Latest results on hadronic resonance production with ALICE at the LHC

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Outline:

- Motivation
- ALICE detector and analysis details
- Results:
  - $p_T$ spectra
  - Mean transverse momentum ($<p_T>$) and Yield (dN/dy)
  - Particle ratios
  - Nuclear modification factors
- Summary and outlook
Why resonances?

Lifetime (fm/c): $\rho^0 (1.3) < K^*\pm (3.6) < K^*0 (4.16) < \Sigma^*\pm (5.0-5.5) < \Lambda^* (12.6) < \Xi^*0 (21.7) < \phi (46.2)$

Resonances are short lived particles and decay by the strong interaction.

Hadronic phase: Timespan between chemical and kinetic freeze-out.

- Modification of yields (re-scattering vs re-generation)
- Estimate the lifetime of the hadronic phase
- Hadrochemistry of particle production
- Study of in medium energy loss
ALICE Detector

Forward detector (V0): V0A (2.8<\(\eta\)<5.1) and V0C (-3.7<\(\eta\)<-1.7)

❖ Trigger, centrality

TimeProjectionChamber (TPC): (|\(\eta\)| < 0.9)

❖ Primary vertex and tracking
❖ Measure momentum
❖ PID through dE/dx

Time-Of-Flight (TOF): (|\(\eta\)| < 0.9)

❖ PID through time of flight
Analysis details: resonance reconstruction

1. **Invariant mass method**: Resonances reconstructed from their decay products

   \[ M_{\text{inv}} = \sqrt{(E_1 + E_2)^2 - (p_1 + p_2)^2} \]

2. **Signal + Background**: Identify decay products and add 4 momenta of unlike charge pairs

3. **Combinatorial background**: Using mixed event or like-charge or background fit function techniques

4. **Residual background**: Background after removing combinatorial background and that arises from other sources of correlations and mis-identified decay products

5. **Signal**: After subtraction of residual background

   Signal (Breit-Wigner or Voigtian function) + Residual background

   **Yield**: Area under the Breit-Wigner
$p_T$ spectra in heavy-ion collisions

The inverse slope of $p_T$ spectra increases from peripheral to central collisions

Similar spectra shape also observed for $K^{0*}$ and $\phi$ in Xe-Xe collisions
\( p_T \) spectra in pp and p-Pb collisions

**p-Pb \( \sqrt{s_{NN}} = 8.16 \) TeV**

\[ \begin{align*}
\text{K*0} & \quad \text{pp} \ \sqrt{s} = 13 \text{ TeV}
\end{align*} \]

- The spectral shape changes with multiplicity for \( p_T < 4 \text{ GeV/c} \)

- The spectral shapes are similar across multiplicity for \( p_T > 4 \text{ GeV/c} \)

The inverse slope of \( p_T \) spectra increasing with event multiplicity

Spectral shape changes with multiplicity are qualitatively similar in pp, p-Pb and Pb-Pb collisions

Similar trend also observed for \( \phi \) in pp and p-Pb collisions (not shown here)
Mean \( <p_T> \) and integrated yield \((dN/dy)\)

- Central Pb-Pb collisions:
  - Mass ordering

- Peripheral Pb-Pb and small collisions (pp, p-Pb):
  - \( <p_T>_{p} < <p_T>_{q} \approx <p_T>K^{*0} \)
  - Mass ordering breaks down

- Small collisions (pp, p-Pb):
  - \( <p_T> \) rises faster with multiplicity than Pb-Pb collisions

- \( dN/dy \) normalised to \( <dN_{ch}/d\eta>\):
  - \( K^{*0} \) production is independent of colliding system or energy for pp and p-Pb collisions with similar multiplicity -> Event multiplicity drives particle production

- Similar trend observed also for other hadron species.
Resonances to long lived particle ratios

Lifetime (fm/c): $\rho^0 (1.3) < K^{*0} (3.6) < K^{*0} (4.17) < \Sigma^* (5.0-5.5) < \Lambda^* (12.6) < \Xi^* (21.7) < \phi (46.2)$

**Pb-Pb collisions:**

- Suppression of the yield of $K^{*0}/K$ in central Pb–Pb collisions in comparison to peripheral Pb-Pb collisions, pp and statistical thermal model predictions
  -> Suggests that re-scattering is dominant over regeneration

- In contrast, $\phi/K$ not suppressed
  -> Re-scattering effects not significant

**Small systems:**

The yield of $K^{*0}/K$ show a possible decreasing trend with multiplicity for pp, p–Pb collisions

- Could be a hint of finite lifetime of the hadronic phase

$<dN_{ch}/d\eta>^{1/3}$: Proxy for system size
Extract lifetime of hadronic phase

Assumption:
- No regeneration effects between chemical and kinetic phase
- No time-dilation effects on the resonance lifetime

\[
\left[ \frac{K^{*0}}{K} \right]_{\text{kinetic}(Pb-Pb)} = \left[ \frac{K^{*0}}{K} \right]_{\text{chemical}(pp)} \times \exp\left(-\frac{\tau}{\tau_{K}^{*0}}\right)
\]

\[\tau_{K}^{*0} = \text{Lifetime of } K^{*0}\]

\[\tau = \text{Timespan between chemical and kinetic freeze out}\]

\[\begin{align*}
K^{*0}/K & \quad \phi/K \\
\text{ALICE} & \\
pp 13 \text{ TeV} & \\
pp \text{INEL 5.02 TeV} & \\
p-Pb 5.02 \text{ TeV} & \\
Ps-Pb 5.02 \text{ TeV} & \\
\text{Pb-Pb 2.76 TeV} & \\
\end{align*}\]

A smooth increase of \(\tau\) (fm/c) with system size from p–Pb to Pb–Pb collisions observed
Nuclear modification factors ($R_{AA}$ or $R_{pPb}$)

$R_{AA,pA} = \frac{\text{Yield}_{AA,pA}}{\langle N_{coll} \rangle \times \text{Yield}_{pp}}$

**High- $p_T (> 8 \text{ GeV/c})$:**

- - < 1, suppression (presence of in medium effects)
- - Light-flavoured hadrons consistent with each other at $p_T > 8 \text{ GeV/c} \rightarrow \text{No flavoured (u,d,s) dependence}

**High- $p_T (> 6 \text{ GeV/c})$:**

- - = 1, no suppression (absence of nuclear effects)
- - Light-flavoured hadrons consistent with each other at $p_T > 6 \text{ GeV/c} \rightarrow \text{No flavoured (u, d, s) dependence}

At high $p_T$, D mesons also exhibit similar suppression as light-flavour hadrons.
Explore new resonances

f0(980): Tetraquark candidate
Mass m : (0.99 ± 0.02) GeV/c^2
Full width Γ from 0.01 to 0.1 GeV/c^2

First measurement of Ξ(1820) with ALICE at LHC,Pb–Pb, Ξ(1820): JP=3/2-
measurement in progress at ALICE in pp , p-Pb and Pb-Pb (ΛK channels)

Search for higher mass resonance K^0*(1420) and K^2*(1430), f0(1525) are ongoing
Summary and outlook

- The spectral shape of $p_t$ distribution changes with multiplicity at low $p_t$, whereas spectral shapes are similar at high $p_t$ -> Hardening of $p_t$ spectra with multiplicity
- At similar multiplicity, the scaled integrated yields are similar in pp, p-Pb and Pb-Pb collisions -> Event multiplicity drives particles production irrespective of collision systems and energies
- $<p_t>$ Mass ordering central Pb-Pb collisions and $<p_t>$ increases faster with multiplicity for small collisions than Pb-Pb collisions
- The yield ratio of $K^*/K$ decreases for central Pb-Pb collisions in comparison to peripheral Pb-Pb collisions, pp, p-Pb collisions and statistical-model predictions -> Rescattering dominates over regeneration
- At high $p_t$, $R_{AA}$ of light flavour hadrons show suppression whereas $R_{pPb}$ consistent with unity -> Presence of in medium effects in Pb-Pb collisions
- Nuclear modification factors of light flavour hadrons are consistent with each other within uncertainties -> No flavour or species dependence
Back up

THANK YOU
Re-scattering vs Regeneration

\[ \sigma(\pi\pi) \gg \sigma(K\pi) \]
Why resonances?

Lifetime (fm/c): $\rho^0 (1.3) < K^{*\pm} (3.6) < K^{*0} (4.16) < \Sigma^{*\pm} (5.0-5.5) < \Lambda^{*} (12.6) < \Xi^{*0} (21.7) < \phi (46.2)$

Particles that are unstable against decay by the **strong interaction**. They have mean lives of the order of $10^{-23}$ seconds (~fm/c)

- **Re-scattering**: Daughter particles undergo elastic scattering through exchange of momentum: **Reduced yield**
- **Regeneration**: Pseudo-elastic scattering through resonance state: **Enhanced yield**

Yield of resonances depend on:
- Chemical freeze-out temperature
- Lifetime of hadronic phase
- Resonance lifetime
- Scattering cross-section of decay products

Hadronic phase: Timespan between chemical and kinetic freeze-out

- **Resonances with different lifetime (~few fm/c) (Re-scattering vs. Regeneration)**
  - Sensitive to the **hadronic phase** and the evolution of system dynamics
  - Modification of yields, particle ratios and **extract lifetime** of the hadronic phase
  - Particle production mechanism

- **Resonance nuclear modification factor** → study **in-medium energy loss**
$p_T$ spectra in heavy-ion collisions

$\phi$ in Pb-Pb and Xe-Xe collisions:

- $p_T$ spectra become harder with increasing multiplicity (from peripheral to central collisions).
- Similar spectra shape also observed for $\phi$ in Xe-Xe collisions.
**$p_T$ -differential particle ratios**

At low $p_T$:
- $K^0/K$, $K^0/\pi$ for central Pb-Pb collisions are lower than peripheral Pb-Pb and pp collisions whereas $\phi/K$ and $\phi/\pi$ are comparable within the uncertainties
  —> Demonstrate the re-scattering process affects low momentum particles

Intermediate $p_T$:
Ratios show greater enhancement for central Pb-Pb collisions than peripheral and pp collisions (more for $\phi/K$, $\phi/\pi$ than $K^0/\pi$)
—— Consistent with expectation for presence of radial flow [1]

Hint of similar behaviour also observed in high multiplicity in pp collisions at $\sqrt{s} = 13$ TeV [2]
**Nuclear modification factors** ($R_{AA}$ or $R_{pPb}$)

**Intermediate-$p_T$ ($2 < p_T < 8$ GeV/c):**
- $K^*0$, π, K and φ suppression is similar but different from proton.

**High-$p_T$ ($> 8$ GeV/c):**
- - $< 1$, **suppression** (presence of final state effects)
- - Consistent with light-flavoured hadrons at $p_T > 8$ GeV/c -> No flavor ($u, d, s$) dependence

**Intermediate-$p_T$ ($2 < p_T < 6$ GeV/c):**
- - Mass dependent for strange baryons, baryons and meson grouped, proton show enhancement

**High-$p_T$ ($> 6$ GeV/c):**
- - $= 1$, **no suppression** (absence of nuclear effects)
- - Consistent with light-flavoured hadrons at $p_T > 6$ GeV/c -> No flavor ($u, d, s$) dependence
**R\textsubscript{AA}** vs Centrality, Energy and System size

### Centrality dependence

- **Suppression decreases from most central to peripheral**
- No significant energy dependence for all centrality classes
- No system size dependence at similar multiplicity

![Graph showing centrality dependence](image1)

### Energy dependence

- **K\textsuperscript{0}**
- **0-10%**
- **10-20%**
- **20-30%**
- **30-40%**
- **40-50%**

![Graph showing energy dependence](image2)

### System size dependence

- **Xe-Xe** \(\sqrt{s_{\text{NN}}} = 5.44\text{ TeV}, 0-30\%

![Graph showing system size dependence](image3)

**R\textsubscript{AA}**: 

- Suppression decreases from most central to peripheral
- No significant energy dependence for all centrality classes
- No system size dependence at similar multiplicity
Mean transverse momentum ($<p_T>$) vs multiplicity

- $<p_T>$ increases with increasing multiplicity.
- Most central collisions: mass ordering, $<p_T>_{\phi} \approx <p_T>_p$, as expected from hydrodynamics.
- Steeper increase of $<p_T>$ with multiplicity in smaller systems.

$\langle p_T \rangle (\text{GeV}/c)$ vs multiplicity.
**$p_T$-differential particle ratios**

At low $p_T$:

K$^{*0}$/K for central collisions are lower than peripheral (pp) collisions whereas $\phi$/K are comparable within the uncertainties —> due to re-scattering process in the hadronic phase must effect on low momentum

Intermediate $p_T$:

Ratios show greater enhancement for central Pb-Pb collisions than peripheral and pp collisions (more for $\phi$ than K$^{*0}$)
$<p_T>$ as a function multiplicity from pp to Pb-Pb collisions

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