Hadronic Resonances in Heavy-Ion Collisions at ALICE

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Introduction

- This Presentation: $K^*^0$ and $\phi$ in Pb–Pb collisions
- Hadronic Phase: Temperature and Lifetime of fireball
  - Resonance formation at hadronization, through regeneration
  - Re-scattering prevents resonance reconstruction
    - Most important at low $p_T$ (< 2 GeV/c)
    - Statistical models and UrQMD predict resonance/stable ratios
  - Given chemical freeze-out temperature and/or time between chemical and thermal freeze-out ($\Delta t$)
- Chiral Symmetry Restoration
  - Resonances that decay when chiral symmetry was at least partially restored would exhibit mass shifts and width broadening

![Diagram showing temperature and lifetime correlations](image-url)
VZERO (scintillators): centrality estimate through measurement of amplitude in VZERO

ITS (silicon): Tracking and Vertexing

TPC: Tracking and Particle ID through dE/dx
$K^*^0$ and $\phi$ in Pb-Pb
Resonance Reconstruction

- Event Selection:
  - $|v_z| < 10$ cm
  - $K^*0$: 8.2 M events
  - $\phi$: 9.5 M events
- Hadronic Decays
- PID: TPC $dE/dx: 2\sigma_{TPC}$ cut
- Combinatorial Background: Event Mixing
  - Require similar $v_z$, multiplicity, event plane
- Fit Residual Background + Peak

$K^*0$ B.R. = 66.6%
$\tau = 4.05$ fm/c

$\phi$ B.R. = 48.9%
$\tau = 46.3$ fm/c
Resonance Reconstruction

- **Event Selection:**
  - \(|v_z| < 10 \text{ cm}\)
  - \(K^*: 8.2 \text{ M events}\)
  - \(\phi: 9.5 \text{ M events}\)

- **Hadronic Decays**

- **PID:** TPC \(dE/dx: 2\sigma_{TPC}\) cut

- **Combinatorial Background:** Event Mixing
  - Require similar \(v_z\), multiplicity, event plane

- **Fit Residual Background + Peak**

![Graph 1](image1.png)

- **Significance:** 55\(\sigma\), \(S/B = 0.00019\)

![Graph 2](image2.png)

- **Significance:** 38\(\sigma\), \(S/B = 0.01\)

\(p_T < 5.0 \text{ GeV/c}, |y| < 0.5\)

\(K^0 + \bar{K}^0 \rightarrow K^+ + \bar{K}^-\)

\(Pb-Pb, S_{NN} = 2.76 \text{ TeV, Centrality 0-20\%}\)

\(|<0.5y, |c<1 \text{ GeV/c}|\)

\(0.8<p_T<1 \text{ GeV/c}, |y|<0.5\)

Statistical Uncertainties

\(12/07/2013\)

\(29/05/2013\)
• **K*⁰**: Mass and width consistent with MC HIJING Simulation
  – No centrality dependence

![Mass and Width](image-url)
• $K^*$: Mass and width consistent with MC HIJING Simulation
  – No centrality dependence

$\phi$: Mass and width consistent with Vacuum Values
  – No centrality dependence

• Signatures of chiral symmetry restoration are not observed
  – Caveat: reconstructing the hadronic decays
• Fit Corrected Spectra (in centrality intervals)
  □ $\phi$: Boltzmann-Gibbs Blast Wave Function
    • Extrapolate $\phi$ yield to low $p_T$ (~15% of total yield)
     – $K^*$: Lévy-Tsallis Function
       • Spectrum reaches $p_T=0$, no extrapolation needed
• $<p_T>$ appears to increase for more central Pb–Pb collisions
• $<p_T>$ in pp at $\sqrt{s}=7$ TeV
  – Consistent with peripheral Pb–Pb
  – Lower than central Pb–Pb
• $<p_T>$ greater at LHC than RHIC
  – For $K^*$: 20% larger
  – For $\phi$: 30% larger
• ALICE $\pi,K,p$ spectra: global blast-wave fit shows ~10% increase in radial flow w.r.t. RHIC
  – See Also: Talk by M. Chojnacki, SQM 2013
Particle Ratios vs. Centrality

- $\phi/\pi$ and $\phi/K$ independent of centrality
  - $K^*/K^-$: apparent decrease for central collisions
    - Suggests re-scattering effects in central collisions

\[
\frac{f}{p} = \frac{0.05}{0.1} \quad 0.15 \quad 0.2
\]

\[
\frac{K^0}{K^-} = \frac{0.05}{0.1} \quad 0.15 \quad 0.2
\]

\[\langle N_{\text{part}} \rangle\]
• Measured $K^*/K^-$ ratio in central Pb–Pb smaller than in pp
  – Similar behavior at RHIC
• Model Predictions:
  
  Andronic [1]
  no re-scattering
  $T_{ch} = 156$ MeV
  Prediction: $K^*/K^- = 0.30$
  
  Torrieri/Rafelski [2-4]
  no re-scattering
  $T_{ch} = 156$ MeV
  Prediction: $K^*/K^- = 0.35$

our assumption, based on thermal model fits of ALICE data

**K*⁰/K⁻ vs. Energy**

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    - Torrieri/Rafelski [2-4]
      - no re-scattering
      - measured K*⁰/K⁻
      - Prediction: $T_{\text{ch}} = 120\pm13$ MeV
      - K*⁰/K⁻ = 0.194±0.051

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    - Prediction: $K^*/K^- = 0.35$
    - measured $K^*/K^-$
    - $T_{ch} = 120 \pm 13$ MeV
    - Prediction: Lifetime $\geq 1.5$ fm/c

Calculation for SPS/RHIC energies

\( \phi/K \) vs. Energy

- \( \phi/K \) independent of energy and system from RHIC to LHC energies
Spectrum Shapes

- $K^0$ yield is modified by re-scattering, $\phi$ yield is not
  - Models (UrQMD) predict re-scattering strongest for $p_T < 2$ GeV/c
  - Can we observe $p_T$ dependence of resonance suppression?
- Generate predicted $K^0$ and $\phi$ spectra:
  - Use blast-wave model, parameters ($T_{\text{kin}}$, $n$, and $\beta_s$) measured in global BW fits of $\pi$, K, and p in Pb–Pb collisions

Fit ranges: $0.5 < p_T(p) < 1$ GeV/c  $0.2 < p_T(K) < 1.5$ GeV/c  $0.3 < p_T(p) < 3$ GeV/c
Predicted Spectra

- **Model (0-20%)**: $T_{\text{kin}}=97.1$ MeV, $n=0.725$, $\beta_s=0.879$
  - $K^0$: Integral = Yield($K^\pm$,Pb–Pb) × Ratio($K^0$/K,pp)
  - $\phi$: Integral = Yield($K^\pm$,Pb–Pb) × Ratio($\phi$/K,pp)
  - Assumes no re-scattering and common freze-out

- **Centrality 0-20%**
  - $K^0$ yield suppressed w.r.t. prediction for $p_T<3$ GeV/c
    - Suppression is flat ($\approx0.6$) for $p_T<3$ GeV/c
  - $\phi$ yield not suppressed
  - $K^0$ and $\phi$ follow similar trend for high $p_T$
Predicted Spectra

- **Model (60-80%)**: \(T_{\text{kin}} = 132.2\) MeV, \(n = 1.382, \beta_s = 0.798\)
  - \(K^0\): Integral = \(\text{Yield}(K^\pm, \text{Pb-Pb}) \times \text{Ratio}(K^0/K, pp)\)
  - \(\phi\): Integral = \(\text{Yield}(K^\pm, \text{Pb-Pb}) \times \text{Ratio}(\phi/K, pp)\)
  - Assumes no re-scattering and common freze-out

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  - \(K^0\) yield suppressed w.r.t. prediction for \(p_T < 3\) GeV/c
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  - \(\phi\) yield not suppressed
  - \(K^0\) and \(\phi\) follow similar trend for high \(p_T\)

- **Centrality 60-80%**
  - Neither suppressed
  - Deviations at high \(p_T\) similar to other particles

![Graph](image-url)
K*0/p and φ/p vs. p_T

- K*0/p and φ/p:
  - Flat for central collisions
  - Increasing slope for peripheral collisions
  - Peripheral Pb–Pb similar to pp (√s=7 TeV)
- Different production mechanism for K*0, p, or φ in central vs. peripheral & pp?
- <p_T> peripheral → central:
  - <p_T> of π±, K±, K*0, and φ increases by ~20%
  - <p_T> of protons increases by 50%
• Ratio in Pb-Pb consistent with Au-Au (200 GeV) for $p_T<3.5$ GeV/c.
• VISH2+1 and HKM (hydro) predictions consistent with data for $p_T<2.5$ GeV/c.
• KRAKOW model (hydro) consistent with data for $2.5<p_T<3.7$ GeV/c.
• HIJING/Bb̅ does not describe data (does predict flat ratio at high $p_T$).

![Graph showing the ratio of $\Omega/\phi$ vs. $p_T$ with various models and data points.](image-url)
• Central Collisions:
  – Low $p_T$: $R_{AA}(\phi)$ follows $R_{AA}(p)$ and $R_{AA}(\Xi)$
  – High $p_T$:
    • $R_{AA}(\phi)$ between $R_{AA}(\pi,K)$ and $R_{AA}(p)$
    • $R_{AA}(\phi)$ tends to be below $R_{AA}(p)$ despite larger $\phi$ mass, but consistent within uncertainties
    • $R_{AA}(\phi)$ below $R_{AA}(\Xi)$, despite similar strange quark content
    • All $R_{AA}$ values converge around $p_T\approx 7$ GeV/c
• Peripheral Collisions:
  – $R_{AA}(\phi)$ follows $R_{AA}(p)$ and $R_{AA}(\Xi)$
  – All $R_{AA}$ values converge around $p_T\approx 4$ GeV/c
• $R_{CP}(K^{*0})$ tends to be lower than $R_{CP}(\phi)$, but same within uncertainties
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- $R_{AA}(\phi)$ follows $R_{AA}(p)$ and $R_{AA}(\Xi)$
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- $R_{CP}(K^{*0})$ tends to be lower than $R_{CP}(\phi)$, but same within uncertainties
Conclusions

• Resonance Mass and Width
  – When $K^*$ and $\phi$ are reconstructed via hadronic decays, no mass shifts or width broadening

• $<p_T>$ larger for more central collisions
  – Larger at LHC than at RHIC (increased radial flow)

□ $\phi/K$ flat with centrality

• But $K^*/K$ decreases with centrality (re-scattering may reduce reconstructible $K^*$ yield)
  – Use measured $K^*/K$ + thermal model + re-scattering [Torrieri/Rafelski] to estimate lifetime of hadronic phase: $\geq 1.5 \text{ fm/c}$

• $K^*$ suppression flat in $p_T$ ($\approx 0.6$) for $p_T<3$ GeV/c

• $K^*/p$ and $\phi/p$ ratios vs. $p_T$:
  – Flat in central collisions
  – Increasing slope for peripheral collisions (despite very similar masses of these particles)

• $R_{AA}$ at low $p_T$: $R_{AA}(\phi) = R_{AA}(p) = R_{AA}(\Xi)$

• $R_{AA}$ at intermediate $p_T$: $R_{AA}(\pi, K) \leq R_{AA}(\phi) \leq R_{AA}(p) \leq R_{AA}(\Xi) \leq R_{AA}(\Omega)$
Backup
Finding Resonances

Event Selection:
\(|v_z| < 10 \text{ cm}\)
8.2 M events for K*\(^0\)
9.5 M event for \(\phi\)

Find \(\pi^\pm, K^\pm\):
- **Track Cuts:**
  - Number of TPC Clusters
  - Track \(\chi^2\)
  - DCA to Primary Vertex
  - Others…
- **Particle Identification:**
  - TPC Energy Loss (\(dE/dx\))
  - \(2\sigma_{TPC}\) cut for \(\pi\) and \(K\)

Find Decay Products

\(K^*^0\) Branching Ratio: 66.6%
\(\phi\) Branching Ratio: 48.9%
Corrections

- Efficiency $\times$ Acceptance from simulation
- PID Efficiency $(2\sigma_{TPC} \, dE/dx$ cuts on each daughter $\rightarrow \varepsilon_{PID} = 91\%)$
\( \phi/\pi \) vs. Energy

- \( \phi/\pi \) independent of energy and system at LHC energies

 uncertainties: stat. (bars), sys. (shaded boxes), \( \sqrt{\text{stat.}^2 + \text{sys.}^2} \) (empty boxes)

- PHENIX Au-Au
- STAR Au-Au
- NA49 Pb-Pb
- PHENIX pp
- STAR pp
- NA49 pp

ALICE Preliminary Pb-Pb

ALICE pp

ALICE

ALI−PREL−26719
\( K^*/\pi \) and \( \phi/\pi \) vs. \( p_T \)

- \( K^*/\pi \) and \( \phi/\pi \): increase with \( p_T \)
  - Slope decreases for peripheral collisions
  - Peripheral Pb–Pb similar to pp (\( \sqrt{s} = 7 \) TeV)
**K*^0/K and φ/K vs. \( p_T \)**

- **K*^0/K and φ/K**: (linear) increase with \( p_T \)
  - Slope decreases for peripheral collisions
  - Peripheral Pb–Pb similar to pp (\( \sqrt{s}=7 \text{ TeV} \))
  - Similar behavior in K*^0/\( \pi \) and φ/\( \pi \) ratios
- Increase with $p_T$ at low $p_T$
- Saturate or begin to decrease at high $p_T$
- Become flatter for peripheral collisions
$p_T$-Dependent Ratios

$|y|<0.5$, Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV, Centrality 0-20%

uncertainties: stat. (bars), sys. (boxes)
Blast-Wave Fit Parameters

• Blast-wave parameters from $\pi/K/p$ paper
  – central $\rightarrow$ peripheral: $T_{\text{kin}}$ and $n$ increase, $\beta_s$ decreases