Resonance production from pp to heavy-ion collisions

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Outline

- Heavy-ion physics - main concepts
- Hadronic resonances - physics motivation
- Hadronic resonances - results from ALICE (mainly)
  - $p_T$ spectra in pp, p–Pb and heavy-ion collisions.
  - $p_T$ integrated yields and $\langle p_T \rangle$.
  - Particle yield ratios.
  - Nuclear modification factors.
- The future of hadronic resonances and summary
Heavy-ion Physics

- **Study matter**
  - At energy densities like 10 μs after the Big Bang.
  - At temperatures $10^5$ times larger than in the Sun core.

- **Study QCD**
  - Without confinement.
  - With quarks at their bare masses.

- **But also:**
  - Study QCD in the non-perturbative regime.
Heavy-ion Physics

- Kinetic freeze-out
  - Elastic reactions cease: $p_T$ spectra (free streaming of hadrons)
- Chemical freeze-out
  - Inelastic reactions cease: The chemical composition of the system is fixed (particle yields)
- Phase transition from QGP to hadron gas
  - Formation of Quark-Gluon Plasma phase (if $T > T_c$)
- "Pre-equilibrium"
- Two Lorentz contracted nuclei approach and collide
Heavy-ion Physics

Region accessible through resonance measurements.

Hydrodynamic Evolution

1 fm/c = 3 \cdot 10^{-24} \text{ s}
Heavy-ion Physics

QCD Phase Diagram

- Early universe
- Particle accelerators
- Phase transition
- Quark-gluon plasma
  - Deconfined
  - Chiral symmetry
- Confined Hadron phase
- Chiral symmetry broken
- Color superconductivity (several phases)
- Neutron stars

Adapted from hep-ph/0503184
The ALICE detector

- Inner Tracking System (ITS)
  - 6 layers of silicon detectors
  - Provide trigger, tracking, vertex, PID (dE/dx)

- Time Projection Chamber (TPC)
  - Gas-filled ionization detector
  - Tracking, vertex, PID (dE/dx)

- Time Of Flight (TOF)
  - PID through particle time of flight

- V0A and V0C
  - Trigger, centrality/multiplicity estimator

<table>
<thead>
<tr>
<th>System</th>
<th>Year</th>
<th>$\sqrt{s_{NN}}$ (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb–Pb</td>
<td>2010</td>
<td>2.76</td>
</tr>
<tr>
<td></td>
<td>2011</td>
<td>2.76</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>5.02</td>
</tr>
<tr>
<td></td>
<td>2018</td>
<td>5.02</td>
</tr>
<tr>
<td>Xe–Xe</td>
<td>2017</td>
<td>5.44</td>
</tr>
<tr>
<td>p–Pb</td>
<td>2013</td>
<td>5.02</td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td>5.02, 8.16</td>
</tr>
<tr>
<td>pp</td>
<td>2009-2013</td>
<td>0.9, 2.76, 7</td>
</tr>
<tr>
<td></td>
<td>2015-2018</td>
<td>8, 13</td>
</tr>
</tbody>
</table>
Geometry and centrality of the collision

Geometry of a heavy-ion collision

b: impact parameter.

b=0-5 fm: 0-10% central collisions
b=10-12 fm: 60-80% peripheral collisions.
Glauber Monte Carlo:

Input: nuclear charge densities. inelastic nucleon-nucleon cross section.

Assumptions:
- Nucleons travel on straight lines
- Collisions do not alter their trajectory (energy of nucleons large enough)
- No quantum-mechanical interference
- Interaction probability for two nucleons is nucleon-nucleon cross-section

Output:
- Number of spectators (nucleons that do not collide).
- Participant or wounded nucleons ($N_{\text{part}}$).
- Number of binary collisions ($N_{\text{coll}}$).

Blue nucleon has suffered 5 NN collisions.

More details in nucl-ex/0701025
Geometry and centrality of the collision

Multiplicity is anti-proportional to b.

Glauber MC + particle production model calculates multiplicity.

Multiplicity is calculated experimentally by detectors.

The experimental distribution is fitted with the one from the Glauber MC. Events are split into classes, called 0−5%, 5−10% etc. The 0−5% class is the most central.
Geometry and centrality of the collision

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

Data

NBD-Glauber fit

$P_{\mu,k} \times \left[ f N_{\text{part}} + (1-f)N_{\text{coll}} \right]$

$f = 0.801$, $\mu = 29.3$, $k = 1.6$

ALICE-PUB-89449

PHYSICAL REVIEW C 88, 044909 (2013)

P. Ganoth, 20 October 2021
Resonances are ideal probes to study the hadronic phase in nucleus - nucleus collisions, as they have lifetimes comparable with the fireball lifetime.

Yields at kinetic freeze-out depend on:

- Resonance lifetime
- Lifetime of the hadronic phase ($\Delta \tau$)
- Yield at the chemical freeze-out
- Scattering cross sections of decay products
### Physics motivation

<table>
<thead>
<tr>
<th>Resonance</th>
<th>( p(770)^0 )</th>
<th>K*(892)^0</th>
<th>K*(892)^0</th>
<th>f_0(980)</th>
<th>( \Sigma(1385)^0 )</th>
<th>( \Xi(1820)^0 )</th>
<th>( \Lambda(1520) )</th>
<th>( \Xi(1530)^0 )</th>
<th>( \phi(1020) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quark composition</td>
<td>( \frac{u\bar{u} + d\bar{d}}{\sqrt{2}} )</td>
<td>( u\bar{s}, \bar{u}s )</td>
<td>( d\bar{s}, \bar{d}s )</td>
<td>unknown</td>
<td>( uus, dds )</td>
<td>( uss )</td>
<td>( uds )</td>
<td>( uss )</td>
<td>( s\bar{s} )</td>
</tr>
<tr>
<td>( \tau(\text{fm/c}) )</td>
<td>1.3</td>
<td>3.6</td>
<td>4.2</td>
<td>large unc.</td>
<td>5-5.5</td>
<td>8.1</td>
<td>12.6</td>
<td>21.7</td>
<td>46.4</td>
</tr>
<tr>
<td>Decay</td>
<td>( \pi \pi )</td>
<td>( K^0 \pi )</td>
<td>( K\pi )</td>
<td>( \pi^+ \pi^- )</td>
<td>( \Lambda \pi )</td>
<td>( \Lambda K )</td>
<td>( pK )</td>
<td>( \Xi \pi )</td>
<td>( K K )</td>
</tr>
<tr>
<td>B.R. (%)</td>
<td>100</td>
<td>33.3</td>
<td>66.6</td>
<td>46</td>
<td>87</td>
<td>unknown</td>
<td>22.5</td>
<td>66.7</td>
<td>48.9</td>
</tr>
</tbody>
</table>
## Observables

<table>
<thead>
<tr>
<th>Observables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle yields and ratios of identified particles</td>
<td>chemistry of the system and chemical freeze out temperature</td>
</tr>
<tr>
<td>$p_T$-differential spectra and ratios, mean $p_T$</td>
<td>system dynamics (radial flow, kinetic freeze out temperature)</td>
</tr>
<tr>
<td>System size scan</td>
<td>evolution with multiplicity of chemistry and dynamics (HIC like phenomena observed in high multiplicity pp and pA events)</td>
</tr>
</tbody>
</table>
Resonance reconstruction - Analysis strategy

- Resonances are reconstructed via the invariant mass technique.
  \[ M_{\text{inv}} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2} \]

- Uncorrelated background is calculated via event mixing or like-sign techniques.

- PID from ITS, TPC, TOF for the daughter tracks.

- Residual background: Correlated pairs or misidentified decay products, usually modelled by a polynomial function.

- Signal: Fit the event-mixing (or like-sign) subtracted distribution with a Breit-Wigner or Voigtian function (signal function) and the polynomial background.

- Yields are calculated by integrating the signal function.
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$p_T$ spectra in heavy-ion collisions

ALICE has measured resonances in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV (but also in Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV).

$\rho^0$

$\Lambda(1520)$

$\Xi^{0}$


ALICE Preliminary


P. Ganioti, 20 October 2021
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**$p^0$**

**$\Lambda(1520)$**

**$\Xi^0$**

Hardening of the spectra with increasing multiplicity caused by radial flow.

P. Ganoti, 20 October 2021
Radial flow: predicted by hydronamics in A–A due to the higher energy density.

- The only type of collective flow in A–A collisions with impact parameter $b = 0$.
- Affects the shape of particle spectra at low $p_T$.

$p = m \beta y$

Common velocity field $\beta y$ fixed $\rightarrow$ mass dependence


\[ p_T \text{ spectra in p–Pb collisions} \]

Qualitatively similar observations as for heavy-ion collisions regarding the shapes.

Collective flow-like effects in small collision systems.
**$p_T$ spectra in pp collisions**

The spectra shapes change with multiplicity in the same way as for the larger systems.

Ratio between the two energies evolves with $p_T$. Hint of saturation at $p_T \sim 5$ GeV/c.

Pythia tunes give good description except the Monash tune for the $\phi$.

HERWIG describes the ratio for $K^*$ but $\phi$ only up to $\sim 3$ GeV/c.

EPOS-LHC underestimates $K^*$ but describes $\phi$ up to $\sim 7$-8 GeV/c.
In pp and p–Pb collisions there is a linear increase of $dN/dy$ following a common trend for all resonances, independent of the collision system and energy.

Similar results are seen for strange hadrons.
In heavy-ion collisions, $K^*$ production is driven by the multiplicity.
$p_T$ integrated yields

dN/dy, scaled by the average charged particle multiplicity measured at midrapidity.

The dependence on $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ is found to be the same regardless of the beam energy.
The $\langle p_T \rangle$ values of $K^0$ and $\phi$ in pp collisions at $\sqrt{s} = 7$ TeV and 13 TeV follow approximately the same trend.

The $\langle p_T \rangle$ values $K^0$ and $\phi$ rise slightly faster as a function of $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ in pp collisions than in p–Pb collisions for $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$. 
Mean transverse momentum

The $\langle p_T \rangle$ values increase with charged particle multiplicity.

The $\langle p_T \rangle$ of $K^0$ and $\phi$ mesons (which have similar masses) are similar for events with the same $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ in Pb–Pb collisions → Consistent with the picture of a growing contribution of radial flow with increasing $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$

The $\langle p_T \rangle$ values are larger for higher energy collisions at similar values of $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$. 
Mean transverse momentum

ALICE Preliminary
- Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
- Xe-Xe, $\sqrt{s_{NN}} = 5.44$ TeV
- $|y| < 0.5$
- $K^{*0}$

Uncertainties: stat. (bars), sys. (boxes)

ALICE Preliminary
- Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
- Xe-Xe, $\sqrt{s_{NN}} = 5.44$ TeV
- $\phi(1020)$, $|y| < 0.5$

Similar evolution of $\langle p_T \rangle$ in Pb–Pb and Xe–Xe collisions.
Mean transverse momentum

Steeper rise of $\langle p_T \rangle$ for the heavier particles.

$K^*$, p and $\Phi$ (they have similar masses):

- At the higher multiplicities have similar $\langle p_T \rangle$ within the uncertainties.
- At lower multiplicities mass scaling is breaking.

arXiv:2106.13113
All particle ratios evolve smoothly with system size for the measured systems and energies.

Short-lived resonances like $p^0, K^{*0}, \Sigma^*; \Lambda^*$ are affected by re-scattering in the hadronic phase.

$\Xi^*$ production is rather independent of the system size.

$\phi$ is not suppressed as it decays after the kinetic freeze-out.

EPOS with UrQMD qualitatively describes the trends, except for $\Sigma^*/\Lambda$.

Short-lived resonances are used to measure the hadronic phase lifetime: 4–7 fm/c (PLB 802 (2020) 135225) in the most central collisions, in agreement with femtoscopic measurements.
**K*/K:**
Gradual decrease with the system size→effect of rescattering.
Lower values for Au–Au and Pb–Pb central collisions in all centre-of-mass energies.

**φ/K:**
approximately constant with the system size (due to the larger lifetime) and centre-of-mass energies.

- The thermal model predictions without rescattering effects agree with the φ/K and the K*/K in small systems, but

K*/K in central Pb–Pb collisions is not described.

- EPOS3 with UrQMD afterburner (Phys. Rev. C 93 (2016) 014911) describes better the two ratios.
**Particle yield ratios**

**K*/K:**
Gradual decrease with the system size → effect of rescattering.

K*/K ratio slightly decreasing with multiplicity in pp and p–Pb → hint of non-zero lifetime of hadronic phase in small systems.
\[ \frac{K^*}{K} \text{kinetic}(\text{Pb--Pb}) = \frac{K^*}{K} \text{chemical}(pp) \times \exp\left(-\frac{\tau}{\tau^*_K}\right) \]

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

\( \tau \): timespan between chemical and kinetic freeze-out.

Lower limit of the hadronic phase by studying the behaviour of \( K^*(892)^0 \). Assume no regeneration effects.
**$p_T$ differential yield ratios**

**Low $p_T$:** $K^0/K$ for central collisions are lower than peripheral (pp) collisions whereas $\phi/K$ are comparable within the uncertainties

- $K^0$ yields in central Pb–Pb collisions are suppressed due to re-scattering in the hadronic phase

- Most effect on low momentum particles

**Intermediate $p_T$:** ratios show greater enhancement for central Pb–Pb collisions than peripheral and pp collisions
Smooth evolution with charged particle multiplicity in all available collision energies and systems (pp, p–Pb, Pb–Pb, Xe–Xe).

Strangeness enhancement increases with strangeness content.

\( \phi \): hidden strangeness. How does it behave?
Particle yield ratios - \( \phi \) meson

\[ \phi/\pi : (|\text{SI}|=0)/(|\text{SI}|=0) \]

\( \phi/\pi \) ratio saturates in Pb–Pb collisions and is consistent with thermal model predictions.

\( \phi/\pi \) ratio increases with multiplicity in small systems, this is not expected for canonical suppression (see next slide).
Particle yield ratios - $\phi$ meson

$\phi/K$ \(\langle ISI=0\rangle/\langle ISI=1\rangle\)

Flat or slightly increasing ratio at lowest multiplicities suggests that $\phi$ behaves like a $S \geq 1$ particle.

$\Xi/\phi$ \(\langle ISI=2\rangle/\langle ISI=0\rangle\)

- Increases at low multiplicity.
- Remains fairly flat across wide multiplicity range.

The $\phi$ has “effective strangeness” of 1–2 units.
Nuclear modification factors ($R_{\text{AA}}$)

\[ R_{\text{AA}} = \frac{dN_{\text{AA}} / dp_T}{\langle N_{\text{coll}} \rangle dN_{\text{pp}} / dp_T} \]

- $p_T$ distribution in A–A collisions
- $p_T$ distribution in pp collisions
- Number of binary collisions, $N_{\text{coll}}$. 
Nuclear modification factors ($R_{AA}$)

$R_{AA}$

ALICE
Pb-Pb $\sqrt{s_{NN}} = 5.02 \text{ TeV (0-10 \%)}

\begin{itemize}
  \item $p_T < 2 \text{ GeV/c}$: \\
  $K^\ast$ $R_{AA}$ values are the smallest $\rightarrow$ \\
  Effect of re-scattering.
  
  \item $2 < p_T < 8 \text{ GeV/c}$: \\
  - hadron mass dependence for mesons. \\
  - Protons have the highest values of $R_{AA} \rightarrow$ \\
  baryon-meson ordering.
  
  \item $p_T > 8 \text{ GeV/c}$: similar $R_{AA}$ values for all hadron species within the uncertainties $\rightarrow$ \\
  the relative particle composition at high $p_T$ remains the same as in vacuum.
\end{itemize}

arXiv:2106.13113

P. Ganoti, 20 October 2021
Exploring new resonances: Ξ(1820)

FASTSUM collaboration: (lattice QCD simulations)

In the presence of unbroken chiral symmetry, it can be shown that positive- and negative-parity baryonic channels are degenerate, and hence there is parity doubling.

Expected signal experimentally: mass shift, width broadening or change in yield ratio between Ξ(1820) and Ξ(1530).
Exploring new resonances: $f_0(980)$

Quark contents of $f_0(980)$ is still controversial.

Study of $f_0(980)$ production would give a hint of its quark contents → tetraquark candidate.

On-going effort in all available collision systems.

Reconstructed via $f_0(980) \rightarrow \pi^+ \pi^-$

Large contributions from other resonances.
The future...

- More statistics accumulated in the forthcoming runs will result in more precision measurements.
- This will enable also multi-differential analyses, for example:

**Dependence of strangeness production on effective energy.**
The future...

- More statistics accumulated in the forthcoming runs will result in more precision measurements.
- This will enable also multi-differential analyses, for example:

\[
S_0 = \frac{\pi^2}{4} \min_{\hat{n}=(n_x, n_y, 0)} \left( \frac{\sum_i |\vec{p}_{T_i} \times \hat{n}|}{\sum_i p_{T_i}} \right)^2
\]

\[S_0 = \begin{cases} 
0 & \text{“pencil-like” limit (hard events)} \\
1 & \text{“isotropic” limit (soft events)}
\end{cases}
\]

Dependence of resonance production on effective energy.
ALICE has provided a comprehensive study of resonances in pp, p-Pb and Pb-Pb collisions at various energies with very interesting results.

- The hardening of $p_T$ spectra is observed in small collision systems $\rightarrow$ collective flow-like phenomena in small systems.

- Rescattering is the dominant process in the hadronic phase for short-lived resonances ($\tau < \sim 15$ fm/c).

- Parton energy loss at high $p_T$ is species independent.

- Resonance production is independent of the collision energy and system and it is driven by the event multiplicity.

- $\rho^0$, $K^{*0}$, $\Sigma^{*+}$, $\Lambda^*$ are suppressed in most central collisions with respect to small collisions systems. $\Phi$ with $\tau = 46.4$ fm/c is not suppressed. It has an effective strangeness of 1-2 units.

- More resonances are being explored: $f_0(980)$ and $\Xi(1820)$. 
Backup
Models

The EPOS3 model describes the evolution of a heavy-ion collision with the reaction volume being divided into a core and a corona part. After hadronization, hadrons are fed into the UrQMD hadron cascade afterburner, which describes hadronic interactions in a microscopic approach.


The statistical hadronization model describes the process of hadron formation at the scale where QCD is no longer applicable. It is assumed that near hadronization the fireball created in heavy-ion collisions is close to thermal equilibrium and hadron yields can be characterized by a grand canonical partition function.