5.02 TeV
- essential constraints for models
Bulk properties and collective expansion
Bulk particle production in Pb-Pb

In a thermalized system the radial expansion is driven by the pressure gradient from inside to outside, resulting in boosted $p_T$ spectra.

Simultaneous Blast-Wave model fit to the $\pi$, K, p spectra in central Pb-Pb collisions:
- radial flow $\langle \beta_T \rangle \approx 0.65 \sim 10\%$ larger than at RHIC
- kinetic freeze-out temperature $T_{kin} \approx 95$ MeV

ALICE, PRL, 109 252301 (2012)
Clear evolution: hardening of the spectrum with increasing centrality
It is more pronounced for the heavier particles
→ Mass ordering as expected from collective hydro expansion
Bulk production in $p$-$Pb$

Hydro models (krakow EPOS-LHC) reproduce data better than QCD inspired models (DPMJET)

A combined BW fit describes the spectra fairly well also in $p$-$Pb$
Bulk production in p-Pb

Hydro models (krakow EPOS-LHC) reproduce data better than QCD inspired models (DPMJET)

A combined BW fit describes the spectra fairly well also in p-Pb

similar trends in the $T_{\text{kin}} - <\beta_T>$ correlation for pp and p-Pb

Qualitatively PYTHIA (with Color Reconnection) shows a similar trend as the data

$\Rightarrow$ other final state mechanisms can mimic the effects of radial flow!
Bulk production in p-Pb

**Differential invariant yields as a function of charged-particle transverse momentum for several intervals of \( \eta \) and \( y^* \)**

**ATLAS, arXiv:1605.06436**
Baryon-to-meson ratio in Pb-Pb

Ratio enhancement at intermediate $p_T$
- **Hydro** describes only the rise $< 2$ GeV/c
- **Recombination** overestimates the effect
- **EPOS** gives good description of the data (with flow)

Baryon-to-meson ratio in Pb-Pb

Ratio enhancement at intermediate $p_T$
- **Hydro** describes only the rise < 2 GeV/c
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B/M ratio in jets significantly lower than in inclusive
⇒ baryon excess w.r.t basic fragmentation picture is not seen in jets, but arises from the bulk
Baryon-to-meson ratio in Pb-Pb

Ratio enhancement at intermediate $p_T$
- **Hydro** describes only the rise $< 2$ GeV/c
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**Flat $p/\phi$ ratio**
Mass dependence of the spectral shapes (**hydro**)

Strangeness enhancement

Long-standing ideas

– J. Rafelski and R. Hagedorn, in Statistical Mechanics of Quark and Hadrons
In **pp collisions** the production of strangeness relative to \( \pi \) at LHC is larger than at RHIC.
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**From pp to Pb-Pb** strangeness production increases.
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**From pp to Pb-Pb** strangeness production increases.

For $N_{\text{part}} > 150$ the ratios saturate and match predictions from the grand-canonical thermal models:
- GSI-Heidelberg: $T_{\text{ch}} = 164$ MeV
- THERMUS: $T_{\text{ch}} = 170$ MeV
Strangeness enhancement in PbPb

In **pp collisions** the production of strangeness relative to $\pi$ at LHC is larger than at RHIC

**From pp to Pb-Pb** strangeness production increases

In high-multiplicity $p$-$Pb$
- $\Xi/\pi$ compatible with central Pb-Pb
- $\Omega/\pi$ compatible with 60-80% Pb-Pb

Neither Pythia 6 nor 8 reproduces the values and the data evolution in any of the tunes tested.

Talk by A. Mischke in this session

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Thermal model of hadron production

chemical freeze-out
end of inelastic interactions
chemical composition is fixed

The analysis of the measured abundances allow one to set the thermodynamic variables \((T, \mu)\) at freeze-out
Thermal model fit

- Describes hadron production assuming chemical equilibrium over seven order of magnitude

\[
\begin{align*}
\pi^+ + \pi^- & \quad K^+ + K^- & \quad K^0_S & \quad K^+ + K^- & \quad \phi & \quad \Lambda & \quad \bar{K}^+ + \bar{K}^- & \quad d & \quad \bar{3}H + \bar{3}H & \quad \bar{3}He \\
\end{align*}
\]

\[dN/dy\]

\[10^3 \quad 10^2 \quad 10 \quad 1 \quad 10^{-1} \quad 10^{-2} \quad 10^{-3} \quad 10^{-4}\]

<table>
<thead>
<tr>
<th>Model</th>
<th>T (MeV)</th>
<th>$\chi^2$/NDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>THERMUS 2.3</td>
<td>155 ± 2</td>
<td>24.5/9</td>
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<td>15.1/9</td>
</tr>
</tbody>
</table>

ALICE Preliminary
Pb-Pb $\bar{N}_{NN} = 2.76$ TeV, 0-10%

Not in fit
Extrapolated

$BR = 25\%$
Thermal model fit

- Describes hadron production assuming chemical equilibrium over seven orders of magnitude.

- Measured absolute yields \( (dN/dy) \) in Pb-Pb collisions are well described by a thermal model with a temperature \( T = 156 \pm 2 \) MeV.

\[
\frac{\pi^+ + \pi^-}{2} \quad \frac{K^+ + K^-}{2} \quad K_S^0 \quad \frac{K^+ + K^-}{2} \quad \phi \quad \frac{D^+ + D^-}{2} \quad \Lambda \quad \frac{\pi^+ + \pi^-}{2} \quad \frac{\Omega^+ + \Omega^-}{2} \quad d \quad \frac{\bar{3}H + 2\bar{H}}{2} \quad \frac{\bar{3}He}{2}
\]

**Model**
- THERMUS 2.3: \( 155 \pm 2 \) MeV, \( \chi^2/NDF = 24.5/9 
- GSI-Heidelberg: \( 156 \pm 2 \) MeV, \( \chi^2/NDF = 18.4/9 
- SHARE 3: \( 156 \pm 3 \) MeV, \( \chi^2/NDF = 15.1/9 

**Data**
- ALICE Preliminary
- \( \sqrt{s_{NN}} = 2.76 \) TeV, 0-10%
- BR = 25%

**References**

\( \text{ALI-PREL-94600} \)
Thermal model fit

- Describes hadron production assuming chemical equilibrium over seven orders of magnitude.

- Measured absolute yields (dN/dy) in Pb-Pb collisions are well described by a thermal model with a temperature T=156 ± 2 MeV.

- Deviations for
  - Protons: incomplete hadron spectrum, baryon annihilation in hadronic phase, ...?
  - K^0 resonance: re-scattering in the late hadronic phase?

Measured absolute yields (dN/dy) in Pb-Pb collisions are well described by a thermal model with a temperature T=156 ± 2 MeV.

ALICE Preliminary
Pb-Pb \( \sqrt{s_{NN}} = 2.76 \) TeV, 0-10%

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\[ \begin{align*}
\frac{\pi^+}{2} & \quad \frac{K^+}{2} & \quad \frac{K^0}{2} & \quad \rho & \quad \phi & \quad \frac{p+\bar{p}}{2} & \quad \Lambda & \quad \frac{\Xi^+}{2} & \quad \frac{\Omega^+}{2} & \quad d & \quad \frac{^3\text{He}}{2} & \quad ^3\text{H} \\
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\end{align*} \]

Anisotropic flow

- Sensitivity to initial anisotropy
  - indicates existence of collective phenomena (flow)

- In non-central collisions, pressure gradients convert the spatial anisotropy in momentum anisotropy
Collective anisotropic flow

spatial anisotropy (collision geometry)

$\rightarrow$ anisotropy in momentum space: $v_2$

- strong collective flow persists at the LHC
- Integrated values of $v_2$ are sensitive to the range of $p_T$ included. A systematically larger $v_2$ is observed for the higher value of $p_T$

**Graphical Representation**

- **ATLAS**
  - Pb+Pb
  - $s_{NN}=2.76$ TeV

- **TKT method**: $L_{int} = 1 \mu b^{-1}$
- **PXT method**: $L_{int} = 0.5 \mu b^{-1}$

- **Data Points**
  - ATLAS TKT $p_T > 0.07$ GeV, $|\eta| < 1$
  - ATLAS PXT $0.1 < p_T < 5$ GeV, $|\eta| < 1$
  - ATLAS PXT $0.3 < p_T < 5$ GeV, $|\eta| < 1$
  - CMS $0.3 < p_T < 3$ GeV, $|\eta| < 0.8$

**Reference**

*ATLAS, EPJC 74 (2014) 2982*
• moderate increase in $v_2(p_T)$ at low $p_T$ from the highest RHIC energy to the LHC, despite the large increase in the centre-of-mass energy.
• integrated $v_2$ increase approximately logarithmically with $\sqrt{s_{NN}}$ with a 20–30% increase from RHIC to LHC.
Collective anisotropic flow

- Anisotropic flow $v_n$ integrated in the $p_T$ range $0.2 < p_T < 5.0$ GeV/c as function of centrality
  - average increase of $(3.0 \pm 0.6)\%$ for $v_2$, $(4.3 \pm 1.4)\%$ for $v_3$ and $(10.2 \pm 3.8)\%$ for $v_4$ from 2.76 to 5.02 TeV
  - results compatible with predictions from hydrodynamic models
The $v_2$ data from two-particle correlations systematically above the multiparticle correlation data → consistent with hydrodynamic models

Same behaviour in Pb-Pb and p-Pb → true collective effect
The ridge

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{\text{trk}}^{\text{eff}} \geq 110$

$1 < p_T < 3$ GeV/c

ALICE, PLB 719 (2013) 29

CMS, PLB 718 (2013) 795

ATLAS, Preliminary

$p+Pb \sqrt{s_{NN}}=5.02$ TeV

$0.5<p_{T}^{\text{ch}}<5.0$ GeV

$N_{\text{ch}} \geq 220$

Talk by A. Mischke in this session

LHCb, arXiv:1512.00439

ATLAS-CONF-2016-026

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Summary

Clear support for the creation of a fireball in local thermodynamics equilibrium in Pb-Pb collisions

Medium created at the LHC appears to be hotter in the initial phase than the medium at RHIC

• **Bulk particle production**
  • Central Pb-Pb hadron production described successfully by thermal fit with $T_{ch} = 156$ MeV
  • Deviations can be attributed to flow

• **Strangeness Enhancement**
  • seen clearly in Pb-Pb, evolution of ratios observed in p-Pb

• **Anisotropic flow**
  • suggestions for collective behaviour in small systems

Many more results and a bright future for soft physics with the complete sample of Run 2
Backup
Identified particles $v_2$

ALICE 10-20% Pb-Pb | $s_{NN} = 2.76$ TeV

mass ordering attributed to common radial expansion velocity

ALICE, JHEP 06 (2015) 190
Identified particles $v_2$

Also in p-Pb mass ordering observed at low $p_T$
- lower $v_2$ for heavier particles
- crossing at higher $p_T$
- reminiscent of A-A observations
Multiplicity: pp vs Pb-Pb

**pp @ 13 TeV**

**Pb-Pb @ 5 TeV**

![Graphs showing multiplicity distributions for pp and Pb-Pb collisions at different energies.](image)

- ALICE (INEL>0)
- ALICE (INEL)
- PYTHIA 8 (Monash-2013)
- PYTHIA 6 (Perugia-2011)

- S. Bufalino - LHCP2016
- Reconstructible resonance yields may be changed by **hadronic processes** after chemical freeze-out:

  - **Regeneration:** pseudo-elastic scattering of decay products (e.g. \(\pi k \rightarrow K^* \rightarrow \pi k\))
  - **Re-scattering:**
    - Resonance decay products undergo elastic scattering
    - Or pseudo-elastic scattering through a difference resonance
    - Resonance not reconstructed through invariant mass
Ratios of Yields

- **K*0/K**
  - Central Pb–Pb: significantly suppressed w.r.t. peripheral, pp, p–Pb, or thermal model
  - Consistent with the hypothesis that re-scattering is dominant over regeneration

- **φ/K**
  - No strong dependence on centrality or collision system
  - φ lifetime ~10x longer than K*0 re-scattering effects not significant
  - Ratio for central Pb–Pb consistent with thermal model

- Ratios in p–Pb consistent with trend from pp to peripheral Pb–Pb
In Pb-Pb collisions, for $p_T > 10$ GeV/c the suppression is the same for different particle species.
$R_{AA,pPb}$ of identified particles

In Pb-Pb collisions, for $p_T > 10$ GeV/c the suppression is the same for different particle species.

Indications for mass ordering of the Cronin peak → presence of other final state effects (flow, recombination, ...)?

ALICE, PLB 720 (2013) 52
ALICE, PLB 736 (2014) 196
Spectra of charged particles are strongly suppressed over a wide transverse momentum range in Pb-Pb collisions.
In p-Pb collisions a small Cronin peak is seen at 3<p_T<6 GeV/c
No nuclear modification factor in p-Pb

In p-Pb collisions a small Cronin peak is seen at 3<p_T<6 GeV/c
No modification is observed up to 50 GeV/c
No nuclear modification factor in p-Pb

In p-Pb collisions a small Cronin peak is seen at $3 < p_T < 6$ GeV/c
No modification is observed up to 50 GeV/c
Jet measurements: no modification up to 100 GeV/c
The double ridge

long-range \( (2 < |\Delta \eta| < 4) \), near-side \( (\Delta \phi \approx 0) \)

h-h correlation observed after removal of jet contribution

→ a double ridge was revealed and this looks like flow