Soft probes of QGP
An overview of recent results at the LHC

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Study of heavy ion collisions at the LHC

Quark-gluon plasma (QGP): A hot and dense medium of deconfined partons

More than 99% of the produced particles have a transverse momentum lower than 2 GeV/c

→ These soft particles are of major interest for the characterization of the QGP
Initial conditions
Study of the correlation between the initial shape of the fireball ($v_2$) and its size ($|p_T|$):

$$\rho_2(v_2^2, |p_T|) = \frac{\text{cov}(v_2^2, |p_T|)}{\sqrt{\text{var}(v_2^2)} \sqrt{\text{var}(|p_T|)}}$$

- Positive correlation between the shape and the size of the fireball
- **Better description with** models using **IP-Glasma initial conditions**
- $T_R$-ENTo-based models display a strong centrality dependence (Trajectum, JETSCAPE, v-USPhydro)
Investigating the initial stages with correlations

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- **Better description with** models using **IP-Glasma initial conditions**
- $T_{\text{RETo}}$-based models display a strong centrality dependence (Trajectum, JETSCAPE, $v$-USPhydro)

- **The difference between IP-Glasma and $T_{\text{RETo}}$ models** is mainly driven by different nucleon size ($w$)

→ ALICE measurements favors a **nucleon width parameter of ~0.4 fm** (supported by recent theoretical calculations [1][2])

→ This is **in contradiction with** state-of-the-art Bayesian analyses (from which are extracted QGP’s transport coefficients)

Investigating the initial stages with correlations

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- **Same measurement** was also performed in ATLAS in Pb-Pb and Xe-Xe.
- Discrepancy between IP-Glasma and T\textsubscript{RENTo} was also observed.

→ **Better description with models using IP-Glasma initial conditions**
Investigating the initial stages with correlations

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- Investigate the sensitivity of $T_{\text{RENTo}}$ to the nuclear deformation parameter $\gamma_{Xe}$ (triaxiality) in central collisions
  - **Large sensitivity to $\gamma_{Xe}$**
  - ATLAS measurement favors a **triaxial Xe** ($\gamma_{Xe} \sim 30^\circ$)
Anisotropic flow fluctuations

Fluctuations in the positions of nucleons in the incident nuclei influence the QGP expansion

→ The elliptic flow fluctuations can provide an insight on the early-stage dynamics of the collision

→ Fluctuation behavior is studied via the multi-particle cumulant values of $v_2$:

Measurements of $v_2$ from 2- to 10-particle cumulant values:

- First measurement of $v_2\{10\}$
- Gap between $v_2\{2\}$ and higher order cumulants

→ Consequence of non-Gaussian properties of the flow fluctuations

→ This non-Gaussian behavior can be quantified by the skewness, kurtosis and superskewness
Anisotropic flow fluctuations

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New constrain for hydrodynamic models
Hadronisation & small systems
The study of QGP signatures in small systems

There are signs of QGP-like phenomenon in small systems (pp and p-Pb)

- **Sizeable anisotropic flow**
  

  CMS

  \[ v_{2}^{\text{sub}}(\eta) \]

  - pPb \( s_{NN} = 5 \text{ TeV} \)
  - PbPb \( s_{NN} = 2.76 \text{ TeV} \)
  - \( |\Delta \eta| > 2 \)
  - \( 0.3 < p_{T} < 3 \text{ GeV/c} \)

  CMS

  \[ v_{3}^{\text{sub}}(\eta) \]

  - \( 0.3 < p_{T} < 3 \text{ GeV/c} \)

  What is the origin of the observed collectivity in small systems?

- **Strangeness enhancement**
  

  ALICE

  \[ \frac{\langle dN_{ch}/d\eta \rangle_{|\eta| < 0.5}}{1} \]

  \[ 10^{-1} \]

  \[ 10^{2} \]

  \[ 10^{3} \]

  \[ 10^{4} \]

  ALICE Preliminary

  - pPb, \( \sqrt{s}_{NN} = 8.16 \text{ TeV} \)
  - pPb, \( \sqrt{s} = 5.02 \text{ TeV} \)
  - Xe-Xe, \( \sqrt{s}_{NN} = 5.44 \text{ TeV} (\chi_{c}, \Xi, \Omega) \)
  - Xe-Xe, \( \sqrt{s}_{NN} = 5.44 \text{ TeV} (\Xi, \Omega) \)
  - Pb-Pb, \( \sqrt{s}_{NN} = 5.02 \text{ TeV} (\chi_{c}, \Xi, \Omega) \)
  - Pb-Pb, \( \sqrt{s}_{NN} = 5.02 \text{ TeV} (\Xi, \Omega) \)
**Initial stage effects on strangeness enhancement**

Is strangeness enhancement in **pp collisions** correlated only with final state particle multiplicities or does the initial stage of the collision play a role?

**Initial stage effects are probed via the effective energy**

The **energy effectively available** for particle production in the **initial stages** of the collision.

Double differential analysis of the $\Xi$ yield normalised to the charged particle multiplicity:

- **Large effective energy**
- **Small effective energy**

Constraining the range of **effective energy** **strongly affects the strangeness enhancement** with multiplicity.

→ **Effective energy plays an important role in the strangeness enhancement**
Two phenomenon are observed in Pb-Pb collisions:

- **Mass ordering at low** $p_T$
  
  → Consequence of the radial expansion of the medium (described by hydrodynamics)

- **Baryon-meson splitting of $v_2$ at intermediate** $p_T$ ($p_T > 3$ GeV/c)
  
  → Presence of partonic collectivity
Observation of collective effects in small system

Study of the elliptic flow of identified particles using hadron-hadron correlations in pp and p-Pb collisions:

- Mass ordering at low $p_T$
- Baryon-meson splitting of $v_2$ at intermediate $p_T$ ($p_T > 3$ GeV/c)

→ Same observations as in Pb-Pb collisions
Observation of collective effects in small system

Study of the elliptic flow of identified particles using hadron-hadron correlations in p-Pb collisions:

• Model with hydrodynamics, quark coalescence and jet fragmentation reproduces the data
• Model without quark coalescence can not describe the trend at intermediate \( p_T \)

→ Partonic collectivity in small systems
Freeze-out & rescattering
Shape of the particle emitting source

Femtoscopy measurement: particle correlation $C(q)$ at low $q$

- Related to the source $S(q)$: $C(q) \approx 1 + |S(q)|^2$
- In the past, mostly Gaussian or Cauchy shapes were assumed for $C(q)$
- A more general source distribution is a Lévy distribution (with core-halo model)

$$C(q) \approx 1 \pm \lambda e^{-|qR|^\alpha}$$

- $\alpha$: Lévy stability index → Source shape
- $R$: scale parameter of the medium → Spatial scale
- $\lambda$: correlation strength → core-halo ratio

→ Use femtoscopy measurement to study the shape of the particle emitting source
**Shape of the particle emitting source**

The average shape parameter is between 1.6 and 2

- The source is described by a Lévy distribution
- The shape is centrality dependent
- Gaussian shape is only approached in the most central events

Linear scaling $1/R^2 = A m_T + B$

- Predicted by hydrodynamics for a Gaussian source
- Same linear behavior for a Lévy source
- Larger slope in peripheral events

→ related with expansion velocity and freeze-out temperature
Precision measurement $\mu_B$ via Baryon/Baryon ratio

$\mu_B$ and $\mu_{I3}$ are extracted from the fit with SHM equation

$$\frac{\bar{h}}{h} \approx \exp \left[ -2 \left( B + \frac{S}{3} \right) \frac{\mu_B}{T} - 2I_3 \frac{\mu_{I3}}{T} \right]$$

with $T = 156.2 \pm 1.5$ MeV

New measurement of the antimatter/matter imbalance

- $[B = 0 ; S = 0] \rightarrow \pi$ Imbalance < 0.5%
- $[B = 1 ; S = 0] \rightarrow p$ Imbalance ~1%
- $[B = 3 ; S = 0] \rightarrow ^3\text{He}$ Imbalance ~6%
- $[B = 3 ; S = 1] \rightarrow ^\Lambda\text{H}$ Imbalance ~10%

Baryon number = B; Strangeness number = S

Precision on the baryochemical potential value has been **improved by a factor 10**

**$\mu_B$ is close to 0** at the LHC
Properties of hadronic phase with resonances

Resonance lifetime (fm/c):

\[ \rho^0(1.3) < K^*(4.0) < \Sigma^*(5.5) < \Lambda^*(12.6) < \Xi^*(21.7) < \phi(46.3) \]

Suppression of the \( \Lambda(1520)/\Lambda \) yields in Pb-Pb events:

- Decreasing trend with \( \sim 7\sigma \) significance in central Pb-Pb events wrt peripherals
- Trend with centrality reproduced by hydrodynamic (MUSIC) with hadronic afterburner (SMASH)
- No suppression observed in pp and p-Pb collisions

→ Yet another confirmation of existence of a hadronic phase lasting enough to cause a significant reduction of the yield of short lived resonances
Conclusion

Initial conditions:
- Correlation between the size and the shape of the fireball better described by models using IP-Glasma
- $T_{\text{ENTo}}$ model shows large sensitivity to the triaxiality of deformed nuclei in the most central collisions
- New hydrodynamic observables via high-order cumulants of the elliptic flow

Hadronisation:
- Strangeness enhancement in pp collisions is correlated with the initial stage of the collision
- Observation of partonic collectivity in small systems

Freeze-out and rescattering:
- The particle-emitting source shape is described by a Lévy distribution
- New measurement of $\mu_B$ with a precision increased by a factor 10
- The suppression of the $\Lambda(1520)$ yield is well reproduced by MUSIC with SMASH afterburner

With the start of LHC Run 3, more measurements are to come!
Longitudinal structure of the initial state

Study of the longitudinal dependence of flow in **pp and Xe-Xe**
- Also called **longitudinal flow decorrelation**
- Provide constraints on the initial longitudinal dynamics

Measurement of the **flow decorrelation**

\[
r_2(|\eta_a|) = \frac{v_{2,2}(-|\eta_a|)}{v_{2,2}(|\eta_a|)} = 1 - 2F_2|\eta_a|
\]

**raw Fourier**: combination of flow and non-flow

**temp. fit**: subtract ~85% of non-flow contribution

**d_1 sub**: subtract ~25% of non-flow contribution

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Study of the longitudinal dependence of flow in **pp** and **Xe-Xe**:

- **Larger decorrelation in pp** than in Xe-Xe at similar multiplicities
- **Good qualitative agreement** between AMPT and the Xe-Xe data, and **poor agreement in pp**
- **Disfavors AMPT pp initial-state model with a small number of strings**
Investigating the initial stages with correlations

![Graphs showing correlations](image)

FIG. 2. Results of the IP-Glasma+MUSIC+UrQMD framework for $\rho(v_2^2, [p_T])$ (left) and $\rho(v_3^2, [p_T])$ (right). Different types of shaded bands correspond to different values of the nucleon width. The orange band with starry hatches corresponds instead to a calculation with reduced viscosities. The dashed lines are estimators using JETSCAPE initial conditions. Symbols are preliminary ATLAS data [23] (diamonds) for charged particles with $0.5 < p_T < 2$ GeV, $|\eta| < 2.5$ and the centrality defined via $\sum E_T$, and preliminary ALICE data [22] (circles) for charged particles with $0.2 < p_T < 3$ GeV, $|\eta| < 0.8$, and the centrality defined via V0M amplitude. We note that the larger upper $p_T$ cut implemented in the ALICE analysis explains in part the larger magnitude of their $\rho_1$ compared to ATLAS data for non-central collisions.

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High multiplicity at midrapidity

Low multiplicity at midrapidity

There is a strangeness enhancement with effective energy, when the multiplicity is fixed

→ Effective energy plays an important role in the strangeness enhancement

$E_{\text{eff}} \simeq \sqrt{s} - \langle \text{ZDC Energy Sum} \rangle$

https://alice-figure.web.cern.ch/node/22044

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